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For the Brown's Creek Watershed District

Saint Anthony Falls Laboratory Project Report #585

Riparian Shading Study

September 5, 2018

Cover Images

Brown's Creek south of Millbrook Circle

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Funding for this project was provided by the Clean Water Land and Legacy Amendment and the Brown's Creek Watershed District.

GLOSSARY

Term	Definition
Aspect	Slope orientation relative to north, south, east, and west.
Atmospheric Transmissivity	The ratio of global solar radiation at the ground to extraterrestrial solar radiation. This value indicates the amount of solar radiation that is scattered by dust particles or water vapor as it travels through the atmosphere. The value is typically between 0.4 and 0.9.
Azimuth (Stream Azimuth)	The direction that the stream is flowing relative to due north measured by orienting a compass downstream with the direction of the meander. In some applications, azimuth is measured relative to due south +/- 90° where a north or south-flowing stream would have an azimuth of 0° and a southeast/northwest flowing stream would have an azimuth of -45°.
Bankfull Width	The width of the channel at the average annual high water mark.
Baseflow	The part of stream discharge sourced from groundwater seeping into the stream.
Climate Change	A long-term change in climate patterns such as temperature and rainfall. Changes in climate have a large impact on water quality, lake and wetland water levels, and stream and river flows.
Critical Temperature	The water temperature at which direct mortality of aquatic biota (i.e. fish and macroinvertebrates) is expected.
Diffuse Radiation	The solar radiation reaching the Earth's surface after the direct solar beam is scattered by molecules or particulates in the atmosphere. Typically expressed in irradiance units (W/m^2).
Direct Radiation	The solar radiation that reaches the Earth’s surface without being absorbed, scattered, or reflected in the atmosphere. Typically expressed in irradiance units (W/m^2).
Dissolved Oxygen	The level of free, non-compound oxygen present in water or other liquids. It is an important parameter in assessing water quality because of its influence on the organisms living within a body of water.
Extraterrestrial Radiation	The intensity (power) of solar radiation at the top of the Earth’s atmosphere. Typically expressed in irradiance units (W/m^2).
Geomorphology	The study of the processes responsible for the shape and form, or morphology, of watercourses. It describes the processes whereby sediment (e.g. silt, sand, gravel) and water are transported from the headwaters of a watershed to its mouth.
Global Radiation	See Total Radiation.
Gradient	The slope of the stream channel.
Height Above River	The difference in elevation of the top of vegetation and the water surface.
Hyporheic Zone	A region beneath and alongside a stream bed where there is mixing of shallow groundwater and surface water.
Impaired Biota	A biotic impairment means that a water body is not supporting the aquatic organisms that it should. The challenge is in determining the stressors (i.e. conditions affecting the biota). The EPA has defined a protocol for identifying stressors and analyzing the Total Maximum Daily Load (TMDL) for each primary stressor.

Impaired Waters	Streams or lakes that do not meet their designated uses because of excess pollutants or other identified stressors.
Impervious	A hard surface that either prevents or retards the entry of water into the soil and causes water to run off the surface in greater quantities and at an increased rate of flow than pervious surfaces prior to development.
Indirect Radiation	See Diffuse Radiation.
Landlocked Basin	A basin or localized depression that does not have a natural outlet at or below the water elevation of the 10-day precipitation event with a 100-year return frequency.
Latent Heat Loss	A type of energy released or absorbed in the atmosphere which is related to changes in phase between liquids, gases, and solids. Such phase transitions include vaporization (evaporation), condensation, fusion (melting), freezing, sublimation, and vapor deposition.
Macroinvertebrates	Organisms without backbones which are visible to the eye without the aid of a microscope. Aquatic macroinvertebrates live on, under, and around rocks and sediment on the bottoms of lakes, rivers, and streams.
Photosynthetically Active Radiation	The spectral range of solar radiation from 400 to 700 nanometers that photosynthetic organisms are able to use in the process of photosynthesis.
Pyranometer	A pyranometer is a sensor used to measure solar radiation flux density (W/m^2) reaching a flat surface from the hemisphere above within a wavelength range of 0.3 µm to 3 µm.
Regression Analysis	A set of statistical modeling processes for estimating the relationships between variables.
Riparian	Situated on the banks of a water body.
River Left	The left-hand side of the river or stream as it would appear to an observer who is facing downstream.
River Right	The right-hand side of the river or stream as it would appear to an observer who is facing downstream.
Rosgen Classification	A classification system for rivers based on channel slope, width to depth ratio, bed material, entrenchment ratio, and sinuosity (Rosgen, 1994).
Senescence	The process of aging in plants due to stress or age. For perennial plants, periods of organ and plant cell senescence lead to plant dormancy such as winter in cold climates. While senescence includes all parts of a plant, it's commonly observed during self-induced organ senescence, such as autumn senescence (shedding) of deciduous leaves from trees, shrubs, or grassy species.
Sensible Heat Loss	A type of energy released or absorbed in the atmosphere which is related to changes in temperature of a gas or object but with no change in phase.
Shade	One minus the ratio of total solar radiation under and over the canopy. Shade is measured or calculated on an instantaneous, daily, or seasonal basis. Shade varies based on the structure of overhead vegetation, adjacent topography, and position of the sun. Temporal variation in shade is due to the varying position of the sun, the variable intensity of incoming solar radiation, and plant growth /senescence.
Sinuosity	The ratio of channel length to valley length.
Solar Constant	The amount of extraterrestrial shortwave radiation received on a surface perpendicular to solar rays above the earth atmosphere.

Solar Radiation	The radiant energy emitted by the sun which includes wavelengths between 300 to 3000 nm. Approximately half of the radiation is in the visible short-wave part of the electromagnetic spectrum. The other half is mostly in the near-infrared part, with some in the ultraviolet part of the spectrum. Typically expressed in irradiance units (W/m^2).
Substrate	The percent of channel bed composed of each size class of material (i.e. bedrock, bolder, cobble, gravel, sand or fines).
Thalweg Depth	The deepest part of the channel measured relative to the water's surface.
Threat Temperature	The water temperature at which aquatic biota experience increased physiological stress, reduced growth, and egg mortality.
Total Hemisphere Gap Fraction	The ratio of the number of pixels in the photograph classified as sky and the total number of pixels in the photograph as calculated in the software WinSCANOPY. The total hemisphere gap fraction does not account for the projection of the lens onto the plane of the photograph, and so it does not reflect the real canopy above the lens.
Total Hemisphere Openness	The ratio of open sky in a hemispherical photograph relative to the total hemisphere area above the lens as calculated in the software WinSCANOPY. This is sometimes referred to as percent open sky. In comparison to the gap fraction, openness accounts for the projection of the area above the lens onto a flat plane (i.e. the image).
Total Radiation	The sum of the diffuse and direct solar radiation reaching a surface. Typically expressed in irradiance units (W/m^2).
Total Site Factor	The ratio of average daily direct and indirect solar radiation under and over the canopy over the simulation period as calculated in the software WinSCANOPY by analyzing hemispherical photographs.
Transect	A straight line or narrow section through an object or natural feature and along which observations are made or measurements taken.
Water Table	The underground surface beneath which earth materials such as soil or rock are saturated with water.
Wetted Width	The width of the wetted surface of a stream measured perpendicular to the direction of flow and subtracting mid-channel point bars and islands that are above the bankfull depth.
Zenith	The point in the sky directly above an observer. Solar radiation is most powerful when the sun is at this location (i.e. at midday).

ACRONYMS

BCWD	Brown's Creek Watershed District
BMP	Best management practice
cm	centimeter
DBH	Diameter at breast height
DEM	Digital elevation model
dm	decimeter
DSM	Digital surface model
EBLF	Eastern Broadleaf Forest
ECS	Ecological Classification System
EOR	Emmons & Olivier Resources, Inc.
fasl	feet above sea level
FVA	Function and Value Assessment
GIS	Geographic Information System
GPS	Global positioning system
HAR	Height above river
HSG	Hydrologic Soil Group
IBI	Indices of biotic integrity
LiDAR	Light Detection and Ranging
masl	meters above sea level
MINUHET	MINnesota Urban Heat Export Tool
MNDNR	Minnesota Department of Natural Resources
MNEIM	Minnesota and Northeast Iowa Morainal
NPC	Native Plant Communities
NRCS	Natural Resources Conservation Service
PAR	Photosynthetically active radiation
PLS	Public Land Survey
RMSE	Root Mean Square Error
SBPM	St. Paul-Baldwin Plains and Moraines
SGCN	Species of Greatest Conservation Need
SNTEMP	Stream Network and Stream Segment Temperature Models Software
SSTEMP	Stream Segment Temperature Model
THPP	Trout Habitat Preservation Project
TMDL	Total Maximum Daily Load
TSMP	Trout stream mitigation project
TSS	Total suspended solids
USACOE	United States Army Corps of Engineers
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WCD	Washington Conservation District
WIDNR	Wisconsin Department of Natural Resources
WMP	Watershed Management Plan
WOMP	Watershed Outlet Monitoring Program

EXECUTIVE SUMMARY

Brown's Creek is a designated trout stream located in Washington County, Minnesota. High stream temperature is one of the primary stressors contributing to the creek's impairment for biota due to lack of coldwater assemblage. The Brown's Creek Watershed District (BCWD) has studied and implemented policies, programs, and projects to lower the stream temperature (See Section 2). The BCWD's Total Maximum Daily Load (TMDL) Implementation Plan (2012) identified increasing shade provided by riparian vegetation as one of the main strategies for lowering stream temperatures to levels that can support biotic health. Since then, the BCWD has collected monitoring data and developed the hydrologic, hydraulic, and thermal watershed model needed to design targeted shade restoration projects.

The purpose of this Riparian Shading Study was to develop a targeted riparian shade restoration plan within the three unforested miles of Brown's Creek located between Manning Avenue/County Road 15 and County Road 55/Stonebridge Trail in order to reduce monthly mean baseflow stream temperatures by 0.5 to 1°C. The study also mitigated potential detrimental impacts of increased shade, such as erosion of stream banks, and identified guidelines for shade restoration design.

Brown's Creek winds through low-lying wetlands and woodlands with hydric soils. Groundwater discharges to the creek at multiple locations and recharges from the creek in others. Historically, the creek supported brook trout and the riparian buffer was primarily oak barrens vegetation. More recently, a stocked brown trout population has struggled to establish. Section 3 describes the study area characteristics pertinent to riparian and stream temperature management decisions.

The first of two literature reviews in this study identified hemispherical photography as the best-suited method for comparing shade provided by grassy and woody riparian vegetation along small streams (See Section 4). Direct measurements of shade using arrays of light sensors are useful in validating hemispherical photography results. Physical characteristics of the stream and vegetation are useful in diagnosing differences in observed shade. Canopy cover, closure, and stream temperature are not acceptable surrogate measurements for shade.

The second literature review compared the functions of riparian buffers composed of grassy and woody species. Controlling sediment and phosphorus, increasing dissolved oxygen, supporting aquatic fauna, and maintaining groundwater inputs are all functions of riparian buffers that contribute to achieving the BCWD's watershed management objectives. The review considers how modifying vegetation may alter these functions. Forested buffers are considered a best practice for protecting coldwater streams, however afforestation of the meadows along Brown's Creek may result in negative changes to channel morphology, exacerbating turbidity levels that are already elevated and causing a loss of trout habitat. Streams with forested buffers are typically wide and shallow whereas streams with grassy buffers are narrow and deep with overhanging banks. The latter is optimal for supporting trout, although opening the canopy to incoming solar radiation too much could radically warm the stream. The practical implication of these trade-offs is that both grassy and woody riparian vegetation are beneficial to small coldwater streams. Riparian management strategies should support a mosaic of grassy and woody vegetation by thinning densely forested buffers and planting trees or shrubs in meadows along the stream. This approach will simultaneously improve stream shade and bank stability, working towards a common overarching goal of supporting the health of coldwater biota.

Shade provided by grassy and woody riparian vegetation on Brown's Creek was assessed using hemispherical photos of the canopy overhanging the creek (See Section 5). Shade was estimated using the program WinSCANOPY by simulating the solar path across each monitoring location relative to the detailed canopy structure from the hemispherical photos. The results of the hemispherical photograph analysis were extrapolated to the entire main branch of Brown's Creek using a correlation with relative shade estimated by LiDAR analysis. The direct use of LiDAR data would have underestimated existing shade and over-estimated the potential stream temperature benefits of shade restoration. Solitary trees in grassy meadows along the creek were found to increase shade above 80%. Shade at locations with no riparian trees ranged from 10% to 61% with an average of 34%. Shade varied from 8% to 97% and was 61% on average across the study area. The segment of the Oak Glen Golf Course that was restored in 2012 was found to have an average shade of 46% which is a significant increase from 10% shade pre-restoration.

The physical characteristics of Brown's Creek and its riparian vegetation were analyzed further to understand how shade restoration projects could be optimized for both stream temperature and bank stability objectives. Tree plantings will be most effective on the south bank of east-west oriented segments and can be set back approximately 10 m from the edge of the stream to prevent detrimental impacts to bank stability while still providing shade benefits. In a narrow stream such as Brown's Creek, optimizing grassy vegetation improvements will greatly increase shade without introducing woody vegetation. Grassy improvements should focus on establishing cover on banks and using species with maximized height and canopy to hang over the stream. The results indicate that optimized grassy vegetation can achieve more than 75% shade where the stream orientation is between 315° to 45° or between 135° to 225° relative to due north.

A targeted shade restoration plan for the BCWD was developed based on the riparian shade analysis. Four stream segments (Segments 10b, 11, 12, and 13) were identified as high priorities for shade restoration. Segments are located between County Road 15/Manning Avenue and the south side of the Millbrook Development. These were amongst the segments identified for in-stream thermal improvements in the District's TMDL Implementation Plan and Watershed Management Plan (WMP). Concept plans were developed for the four segments to illustrate the proposed grassy vegetation enhancements and tree plantings in addition to stream meander restoration, where applicable (See Figure 49 to Figure 52). These projects are expected to increase the average shade from 76% to 84% between County Road 15/Manning Avenue and the St. Croix River. Shade is expected to increase by 2% to 4% within 5 to 10 years of planting when grassy vegetation is mature. Shade will continue to increase, albeit at a slower pace, for 50 to 150 years as the woody vegetation matures. The estimated cost of each project ranges from $92,000 to $498,000, including administrative, engineering, construction/implementation, 2-year maintenance, and a 20% contingency. The total cost of implementing the four projects is estimated to be $928,152. This will be an important long term investment that will also help the stream adapt to climate change as air temperatures continue to rise.

The cumulative benefit of shade restoration throughout the study area may be a tipping point for supporting brown trout and coldwater biota at critical periods in Brown's Creek. The stream temperature benefits of shade restoration were assessed using the District's CE-QUAL-W2 stream temperature model under various wet/dry precipitation and cool/warm air temperature conditions (See Section 6). The modeling indicates that shade restoration will decrease monthly mean stream temperatures in the summer by 0.16 to 0.52°C. This will provide much needed refuge for brown trout at the bottom of the gorge in warm and dry summers. When the summers are cool and wet, brown trout will be supported by cooler stream temperatures up through the middle reach of Brown's Creek. Daily maximum stream temperatures will still occasionally exceed the threat and critical thresholds for brown trout and the duration of exceedances will continue to be challenging for coldwater biota in July under warm/dry climate conditions. Shade restoration alone will not fully address high stream temperatures in Brown's Creek although they will shift stream temperature trends below the threat and critical thresholds under some circumstances. The BCWD will need to continue implementing other stream cooling measures identified in the District's TMDL Implementation Plan and WMP, such as baseflow augmentation, pond disconnection, and beaver management. These other strategies will be more effective when shade is restored along the creek.

The recommendations of the Riparian Shading Study are described in Section 7. The recommendations include an implementation plan for the four high priority shade restoration projects in addition to the remaining in-stream morphological and riparian buffer projects identified in the District's TMDL Implementation Plan and WMP. Additional shade restoration activities and programs are recommended through invasive plant management, guidance on best practices for increased shade, and management plans for plant communities. Continued use of the hemispherical photography equipment, modeling tools, and approaches applied in this study is recommended as part of the District's annual monitoring program to assess the long term success of shade restoration efforts as detailed in Appendix E. Shade maintenance should include annual enhancements to small riparian areas that have stunted grassy vegetation, emergent vegetation, exposed banks, or new sediment accumulation.

Shade is yet another benefit of buffers that should be considered when restoring and managing riparian vegetation along small coldwater streams. The mosaic approach to riparian vegetation management presented in this study is different from current guidance in Minnesota developed with a focus on rural setting sand non-thermal pollutants. The applicability of this study to other watersheds should be tested using similar methods. The District will continue monitoring riparian shade along Brown's Creek as recommendations are implemented and will continue learning from this unique case study in restoring an urbanizing coldwater trout stream.

1. INTRODUCTION

Brown's Creek is a designated trout stream located in Washington County, Minnesota. It flows through the communities of May Township, Stillwater Township, the City of Grant and the City of Stillwater before discharging to the St. Croix River. High stream temperature is one of the key stressors contributing to the creek's impairments for biota and lack of coldwater assemblage. The Brown's Creek Watershed District (BCWD) has identified increasing shade provided by riparian vegetation as one of the main strategies for controlling stream temperatures to levels that can support biotic health. However, the BCWD has also observed that dense canopy cover can have detrimental impacts on other water quality parameters, such as streambank erosion exacerbating already elevated turbidity levels.

The purpose of this Riparian Shading Study was to develop a targeted riparian shade restoration implementation plan within the three unforested miles of Brown's Creek to reduce monthly mean baseflow stream temperatures by 0.5 to 1°C. Development of this plan should mitigate potential detrimental impacts of increasing shade in the riparian corridor and should identify best practices for designing shade restoration plans.

This report is a record of the study's methodology, findings, and recommendations organized as follows:

Background: The history of managing stream temperature and biotic health of Brown's Creek.

Study Area Characterization: A summary of the soils, hydrology, channel, and other characteristics of the study area relevant to riparian management decisions.

Literature Reviews: A review of literature on the analysis of riparian shading, its impacts on stream temperature and biotic health, and what additional research is needed to guide riparian management decisions. An additional review conducted to identify the trade-offs of grassy or woody riparian vegetation for coldwater streams.

Riparian Shade Analysis: An updated shade analysis using hemispherical photographs and a sensitivity analysis of shade to physical channel and vegetation characteristics. Concept plans and estimated benefits of targeted shade restoration.

Stream Temperature Model: An updated stream temperature model for Brown's Creek with revised riparian shade in the existing conditions scenario and analysis of shade restoration scenarios.

Recommendations: Shade restoration implementation plan, monitoring, and next steps for controlling temperature in Brown's Creek, including estimated costs.

The scope of the study did not include assessing the contributions of groundwater inputs to Brown's Creek as a means to lower stream temperature.

2. BACKGROUND

Brown's Creek is one of the few remaining designated coldwater trout streams in the Twin Cities Metropolitan Area. From Highway 15 to the St. Croix River, Brown's Creek is classified as a Class 2A stream. Class 2A waters are protected to permit the propagation and maintenance of a healthy community of cold water sport or commercial fish and associated aquatic life, and their habitats (MN Rule 7050.0222, Subp. 2). Since its establishment in 1997, the BCWD has taken a proactive approach to restoring and protecting the ecological integrity of Brown's Creek as illustrated in Table 1. This section provides background on stream temperature mitigation in Brown's Creek in relation to supporting the health of the stream's ecosystem, of which the trout fishery is a major indicator.

Table 1. BCWD Projects and Programs Timeline (Emmons & Olivier Resources, 2017)

2018	Adopted Rules and Regulations (Jan. 10, 2018)
2017	• Acquire the Brown's Creek Conservation Area • McKusick Road Water Quality Improvements
2016	Brown's Creek Rock Crib
2015	Initiate 4th Generation Management Plan
	• Brown's Creek Thermal Study
2014	• Brown's Creek Trail • Countryside Auto Repair Improvement Water Quality Project • Brown's Creek Stream Rehabilitation • Northern Chain of Lakes Mgmt. Plan
2013	• Long Lake Water Quality Improvements Study • Installation of Iron Enhanced Sand Filter
2012	• Brown's Creek TMDL Implementation Plan • Groundwater Monitoring Program Initiated
2011	• Oak Glen Golf Course Restoration & Buffer Project • Fish Baffle Project • One-half mile of Long Lake planted with natives • Woodpile Lake Management Plan
2010	• Stillwater Country Club Projects • Masterman Lake Management Plan • Brown's Creek Impaired Biota/TMDL Report
2009	• Stormwater Retrofit at Ann Brodlovich Site in Marketplace Area • Confirmation of Eurasian Water Milfoil (Long Lake) • Long Lake temporary drawdown study • Partnered with TU on two restoration projects on Brown's Creek • Benz Lake Management Plan
2008	• G-DNR Mgmt Plan-Fen, Indian Hills Golf Course • Developed Land Conservation Priorities
2007	3nd Generation Management Plan
	• Adopted Rules & Regulations (April 24, 2007) • North Marketplace Pond Improvements • Herberger's Pond Improvement • Tower Drive Pond Improvement • Brown's Creek TMDL Stressor Identification • McKusick Lake Management Plan • Brown's Creek Erosion Inventory • Revised Rules & Regulations • THPP Infiltration Recovery Project
2006	• East Metro Water Resource Education Program • Long Lake Management Plan • BMP Cost-share Program
2005	• Stillwater Marketplace Area Analysis • Kern Center Pond Examination • Monitoring of THPP
2004	• H/H Study II • DNR Streambank Stabilization Project
2003	• TSMP • Long Lake Outlet Evaluation
2002	North Washington Groundwater Study
2001	Construction of THPP and Kismet Basin Project
2000	2nd Generation Management Plan
1999	• Adopted Rules & Regulations (January 1, 2000) • DNR Oak Glen Golf Course Stream Restoration
1998	Hydrologic/Hydraulic Study
1997	Brown's Creek Watershed District Established
1990	1st Generation Management Plan

The BCWD recognized that as a Class 2A stream, Brown's Creek was particularly sensitive to upland development activities and so developed the first watershed-wide hydrologic and hydraulic model in 1998 to better understand the water budget in Brown's Creek and the impacts of land development throughout the watershed. The District used this understanding to define its first Rules and Regulations in 1999 which included volume control standards to maintain surface water-groundwater interactions after land developments increase impervious surfaces in the watershed.

These rules were developed to mimic the natural hydrology of the system and required a Permit Applicant to match a pre-development runoff volume under post-development conditions. In 2007, the District revised its Rules to require a Permit Applicant to match a pre-settlement runoff volume under post-development conditions. In the same year as defining the BCWD's first Rules and Regulations (1999) the Minnesota Department of Natural Resources (MNDNR) realigned the segment of the Brown's Creek in the Oak Glen Golf Course upstream of McKusick Road that previously ran through McKusick wetland in order to improve fisheries habitat and reduce thermal pollution (Emmons & Olivier Resources, 2017). The District balanced the need for flood control and protecting the trout fishery from extreme stream temperatures by constructing the Trout Habitat Preservation Project (THPP) and Kismet Basin in the headwaters of the watershed in 2001. In 2002, the City of Stillwater constructed a diversion structure for the trout stream mitigation project (TSMP) to direct flows from the Long Lake drainage area into the McKusick Lake to avoid, minimize, and mitigate the environmental impacts of developing the Annexation Area. By diverting storm events up to a 2.6-inch rainfall event into McKusick Lake, instead of discharging to Brown's Creek, the diversion significantly reduced the heat load contributed to the creek from the Long Lake (Emmons & Olivier Resources, 2012).. The City constructed a small weep orifice at the bottom of the diversion structure in 2002 to maintain cold baseflow contributions to Brown's Creek, however assessment of the performance of this orifice and feasibility of retrofitting the structure found that the soils are not conducive to maintaining baseflow contribution to the creek. In the first decade of its existence, the BCWD also collected valuable monitoring data in understanding and diagnosing the health of the creek.

Brown's Creek is split into three reaches: the headwaters upstream of Highway 96 near County Road 15/Manning Avenue, the middle reach between Highway 96 and County Road 55/Stonebridge Trail, and the gorge reach downstream of County Road 55/Stonebridge Trail to the St. Croix River. All three reaches are impaired for aquatic recreation and aquatic life due to low levels of dissolved oxygen, lack of coldwater fish assemblage, and high levels of *E. coli* bacteria (Figure 1). Upstream of County Road 15/Manning Avenue, the headwaters reach is also impaired due to a low score of the Minnesota Macroinvertebrate Index of Biological Integrity (M-IBI). These impairments were listed on the federal 303(d) list between 2002 and 2008.

The District began a Total Maximum Daily Load (TMDL) Impaired Biota study in 2007 to diagnose the main factors causing the aquatic life impairment. Naturally occurring wetland conditions were identified as the main stressor to aquatic life in the headwaters reach upstream of County Road 15/Manning Avenue. Downstream of County Road 15/Manning Avenue and in the middle and gorge reaches, the study found that high stream temperature was a primary stressor contributing to the low indices of biotic integrity (IBI) in Brown's Creek, in addition to excess total suspended solids (TSS) and high concentrations of copper. Further monitoring and investigation of possible TSS sources since the TMDL Impaired Biota study has not identified concentrated TSS loads in the upper and middle reaches of Brown's Creek. Due to uncertainties related to the reliability of the copper monitoring data, copper loading allocations were not developed.

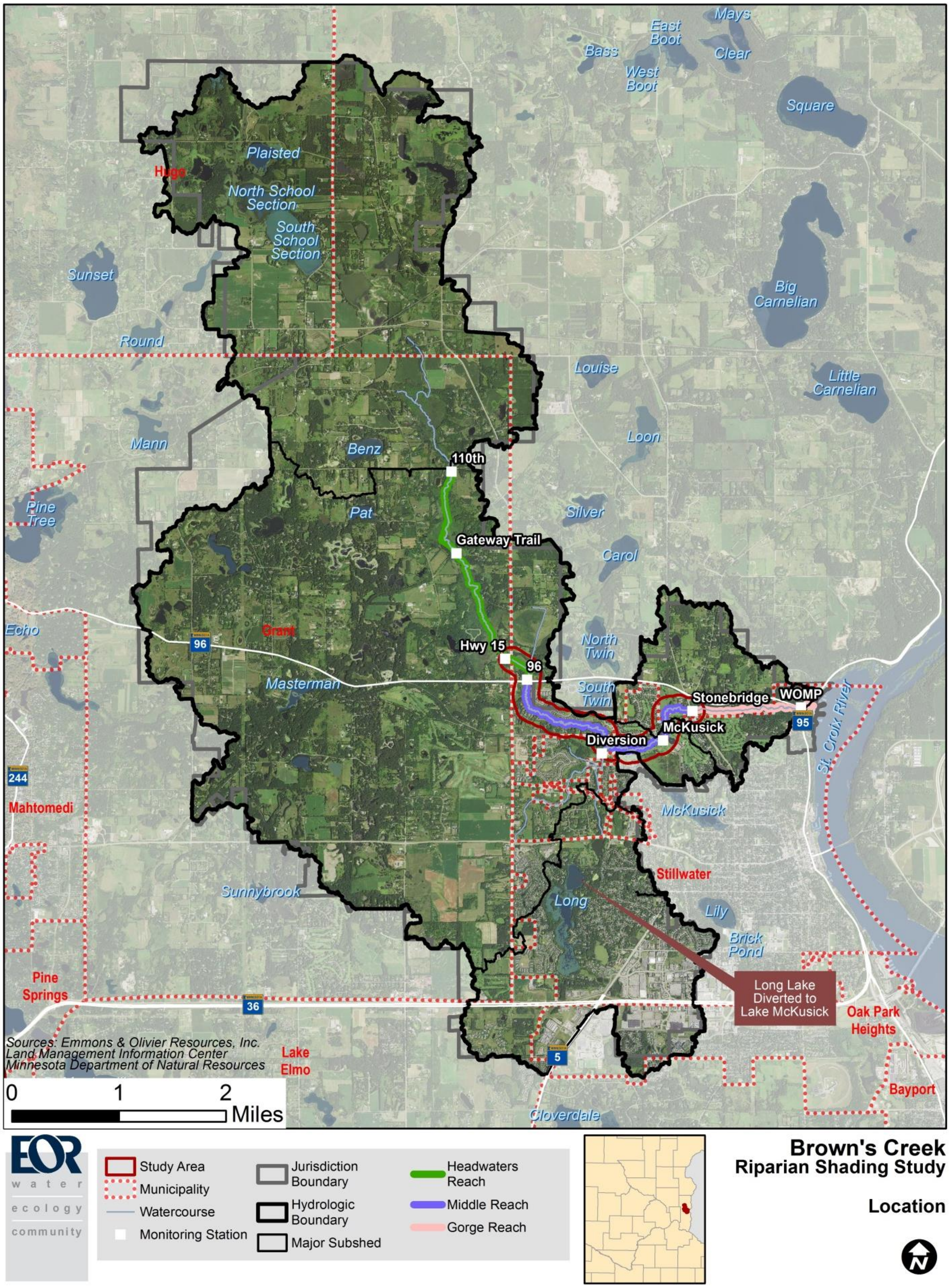

Figure 1. Location Map of Brown's Creek and Impairments

In the absence of a numeric temperature standard for streams across Minnesota, the BCWD developed water temperature goals to protect the long-term survival of cold water species in Brown's Creek. The analysis of stream temperature's impact on biota in Brown's Creek focused on the brown trout threat temperature of 18.3°C or 65°F, which is defined as the point of physiological stress, reduced growth, and egg mortality (Table 2). The failure of trout to establish a breeding population taken together with the absence of cold water fish and invertebrate species were evidence that the high stream temperatures had sustained effects on biota. The temperature in

Brown's Creek exceeded the threat temperature at both Highway 15 and McKusick Road based on 15-minute interval stream temperature data collected from 2000 to 2008. The study also reviewed the frequency of high temperatures, duration of high temperatures, and rate of change in temperature, all to which brown trout are sensitive. A period of 48 hours when the threat temperature is exceeded is generally considered significantly stressful and 72 hours as extremely stressful (Emmons & Olivier Resources, 2010).

Table 2. Water Temperature Criteria for Brown Trout (Emmons & Olivier Resources, 2010; Mccullough, 1999)

Criteria	Temperature		Impact of Exceedance on Brown Trout
	(°C)	(°F)	
Threat	18.3	65	physiological stress, reduced growth, and egg mortality
Critical	23.9	75	direct mortality

As part of the Impaired Biota TMDL study, the TMDL and heat load allocations for Brown's Creek were developed with the threat temperature of 18.3°C as the water quality goal to provide a margin of safety as opposed to the critical temperature of 23.9°C, at which direct mortality can be expected. An energy budget was developed to assess the heat load capacity of Brown's Creek under specific flow ranges at the WOMP station, as illustrated in the heat load duration curve (Figure 2). The energy budget indicated that a 6% reduction in thermal loading (i.e. energy input) was needed across the entire contributing drainage area to Brown's Creek[1] to sufficiently lower stream temperatures and mitigate exceedances of the threat temperature. The required load reduction was based on the difference between the allowed heat input and the average heat input observed during the 198 days when the threat temperature was exceeded from 2003 to 2009 (EOR, 2010).

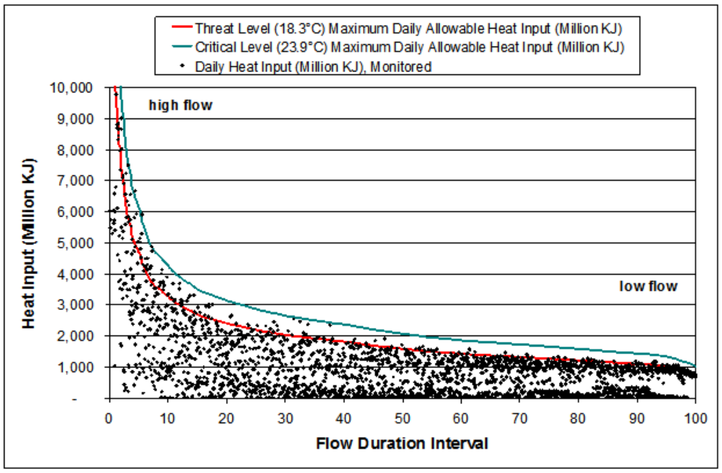

Figure 2. Heat Load Duration Curve 2000-2007 WOMP Station (Emmons & Olivier Resources, 2010)

[1] The contributing drainage area to Brown's Creek is everything east of Manning Avenue minus the drainage area to the Diversion Structure and some smaller landlocked areas identified near County Road 5 (Emmons & Olivier Resources, 2012).

After understanding the stressors and load capacity of the creek, the BCWD then developed a TMDL Implementation Plan in 2012 to define the mitigation strategies needed to meet the goals of the TSS and stream temperature TMDLs. The plan was focused on addressing the impairment for aquatic life due to lack of coldwater fish assemblage and due to high turbidity from Highway 15 (Manning Avenue) to the St. Croix River (river ID 07030005-520). During the development of the plan, further analysis of stream temperature and weather data was conducted to assess the potential impacts of the Long Lake Diversion Structure installed in 2002. The analysis concluded that lower flows and lower water temperatures after 2002 were due to multiple factors, including construction of the diversion, lower precipitation, and lower air temperature relative to 2001 and 2002. Additional analysis is needed to quantify the relative impacts of these factors on groundwater contribution to Brown's Creek as well as appropriations. All subsequent data analysis only looked at the years after 2002 when the diversion structure was installed.

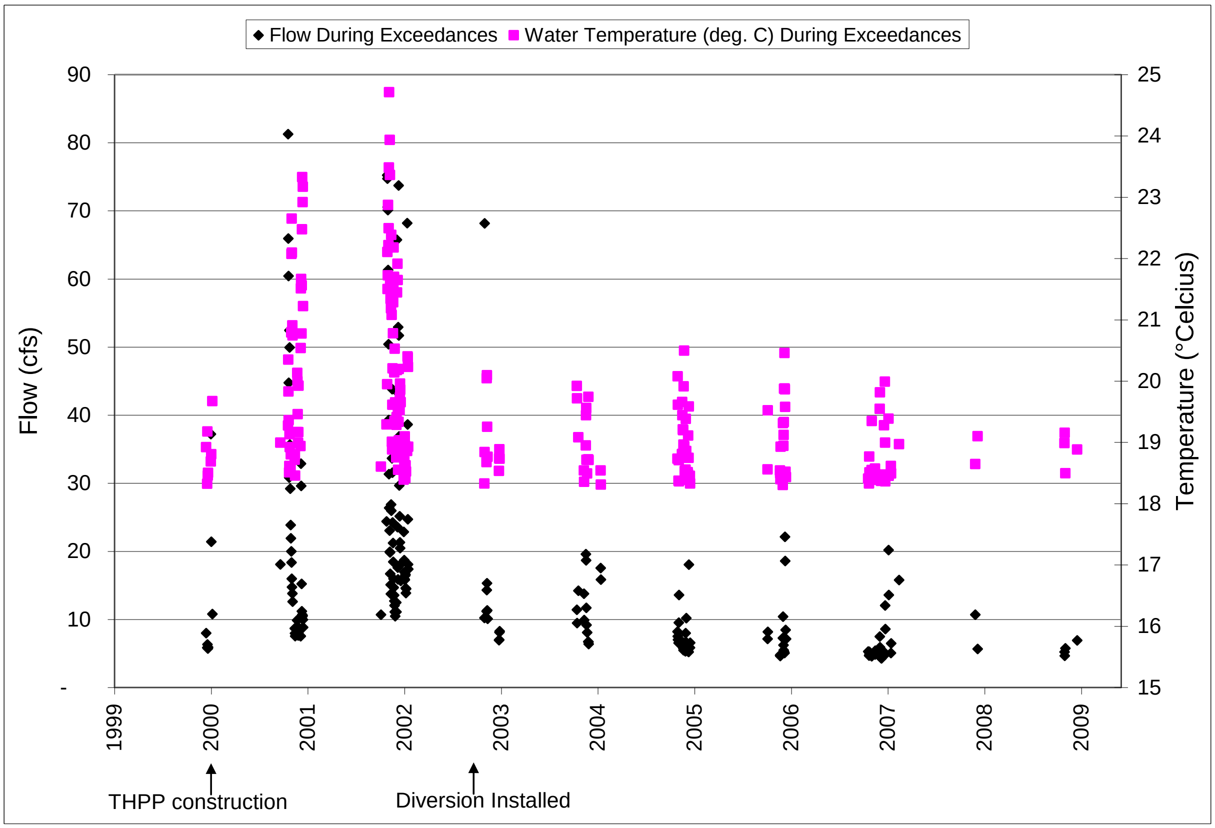

Figure 3. Daily Average Flow and Temperature During Days When the Daily Average Temperature Exceeded 18ºC at the WOMP Site (Emmons & Olivier Resources, 2012)

Each point represents one day.

The importance of baseflow thermal conditions was reviewed in the TMDL Implementation Plan in comparison to thermal loads during storm events. From 2003 to 2009, approximately 80% of the exceedances of the threat temperature (18.3°C) occurred during baseflow conditions due to factors such as lack of riparian shading, changes in stream geomorphology, decreases in baseflow, and changes in climate. Approximately 20% of the exceedances occurred during stormflow conditions due to the thermal load from direct stormwater runoff or from ponds.

The TMDL Implementation Plan identified strategies to address baseflow condition exceedances, including increased shading through vegetative buffers, in-stream morphological improvements, and increasing the groundwater contribution to the stream (i.e. re-establishing groundwater connections lost as a result of the Diversion Structure and/or evaluating the impacts that groundwater appropriations for irrigation of golf courses have on the stream). The Plan prioritized opportunities for in-stream cooling improvements through stream geomorphology and thermal buffer improvements as shown in Figure 4 and Figure 5, including 2.5 miles of high priority buffer improvements. The costs and estimated benefits of the stream geomorphology and thermal buffer improvements are detailed in the Implementation Plan Table. In addition, the Plan identified non-structural BMPs that would reduce thermal load to Brown's Creek, including minimizing impervious areas, disconnecting impervious surfaces, and achieving additional volume control through rainwater harvesting. Stormflow implementation activities were also identified but are not relevant to this study (Emmons & Olivier Resources, 2012).

The highest priority stream restoration project identified in the TMDL Implementation Plan was the lower stream segment through the Oak Glen Golf Course where turf grass was mowed to the edge of the stream. The potential stream temperature benefits were assessed using a simplified thermal model developed using the Stream Segment Temperature Model (SSTEMP) which works on an individual stream segment basis and uses steady-state hydrology and meteorology in addition to defined stream geometry and shading inputs. The SSTEMP model results indicated that the stream and buffer restoration would reduce would reduce the predicted daily mean temperature by 2.8°C (5°F) and the maximum daily temperature by 3.3°C (6°F). Instead of modeling all of the planned improvements, the BCWD decided to collect additional climatological data to improve certainty of future modeling efforts and committed to monitoring the stream temperature benefits of the Oak Glen Golf Course restoration in comparison to the predictions from the model (Emmons & Olivier Resources, 2012).

Through the TMDL Implementation Plan, the BCWD also committed to taking an adaptive management decision making approach to implementing the Plan given uncertainties in quantifying the improvements associated with thermal load reduction projects. This meant that the District was committed to continuing monitoring activities to measure the stream temperature and biotic health response to implementation activities while also reducing the uncertainty and identifying if additional implementation activities are needed (Emmons & Olivier Resources, 2012).

Since finalizing the TMDL Implementation Plan, the BCWD has constructed or participated in the construction of multiple stormwater retrofits to mitigate stormflow heat loads to Brown's Creek. In addition, the District restored the lower segment of Brown's Creek through the Oak Glen Golf Course in 2012 to lower baseflow stream temperatures. The District has also reviewed all proposed development activities to ensure compliance with the District's Rules and Regulations, which include requirements for Better Site Design (e.g. reduce impervious cover and disconnect impervious surfaces) and providing volume control for the 2-year, 24-hour event. The district has also enhanced the monitoring program to include a weather station, baseflow surveys, macroinvertebrate surveys, and additional groundwater monitoring in addition to the stream temperature and flow monitoring called for in the TMDL Implementation Plan. The BCWD assessed the period of monitoring data collected from 2009 to 2012 to evaluate trends in water quality,

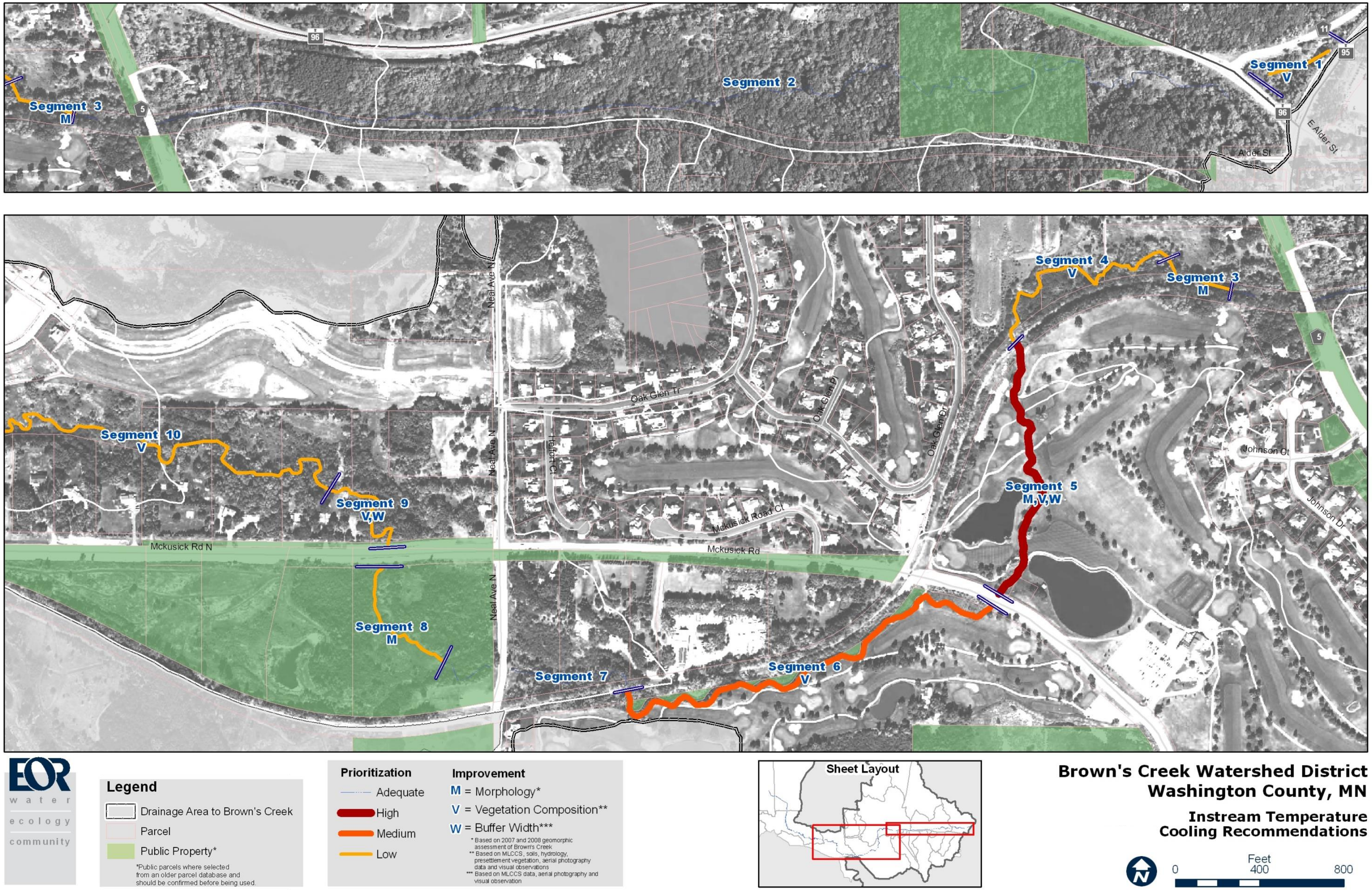

Figure 4. Stream Geomorphology and Thermal Buffer Improvements (1 of 2) (Emmons & Olivier Resources, 2012)

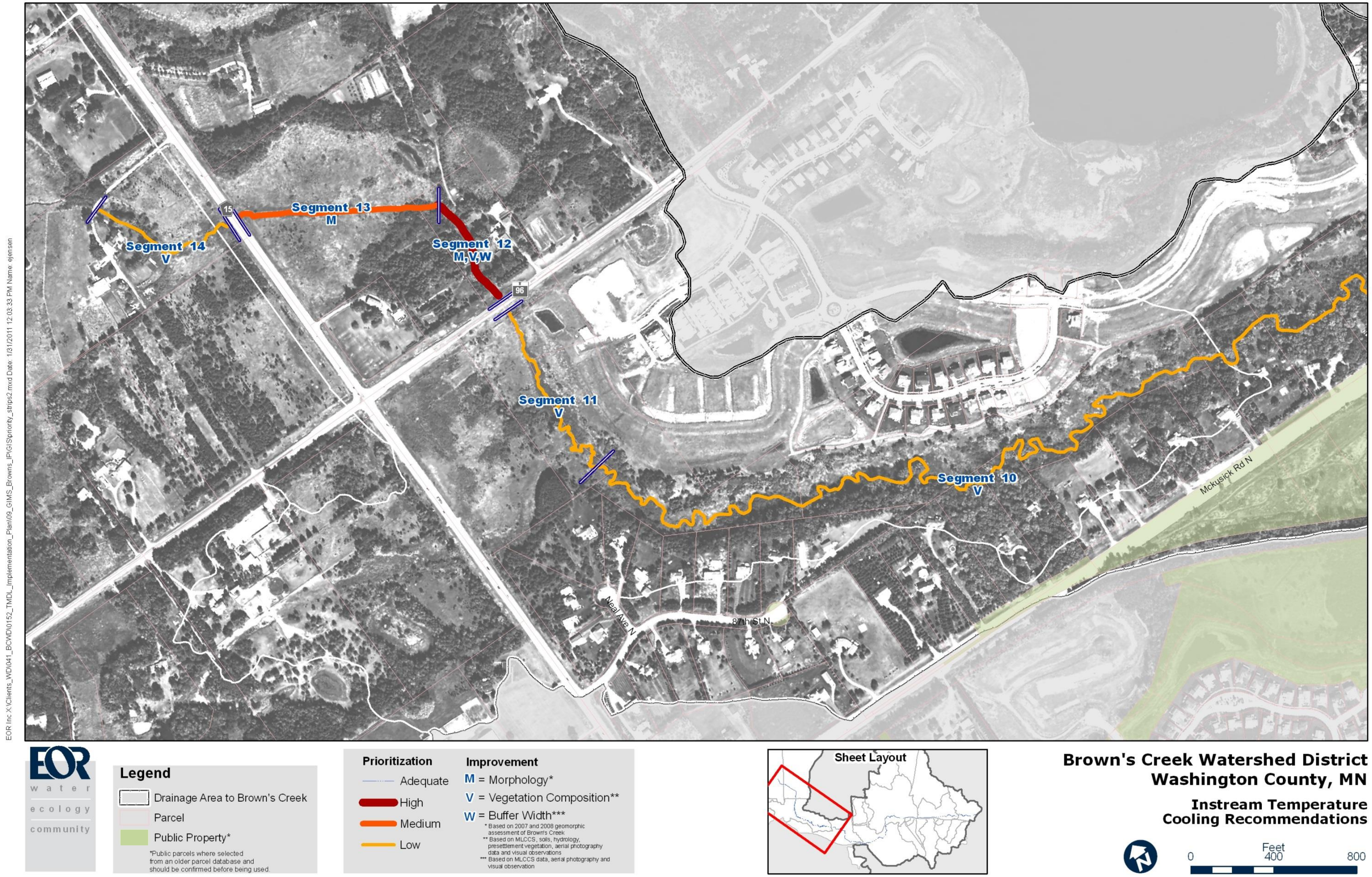

Figure 5. Stream Geomorphology and Thermal Buffer Improvements (2 of 2) (Emmons & Olivier Resources, 2012)

including stream temperature. The assessment identified a warming trend in stream temperature over the study period that was largely attributed to decreasing groundwater levels and higher than normal air temperatures (Emmons & Olivier Resources, 2016). The District's monitoring program is continuing to develop a record by which the effectiveness of structural and non-structural BMPs can be evaluated relative to the TMDL goals for stream temperature. A long-term data record is needed to capture variability in climate in order to specifically assess the response of stream temperature and biotic health to BMPs implemented in the watershed.

In order to address limitations to stream temperature modeling identified in the TMDL Implementation Plan, the BCWD installed its own weather station 2011. The meteorological data collected at the station, in addition to other data collected as part of the District's full monitoring program, provided the input and calibration data necessary to develop a more detailed stream temperature model for estimating the benefits of potential thermal BMPs.

From 2014 to 2016, the BCWD developed a stream temperature model to assess the impact of stream temperature mitigation options, including increased riparian shading, increased stream baseflow, and disconnection of stormwater ponds. The model was developed in CEQUAL-W2 to simulate stream temperature at an hourly time step in Brown's Creek from Highway 15 (Manning Avenue) to the St. Croix River for a continuous period (April to October) in 2012 and 2014. The calibration to observed stream temperature, stream flow, and groundwater levels using lateral inputs (i.e. groundwater distribution, rate, and temperature) and the wind sheltering coefficient was able to reproduce observed stream temperatures within 1.0 to 1.3°C. Two future riparian shade scenarios were assessed by increasing shade to new minimum thresholds of 50% and 75%. The model results indicated that increasing riparian shade will provide the greatest stream temperature reduction in comparison to the other mitigation options, although some uncertainties remain regarding the other mitigation options. Even further, increasing shade would enhance the benefit of other mitigation strategies. In other words, increasing riparian shading may lower in-stream temperatures to the point where the benefits of stormwater pond retrofits is more noticeable. The expected benefit of increasing riparian shade to a minimum threshold of 75% was a reduction in monthly mean stream temperature on the order of 0.5 to 1°C over the entire modeled section of the creek (Herb & Correll, 2016).

The Brown's Creek Thermal Study also made recommendations for targeting shade improvements. Understanding the amount of shade provided by riparian vegetation is crucial in determining stream temperature and is an important parameter specified in stream temperature models. Although the development of the Brown's Creek stream temperature model utilized several tools and methods to assess the percentage of the creek shaded by tree canopy, one of the limitations in model development was in the riparian shading analysis. The analysis was based on a geospatial analysis using Light Detection and Ranging (LiDAR) data, which is collected through remote sensing method of examining the surface of the Earth. The State's LiDAR data (Table 3) was the best available data for riparian analysis at the time, but generally LiDAR does not work well for characterizing shading at smaller scales, such as tall grass shading a narrow stream channel, and so the analysis focused on tree canopy coverage. The percent shade estimated using ArcMap solar radiation analysis tool to analyze LiDAR data is illustrated in Figure 6.

Figure 6. Existing Riparian Shade in Fall 2011 Estimated Using LiDAR and Calibrated to Observed Stream Temperatures (Herb & Correll, 2016)

Table 3. LiDAR Survey Specifications for Washington County (Block F) (Minnesota Department of Natural Resources, 2017)

Flight date	November 14, 2011
Sensor	Leica sensor ALS50-II MPiA with IPAS inertial measuring unit and a dual frequency airborne GPS receiver
Scan angle (cutoff)	40°
Average flying height	2012 m (6,600 feet) above mean terrain
Pulse rate frequency	99.5 kHz
Swath overlap	10%
Returns collected	First, second, third, last
Point density	1.5 points/m^2
Area used in study	26 km^2

The Brown's Creek Thermal Study recommended that additional analysis should be conducted to better determine local shading conditions in the understory and areas with predominantly grass or shrub vegetation. The increase in riparian shading required to lower stream temperatures by 1°C would be a substantial effort along 2.5 miles of the stream. The Brown's Creek Thermal Study recommended targeting which reaches are most suitable for riparian shade restoration based on factors such as channel width and orientation. Additional consideration is also needed for what type of vegetation could be supported by the soils found along Brown's Creek (Herb & Correll, 2016).

The Fourth Generation Watershed Management Plan (WMP) for Brown's Creek outlines the steps the BCWD will take from 2017 to 2026 to meet a set of 15 issue categories (Emmons & Olivier Resources, 2017). While many of the issues, goals and implementation items are related to riparian vegetation, stream temperature, and biotic health, the primary goal related to this Riparian Shading Study is the following:

> **Goal #3:** Stream Management - Improve the water quality and ecological integrity of Brown's Creek and its tributaries.
>
> > **Sub-Issue:** Water Quality, Aquatic Habitat, and Fisheries Protection
> >
> > **Policy:** The BCWD is committed to the improvement of the water quality and ecological integrity of Brown's Creek and its tributaries, including maintaining a viable cold-water fishery
> >
> > **Sub-Goal D:** Achieve and maintain in-stream water temperatures of 18.3°C (65°F) or lower in the trout stream portion of Brown's Creek
> >
> > > **Implementation Item #3:** Implement thermal improvements listed in Table 61 of the WMP, which includes increasing shade from riparian vegetation along 2.5 miles of the creek as called for in the Brown's Creek Thermal Study and the TMDL Implementation Plan.

The Riparian Shading Study was undertaken to address the recommendations of the Brown's Creek Thermal Study such that thermal buffer improvements to increase shading could be targeted and implemented within the 2017-2026 planning cycle by the BCWD.

3. STUDY AREA CHARACTERIZATION

This section summarizes the characteristics of natural resources in the study area that are pertinent to riparian vegetation and stream temperature management decisions. The characteristics of the study area also provide context for our review of literature on the comparative benefits of riparian vegetation types (Appendix B) by focusing on studies with similar characteristics. Characteristics were based on previous studies and monitoring data collected by the BCWD and other agencies. Appendix A of the BCWD 2017-2026 WMP outlines a comprehensive inventory of the natural resources in the watershed and available data. The District's Impaired Biota TMDL study and TMDL Implementation Plan are also useful sources for additional information on the characteristics of the study area.

3.1. Climate

The climate of the Brown's Creek watershed is consistent with the climate for the Seven County Metropolitan Area. The summers are fairly short with an average temperature of about 70 degrees F. Snowfall covers much of the ground from late fall to early spring. The average winter temperature is about 18°F. The average annual temperature is 46.3°F and the average annual precipitation is 33.6 inches (Emmons & Olivier Resources, 2007b).

The BCWD operates a weather station (45.063857, -92.855826) installed on July 22, 2011 to monitor multiple parameters, including air temperature, humidity, wind speed, wind direction, precipitation, and solar radiation. Air temperature and precipitation observed at the station in 2012 and 2014 are illustrated in Figure 7. These two years are simulated in the District's stream temperature model in the Brown's Creek Thermal Study and this Riparian Shading Study to assess a warm-dry year (2012) and a cool-wet year (2014).

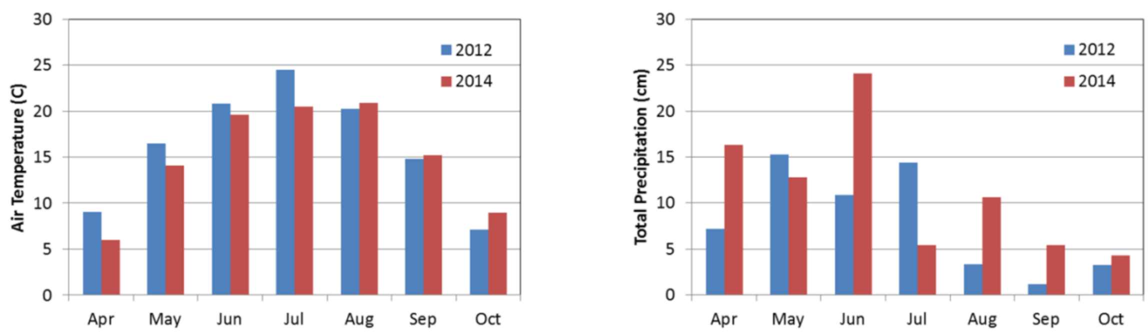

Figure 7. Summary of Monthly Air Temperature and Precipitation in 2012 and 2014 (Herb & Correll, 2016)

A trend analysis of local climate data indicates that the Brown's Creek watershed is experiencing changes in precipitation and temperature which presents challenges to watershed management decision-making. The trends in climate being seen in the BCWD include: annual average air temperature is increasing, air temperature in winter months in particular is increasing, annual rainfall depths are increasing an average of 0.16 inches per year and there is an increasing trend in the mean rainfall depth during wet periods (Emmons & Olivier Resources, 2017). Amongst multiple statewide trends, droughts are expected to become more common as the increases in rainfall cannot compensate for the drying effects of a warmer climate (Emmons & Olivier Resources & Barr Engineering, 2016).

Stream temperatures are directly and indirectly affected by climate. All climate parameters have a role in defining the heat energy budget of a stream system (see Appendix A). For example, increasing air temperatures result in warmer stream temperatures. Climate also influences the water budget across the watershed. For example, more intense rainfall events fall too quickly to be absorbed into the ground, decreasing groundwater recharge (Emmons & Olivier Resources, 2017) and subsequently the amount of cool groundwater contributions to the stream's baseflow. Indirectly, climate changes are also expected to change the composition of vegetation across the state (see Appendix B).

3.2. Watershed, Water Resources, and Hydrology

The study area is located within the Big Marine Lake-St. Croix River HUC 10 Watershed and the Brown's Creek HUC 12 Watershed. The watershed of Brown's Creek includes a total of 28 square miles composed of rural and suburban headwaters that drain into a forested valley in the urban core of Stillwater, Minnesota. The creek then joins the St. Croix River at the state border with Wisconsin. Impervious surfaces cover 8% of the watershed (Emmons & Olivier Resources, 2017). Brown's Creek is designated by the MN DNR as a Class 2A trout stream from County Road 15 / Manning Avenue to the St. Croix River. Near the creek's mouth to the St. Croix River, streamflow ranges from low flows of 5 cfs to high flows of 81 cfs (0.14 to 2.29 m^3/s). The study area extends along Brown's Creek from Manning Avenue North to Stonebridge Trail in Stillwater, Minnesota.

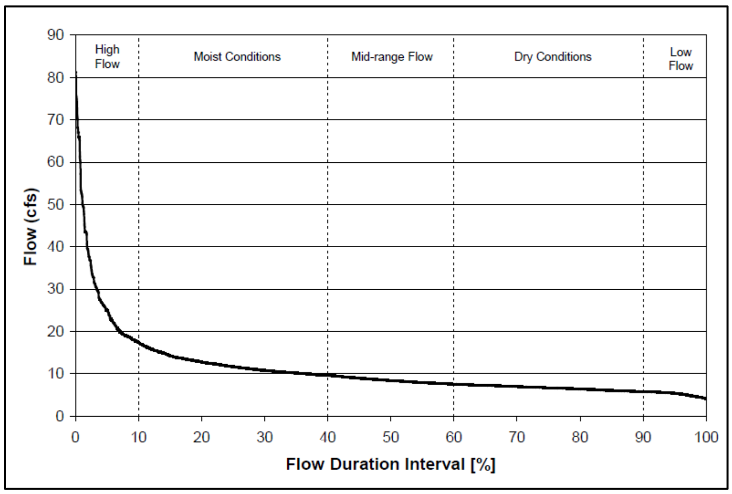

Figure 8. Flow Duration Curve (2000-2007) at WOMP Station
(Emmons & Olivier Resources, 2010)

The headwaters of the Brown's Creek watershed include a semi-landlocked area that contains a number of groundwater-fed lakes (e.g. Goggins Lake, North School Section, and South School Section Lakes). When lake levels are high, these lakes discharge to the Trout Habitat Preservation Project (THPP) which is designed to retain and infiltrate water prior to discharging to the headwaters of Brown's Creek. The western portion of the watershed is landlocked and does not discharge to Brown's Creek by overland flow. However, this western portion of the watershed does contribute to the local groundwater system which contributes to baseflow to Brown's Creek. The landlocked basins and the subwatershed of the Long Lake tributary are delineated in Figure 9. Approximately 71% (19.9 square miles or 51.5 km^2) of the watershed flows overland to the St. Croix River contributes to the creek, including the Long Lake tributary which is partially diverted away from the creek and into Lake McKusick (Emmons & Olivier Resources, 2017).

The shape of the Brown's Creek channel influences the quality of habitat for fish and macroinvertebrates. Within the study area, Brown's Creek is classified under the Rosgen Classification System (Rosgen, 1994) as C3, C4, C4c, E4, and E4/5. Channel substrate in the study area includes sand, cobble, and fine to coarse gravels in addition to the organic soils common to the wetland areas along the creek. Bankfull width varies from 2 to 5 m. The longitudinal slope of the creek is flat (less than 1%) and sinuosity ranges from 1 to 1.3 (Emmons & Olivier Resources, 2008). Several segments within the study area have been identified as priorities for stream restoration to provide healthy, diverse, and sinuous aquatic habitat for coldwater biota, including the segment east of Manning Avenue North that was likely straightened for agricultural purposes and several points south of the Millbrook development where sedimentation is straightening the channel. Sites with severe bank erosion are also identified on an ongoing basis to protect properties and mitigate sediment loads to the creek. Channel restoration projects are also opportunities for riparian vegetation improvements.

Multiple wetlands are located within or adjacent to the creek in the study area and include seasonally flooded basins, hardwood wetlands, shallow marsh, shrub wetland, and shallow open water communities (Figure 10). The District conducted a Function and Value Assessment (FVA) of all wetlands in terms of the functions they serve on the landscape and the value they provide based on an inventory of all wetlands in the watershed greater than 1 acre in size in 1998 and updated in 2005. The management classifications resulting from the FVA for wetlands in the study area are shown in Figure 11.

Many of the water resources in the study area are either wholly or partially groundwater dependent. The shallow groundwater table actively contributes to the Creek's baseflows to varying degrees throughout the year and along the length of the stream as explained in the Brown's Creek Thermal Study:

> "The downstream section, from the WOMP station to Stonebridge, represents a higher slope reach with relatively high rates of baseflow input with a low temperature (9 °C). The middle section, extending from Stonebridge to McKusick/Neal, represents a low slope reach with no baseflow input (based on the 2014 baseflow surveys). However, piezometer measurements in 2015 by EOR staff suggest that the middle reach was a losing reach in early summer and a gaining reach later in the year. The upper reach extends from McKusick/Neal to Manning Avenue, and is low slope with variable temperature baseflow inputs, based on the 2014 piezometer measurements." (p. 4)

Water appropriations in the Brown's Creek watershed are primarily from groundwater. The largest groundwater appropriations in the Brown's Creek watershed come from municipal water supply wells and golf course irrigation wells. Groundwater appropriations affect groundwater levels below groundwater dependent natural resources. In 2014 a BCWD Groundwater Appropriations Study found that large pumping wells were lowering groundwater levels in bedrock aquifers below Brown's Creek by more than two feet. Further studies are required to determine the connection between the creek and the bedrock aquifers and the effect of the pumping on groundwater dependent natural resources (Emmons & Olivier Resources, 2017). Appendix A of the District's 2017-2026 WMP provides a detailed overview of the groundwater resources underlying the watershed.

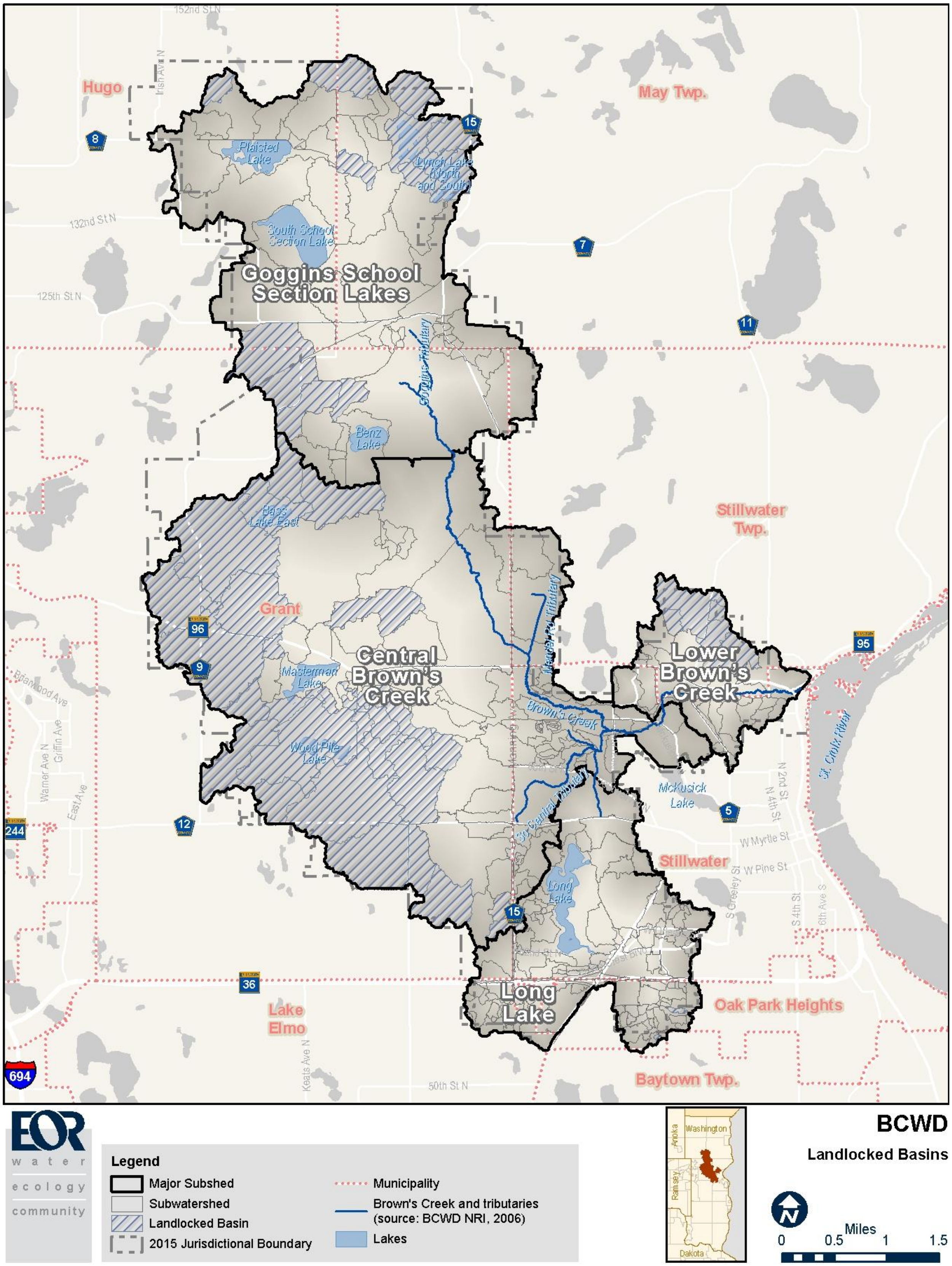

Figure 9. Landlocked Basins of Brown's Creek Watershed (Emmons & Olivier Resources, 2017)

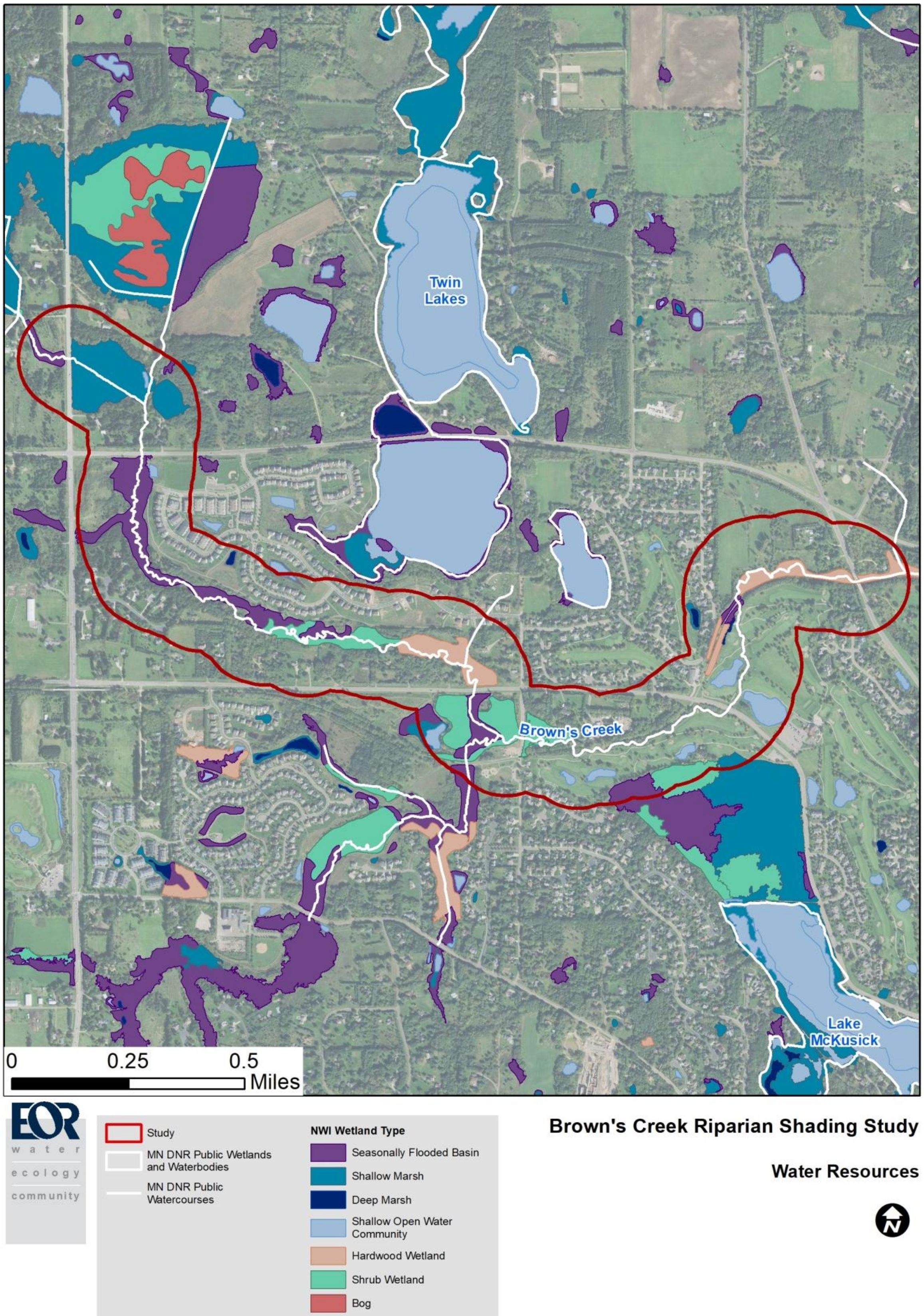

Figure 10. Water Resources in Study Area

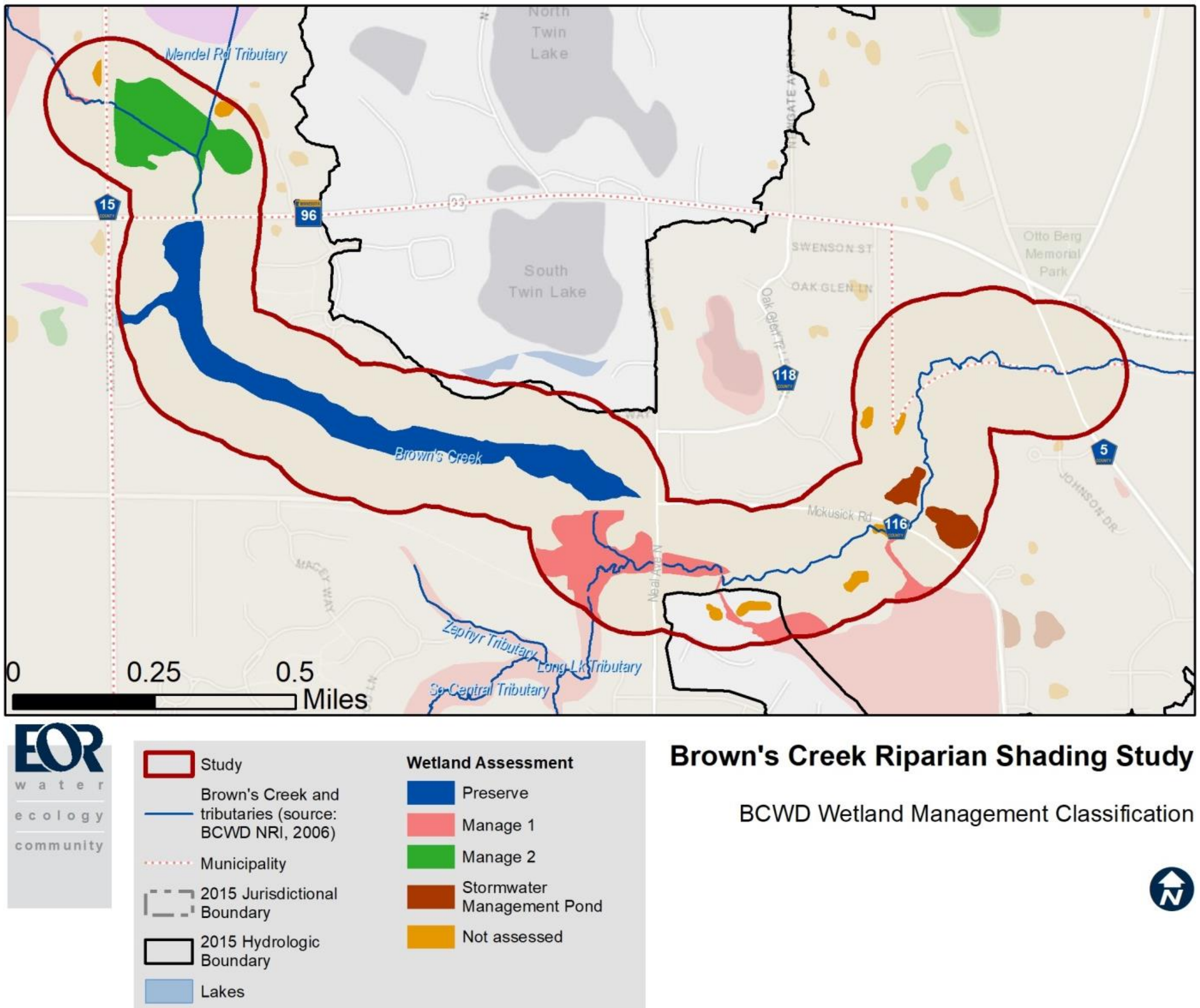

Figure 11. BCWD Management Classifications of Wetlands in Study Area

3.3. Ecological Classification

The Minnesota Department of Natural Resources and U.S. Forest Service Ecological Classification System (ECS) identify contiguous areas of increasingly uniform physiological and ecological features based on the National Ecological Unit Hierarchy design criteria. The ECS in Minnesota is described by the MN DNR as a three-tier hierarchy including Provinces, Sections, and Subsections. Provinces are units of land defined primarily by climate zones and potential native vegetation. Sections are units of land defined primarily by geology, regional climate, soils, and potential native communities. Subsections are the most resolute level of classification, covering smaller and more congruent ecological areas with similar geologic processes, vegetation, local climate, topography, and soils.

The study area is located in the St. Paul-Baldwin Plains and Moraines (SBPM) Subsection of the Minnesota and Northeast Iowa Morainal (MNEIM) Section within the Eastern Broadleaf Forest (EBLF) Province as shown in Figure 12 (MN DNR, 2017). Details regarding the characteristics of these units as they pertain to the study area are provided in the following sections.

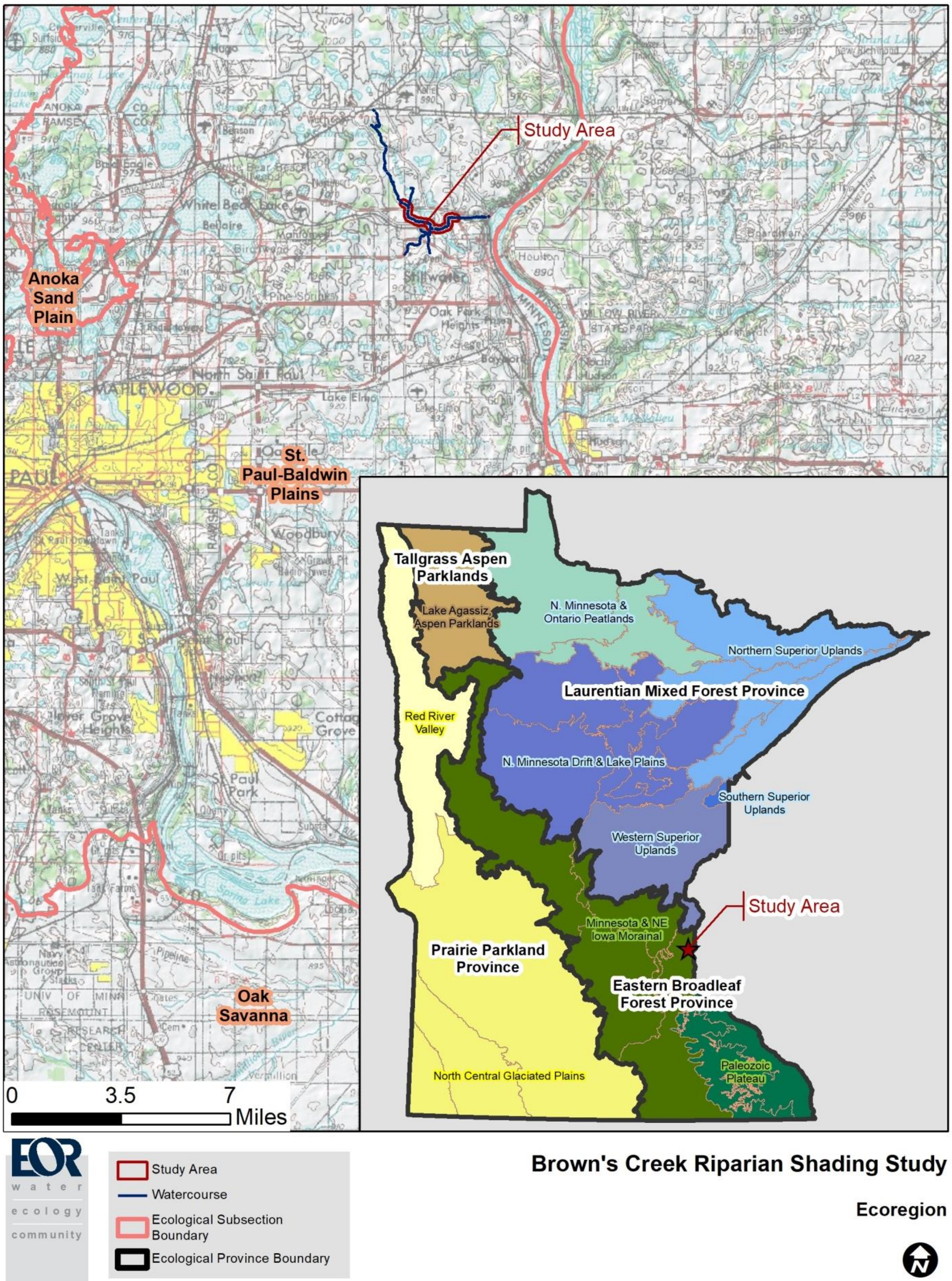

Figure 12. Ecoregion of Study Area

3.4. Topography and Geology

Topography and aspect are important factors in the development and formation of soil, soil erosion potential, and the type and stability of vegetation for a given location. Topography within the study area includes gently rolling hills and low-lying wetland areas. Elevation in the study area ranges from 826.1 to 940.3 fasl (251.8 to 286.6 masl). Slope in the study area ranges from 0 to 170 percent, where the very steep slopes are on roadside embankments and valley banks.

The District's 2017-2026 WMP characterized and categorized three distinct landforms along Brown's Creek, as follows and as illustrated in the typical cross sections on the next pages:

> **Headwaters Region of Brown's Creek** includes the northern portion of the watershed from Highway 96 to the Goggins-School Section Chain-of-Lakes (Figure 15). The study area includes the lower headwaters region from Highway 15/Manning Avenue to Highway 96.
>
> **Brown's Creek Middle Reach** includes the central portion of the Brown's Creek south of Highway 96 to County Road 55 (Figure 16) and is entirely within the study area.
>
> **Brown's Creek Gorge** includes the Brown's Creek corridor downstream of County Road 5 to the St. Croix River (Figure 17). The gorge is downstream of the study area but is included in the District's stream temperature model.

The bedrock geology formations below the study area, from youngest to oldest, include the Prairie du Chien Group dolostone, the Jordan Sandstone, and the St. Lawrence Sandstone (Figure 13). Brown's Creek Middle Reach is less influenced by the bedrock than is the Brown's Creek Gorge. Bedrock valleys exist where ancient streams eroded the bedrock, but those valleys have since been buried by thick glacial sediments. In the study area, Brown's Creek runs across the buried bedrock valleys rather than parallel to them.

The surficial geology is dominated by moraines and outwash related to the Superior Lobe glaciation (Cromwell Formation)(Figure 14). Later alluvial deposits of sand and gravel are found along the creek bed. Lacustrine clay deposits, likely from a pro-glacial lake, are found in the area near Brown's Creek Park. The glacial deposits are eroded away where the middle section of Brown's Creek enters the lower gorge.

Many springs and seeps have been identified within the study area along the creek (Figure 14) as part of the MN Geological Survey Karst Features Database, a compilation of historical documentation, field surveys by DNR staff, and approved citizen submittals up to date as of February 16, 2018. In the middle section of Brown's Creek the seeps emanate from glacial deposits close to the creek bed. This contrasts with the gorge area where the springs and seeps often emanate from the bedrock away from and at higher elevation than the creek bed. Springs and seeps are more common in the coarser sand and gravel deposits than in the lacustrine clay deposits near Brown's Creek Park. In a 2015 study, comparison of water levels in Brown's Creek and groundwater levels from in-stream piezometers showed that the middle section of Brown's Creek can be gaining or losing groundwater during different times of the non-winter months (Emmons & Olivier Resources, 2015).

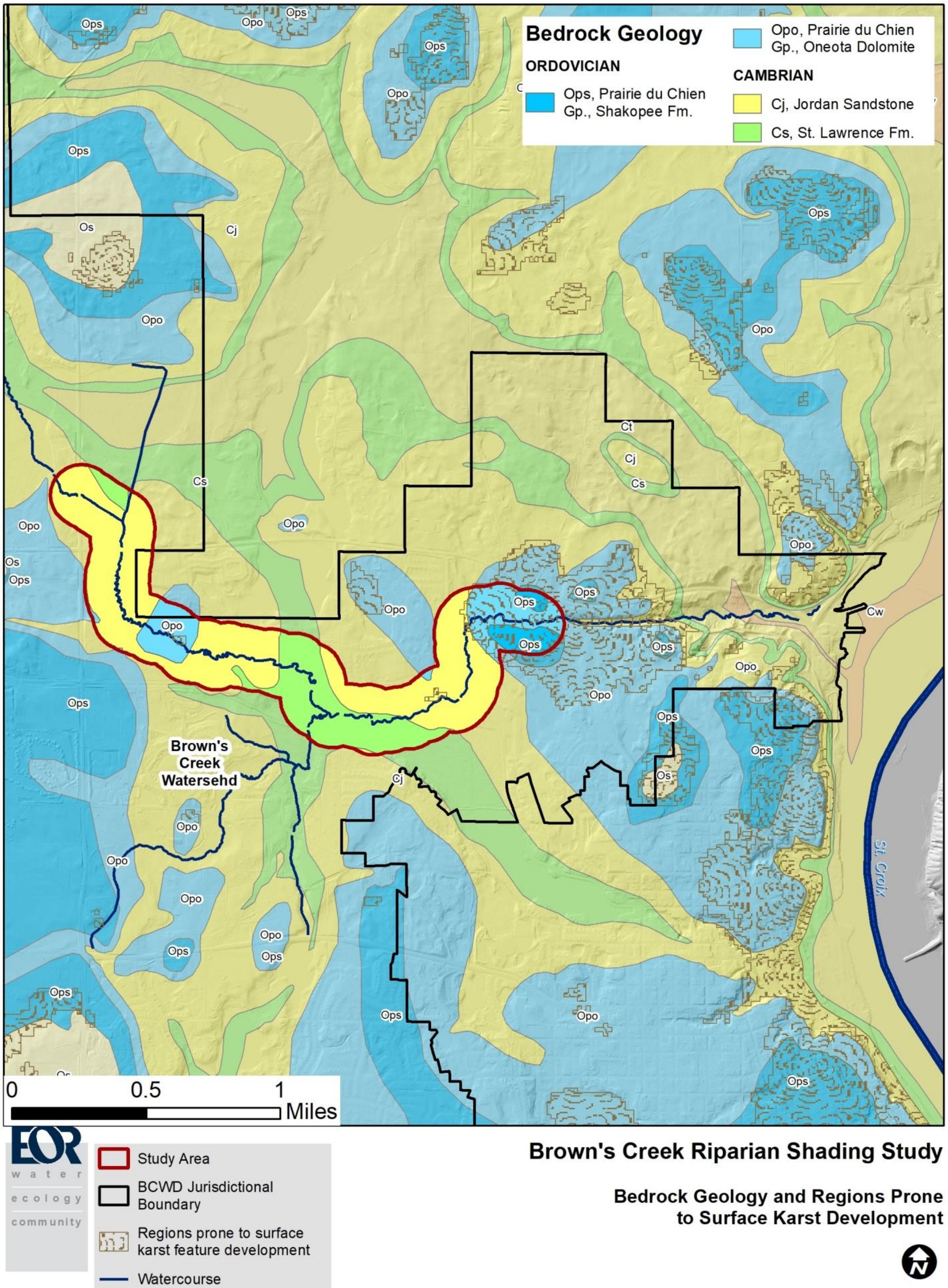

Figure 13. Bedrock Geology of Study Area

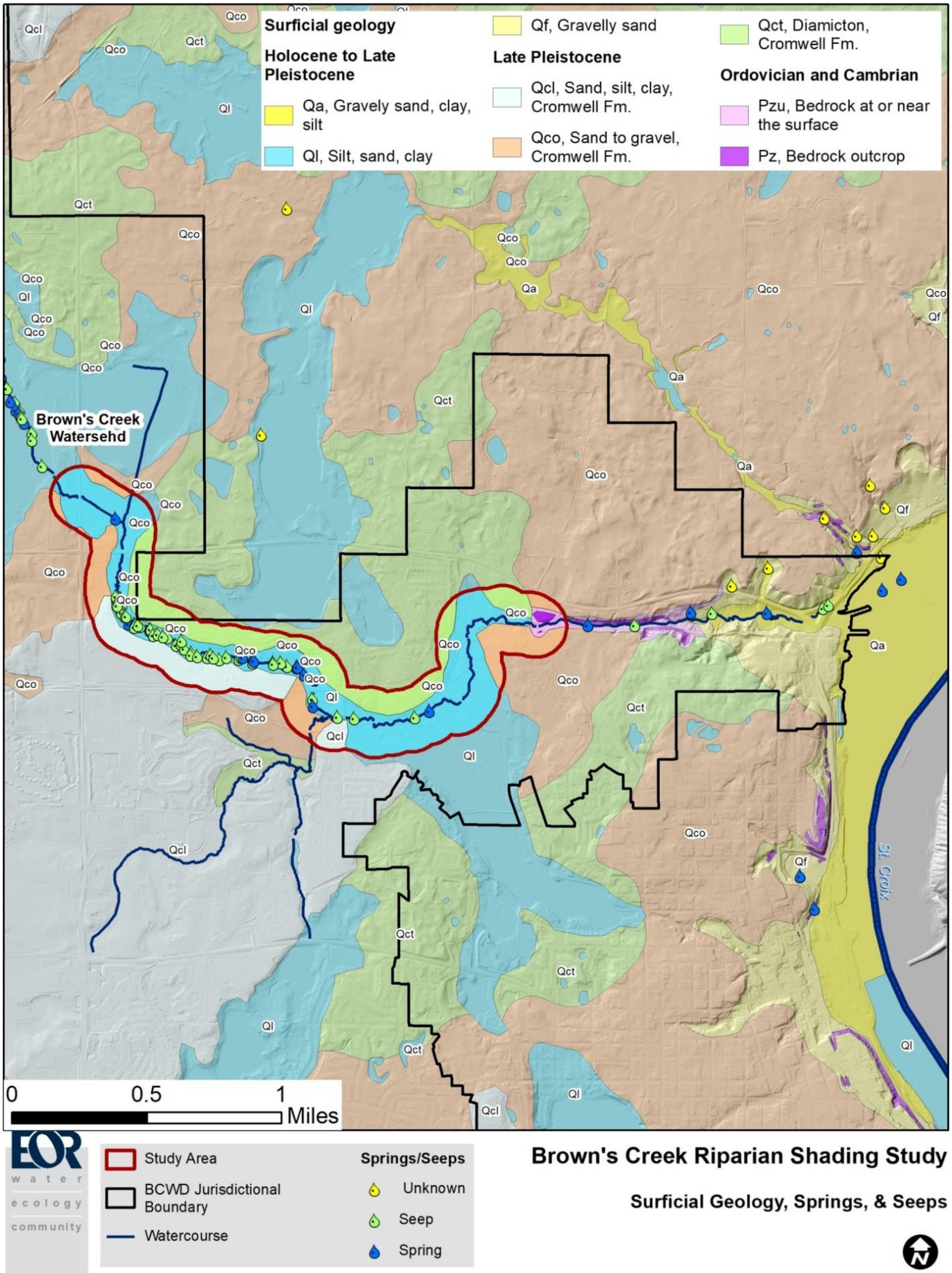

Figure 14. Surficial Geology of Study Area

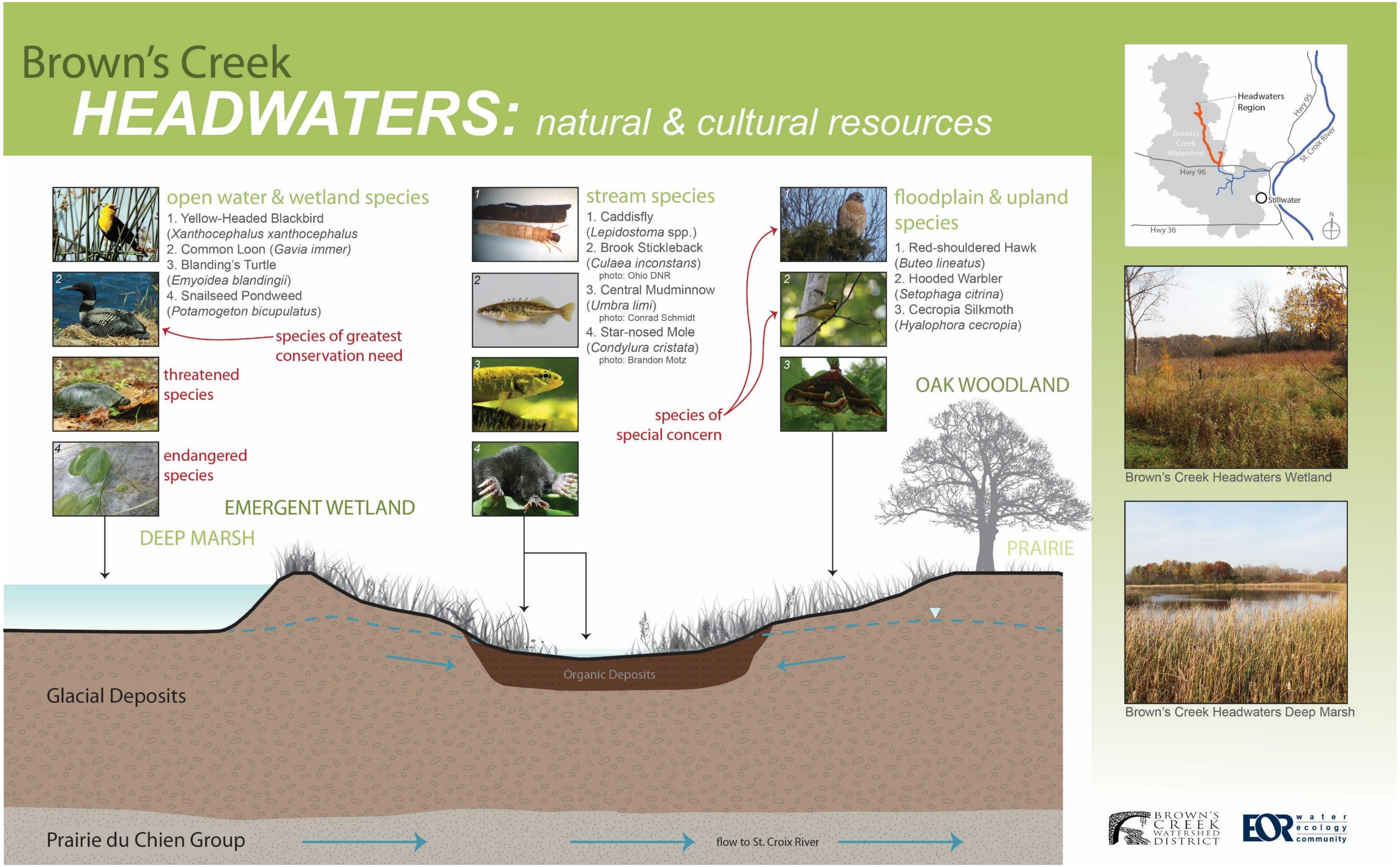

Figure 15. Typical Cross Section of the Brown's Creek Headwaters Region (Emmons & Olivier Resources, 2017)

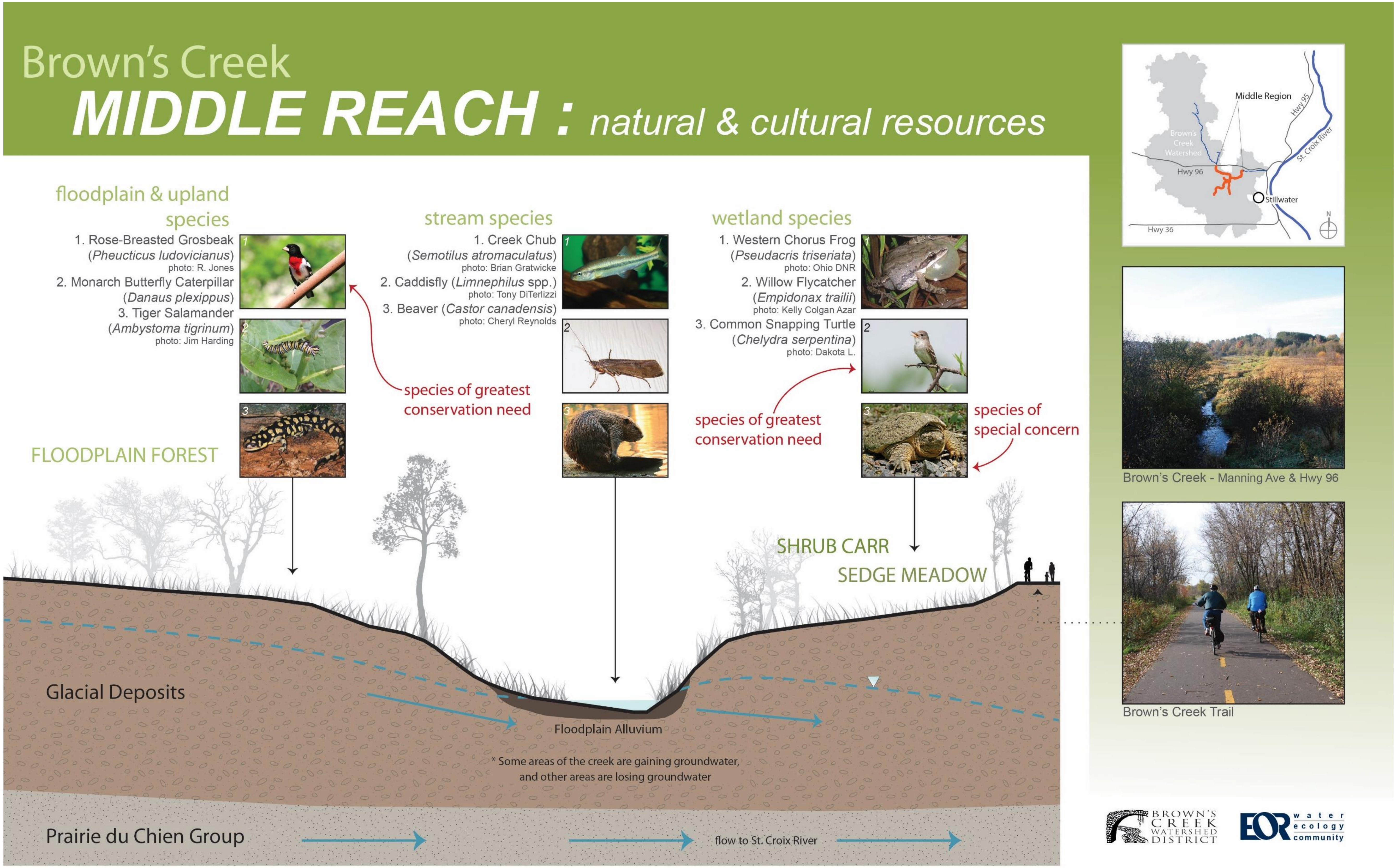

Figure 16. Typical Cross Section of the Brown's Creek Middle Reach (Emmons & Olivier Resources, 2017)

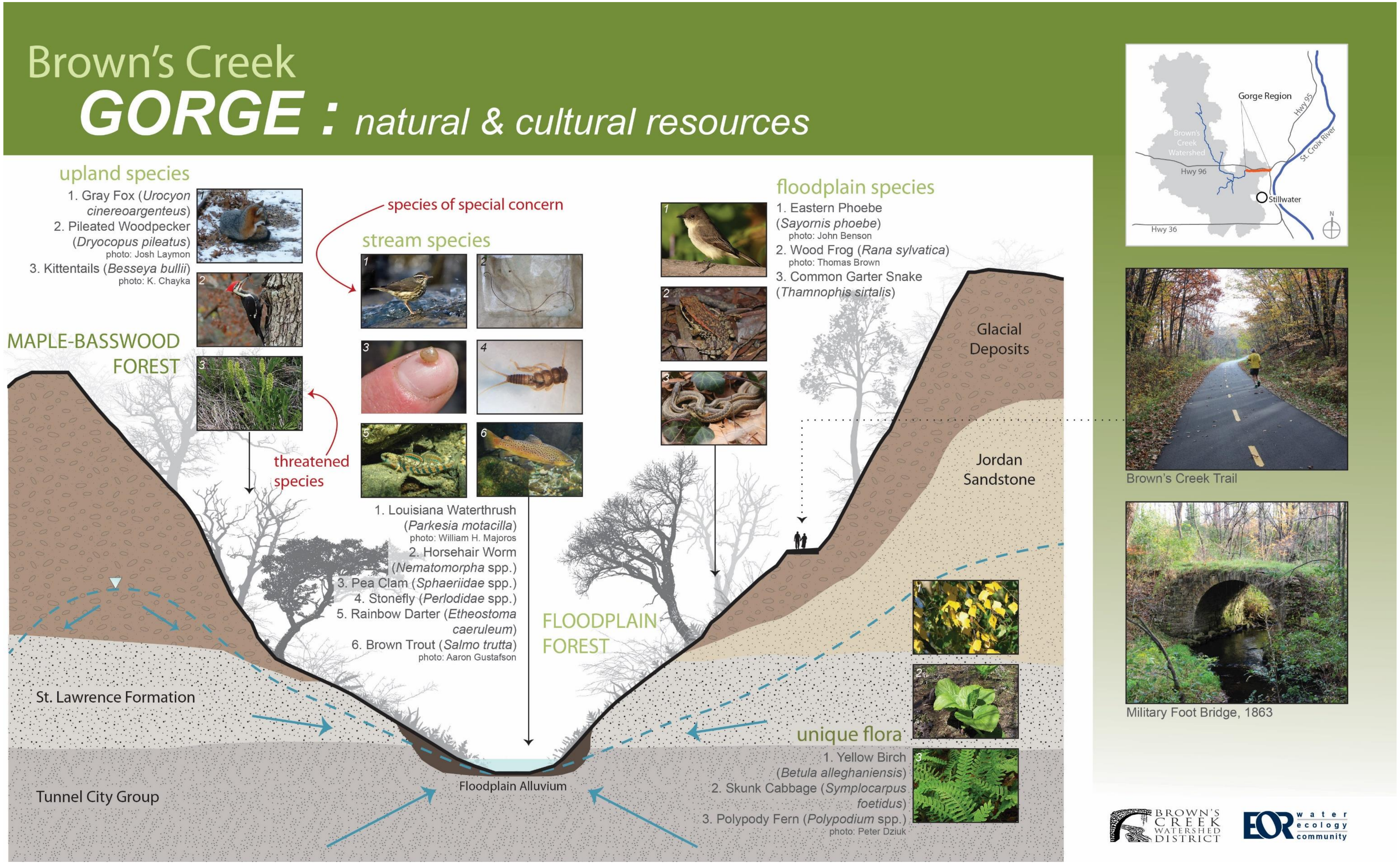

Figure 17. Typical Cross Section of the Brown's Creek Gorge (Emmons & Olivier Resources, 2017)

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The topography and geology in these regions of the creek's riparian corridor were the basis for the hydrologic cycle of the watershed and the resulting unique flora and fauna in each region. For example, the level and gently rolling topography in the headwaters region and middle reach formed the many lakes and wetlands that provide significant recharge to the groundwater table which, in turn, supports cool flows in Brown's Creek. Topography also relates to stream temperature in that it defines the local time of sunset and sunrise and can significantly shade the stream throughout each day, depending on the height of the valleys.

3.5. Soils

Soil formation is the result of the interaction of parent material, climate, organisms, topographic position or slope, and time. Collectively, these factors help determine the dominant plant and animal communities, which in turn influences future soil development. Soils within the SBPM Subsection are typically characterized as Alfisols and Molisols, with parent material classified as clay loams, sandy loams, loamy sands, and sands. Twenty soil units are identified by the USDA/NRCS Web Soil Survey to occur within 200 feet of the creek in the study area including silt loam, sandy loam, muck, and rock outcrop. Seelyeville muck (540) and Rifle muck (541) soils units are comprised of all hydric soil groups and characterized as very poorly drained soils (Table 4 and Figure 18). In addition, Markey muck (543), Aburndale silt loam, baronet silt loams are considered predominately hydric. The aforementioned soils units are primarily located directly adjacent to or below the creek in the study area. Remaining soils within 200 feet of the creek were classified as not hydric or predominately not hydric. The hydric classifications of the soils indicate which plant species will be best-suited for plantings in the study area (i.e. only certain trees succeed in wet and hydric soils).

Table 4. Soils Located within 200 Feet of Stream in Study Area

ID	Soil Unit Name	Dominant Drainage Class	HSG	% Hydric Soil	% Distribution
49	Antigo silt loam, 0 to 2 percent slopes	Well drained	B	0	4
49B	Antigo silt loam, 2 to 6 percent slopes	Well drained	B	0	18
49C	Antigo silt loam, 6 to 15 percent slopes	Well drained	B	0	9
49D	Antigo silt loam, 15 to 35 percent slopes	Well drained	B	0	1
189	Auburndale silt loam, 0 to 2 percent slopes	Poorly drained	B/D	95	11
456	Barronett silt loam	Poorly drained	C/D	92	1
1847	Barronett silt loam, sandy substratum	Poorly drained	B/D	90	2
120	Brill silt loam	Moderately well drained	C	5	0.8
155C	Chetek sandy loam, 6 to 12 percent slopes	Somewhat excessively drained	A	0	1
452	Comstock silt loam	Somewhat poorly drained	B/D	4	0.5
449	Crystal Lake silt loam, 1 to 3 percent slopes	Moderately well drained	C	3	0.1
264	Freeon silt loam, 2 to 6 percent slopes	Moderately well drained	C/D	3	1
266	Freer silt loam	Somewhat poorly drained	C/D	5	0.02
177B	Gotham loamy sand, 1 to 6 percent slopes	Excessively drained	A	0	0.2
342D	Kingsley sandy loam, 12 to 18 percent slopes	Well drained	C	0	2
454C	Mahtomedi loamy sand, 6 to 12 percent slopes	Excessively drained	A	0	8
454D	Mahtomedi loamy sand, 12 to 25 percent slopes	Excessively drained	A	0	7
1820F	Mahtomedi variant-Rock outcrop complex, 25 to 60 percent slopes	Excessively drained	A	0	2
543	Markey muck	Very poorly drained	A/D	95	0.5
507	Poskin silt loam	Somewhat poorly drained	B/D	3	1
153B	Santiago silt loam, 2 to 6 percent slopes	Well drained	B	0	5
153C	Santiago silt loam, 6 to 15 percent slopes	Well drained	B	0	9
540	Seelyeville muck	Very poorly drained	A/D	100	15

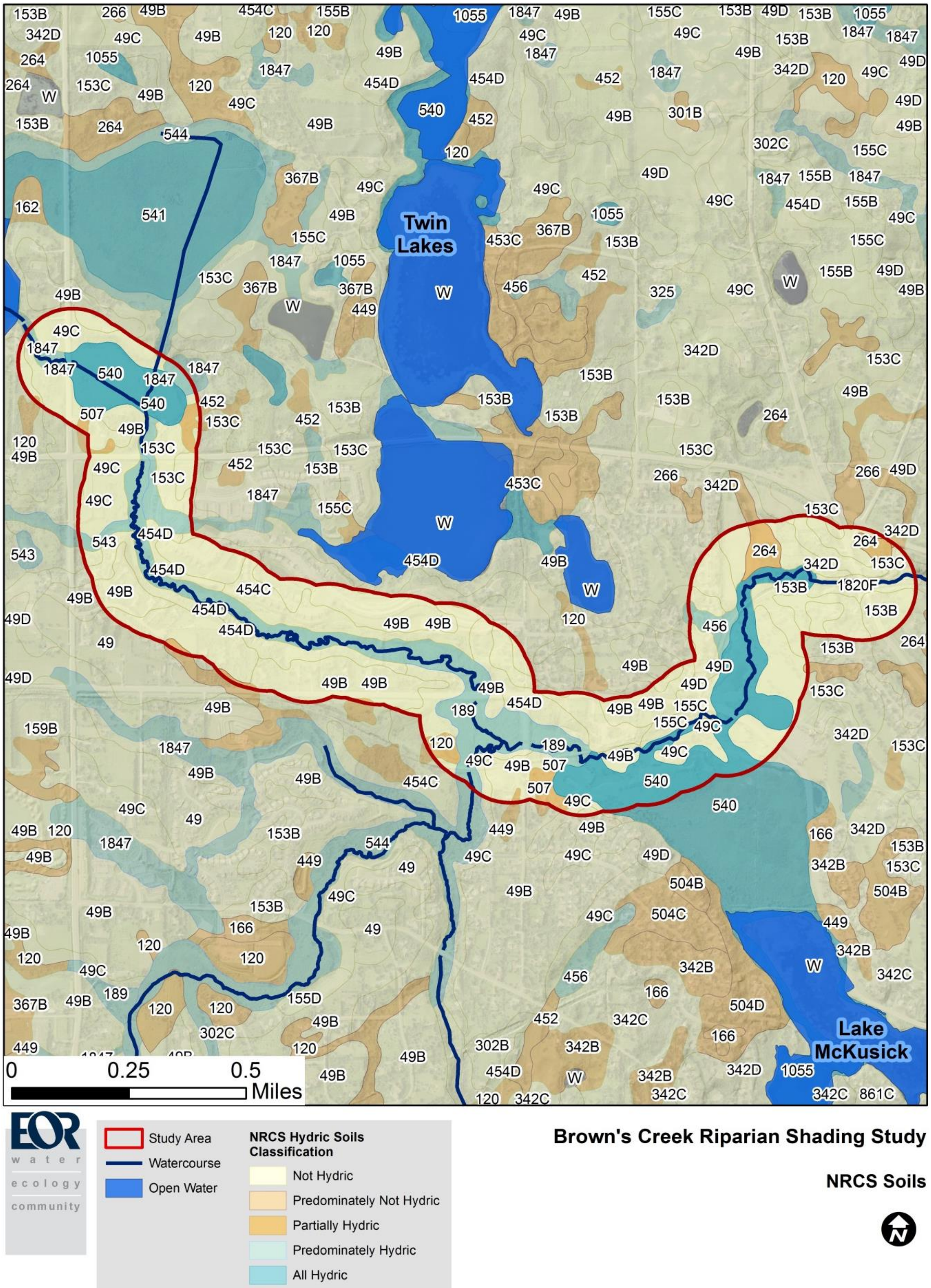

Figure 18. Soils of Study Area

3.6. Plant Communities

3.6.1. Historic Vegetation

Oak and aspen savannas were dominant pre-settlement plant communities of the SBPM Subsection, especially on moraine ridges and along streams. Tallgrass prairie and maple-basswood forest were also found within the Subsection, found primarily in rolling plains and along steep ravines, respectively. Marschner's map of the Original Vegetation of Minnesota (1974) and later adaptation of Marschner's Map (Wendt and Coffin 1988) provide a unique overview of the vegetation that existed prior to European settlement across the state. The maps are based on the Public Land Survey (PLS) of 1847-1907; the latter generalizes the vegetation types identified in the former. Restrictions of map accuracy, due to limitations of the PLS methodology, inhibit the level of resolution the maps provide; therefore, adjacent historic land cover and bearing tree[2] data were also examined to identify historic vegetation communities that likely existed within the study area and along the Study reach. The mapping data indicate that the study area was historically comprised of oak openings and barrens (Figure 19). Wet prairie, big woods-hardwoods (e.g. oak maple, basswood, and hickory), conifer bogs and swamps, prairie, and lakes are also indicated in the surrounding area and may have also historically occurred within the study area. Bearing tree data within the study area include black oak, white oak, and bur oak. Other tree species identified in surrounding areas included tamarack, spruce, aspen, and birch.

Historical disturbance associated with grasslands and savannas such as oak barrens likely included fire, high wind events, periodic flooding, and grazing by large mammals. These disturbances sustained the oak barrens landscape, preventing woody vegetation from establishing into a later-succession, dense forest.

3.6.2. Existing Vegetation

The typical vegetation within the headwaters region and middle reach of Brown's Creek illustrated in Figure 15 and Figure 16 include shrub carr wetlands, sedge meadow, oak woodlands, and floodplain forests. As such, riparian vegetation within the study area varies from forested to grassy vegetation, in addition to one segment north of Highway 96 with riprap, mowed turf grass, and ornamental vegetation bordering the stream.

There are no MNDNR Native Plant Communities (NPC) mapped within the study area. However, several NPCs are mapped in adjacent areas. Native communities in the surrounding vicinity include Northern Very Wet Ash Swamp, Northern Wet Meadow/Carr, Southern Rich Conifer Swamp, Southern Dry-Mesic Oak Forest, Southern Dry Prairie, and Southern Mesic Maple-Basswood Forest

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[2] As part of the PLS, surveyors notched, blazed and scribed bearing trees to facilitate the relocation of the corners of rectangular survey grids should the wooden corner post or corner stone be lost or moved. Bearing trees were also required where surveyors had to meander around impassable areas, such as lakes. Surveyors recorded the species, diameter distance to corner, and azimuth (i.e. bearing from the corner) of each bearing tree. Surveyors also recorded witness and line trees that were found along the line or near the corner but were not required to record as much information as for the bearing trees. The Natural Heritage Information System Bearing Tree Database contains computerized records only of the bearing trees at standard section and quarter-section survey corners (Almendinger, 1996).

(Figure 20). The BCWD has also mapped natural communities such as the Maple-Basswood Forest that extends into the eastern extent of the study area (Figure 20). The Maple-Basswood Forest connects to a similar NPC identified by the DNR with a 'C' condition ranking which means that the community has "fair ecological integrity" which means they show strong evidence of human-caused degradation, but retain some characteristic species and have some potential for recovery with protection and management (Minnesota Biological Survey, 2018).

Exotic and invasive species are present and ever increasing within the Brown's Creek watershed. They affect the quality of our natural resources in many ways by degrading wildlife habitat and water quality, and can negatively affect the quality of our native plant communities. The BCWD is managing invasive terrestrial plant species, such as reed canary grass and buckthorn, to restore healthy plant communities in the watershed and along the creek. Heavy growth of curly leaf pondweed was found in the creek at Highway 15 and above McKusick Road which could hinder trout suitability by slowing water, warming water temperature, and increasing fine sediment deposition over spawning gravel (Washington Conservation District, 2016). Several of the woodlands in the headwaters region are in good condition and do not display the heavy levels of buckthorn that frequently characterize oak communities within the region. In general, the woodland communities tend to be in better condition in the areas adjacent to the wetlands and to show more evidence of disturbance away from the wetlands (Emmons & Olivier Resources, 2017). A complete list of invasive plant species found in the watershed is provided in Appendix A of the District's WMP.

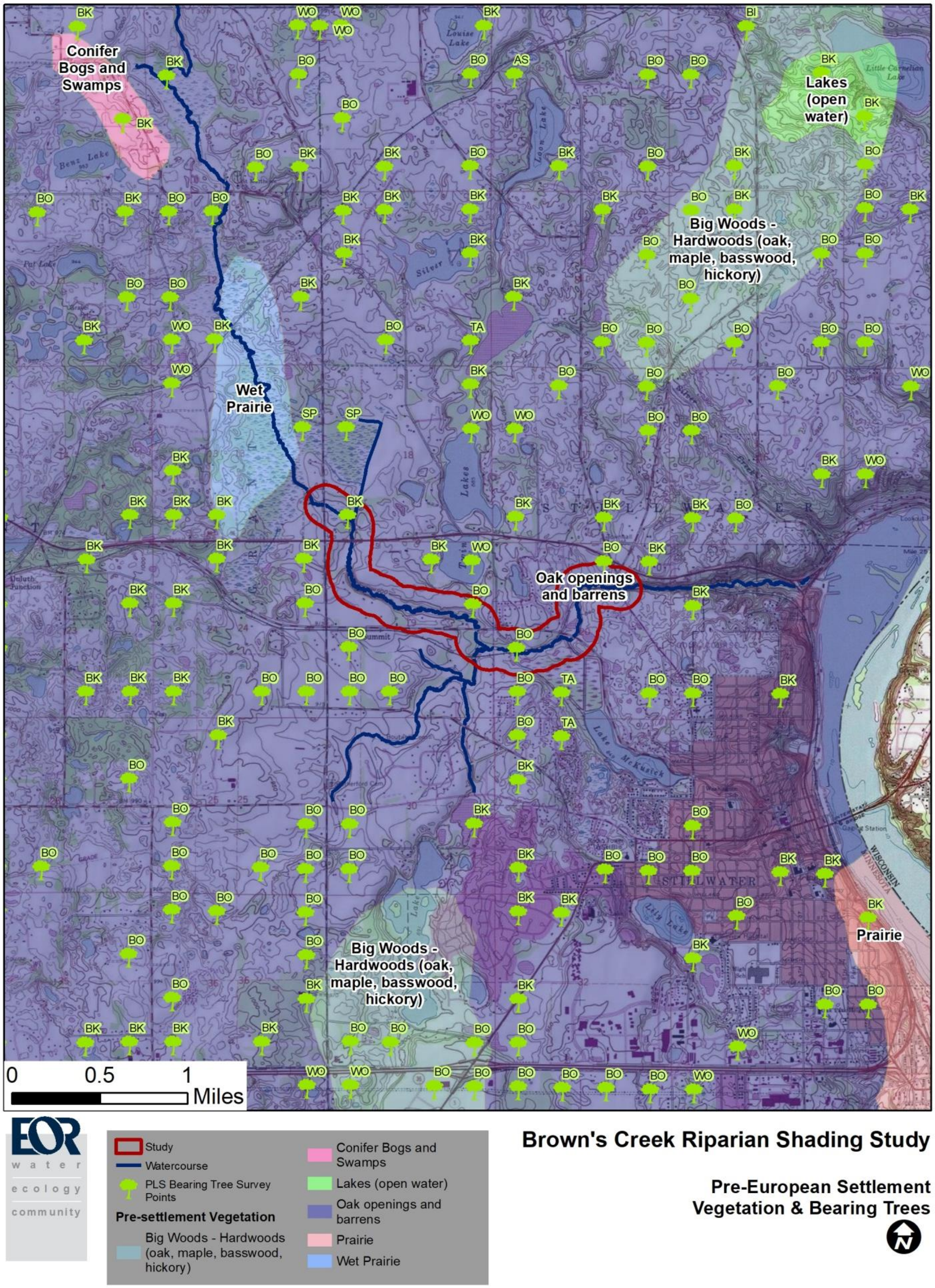


Figure 19. Pre-Settlement Vegetation near Study Area

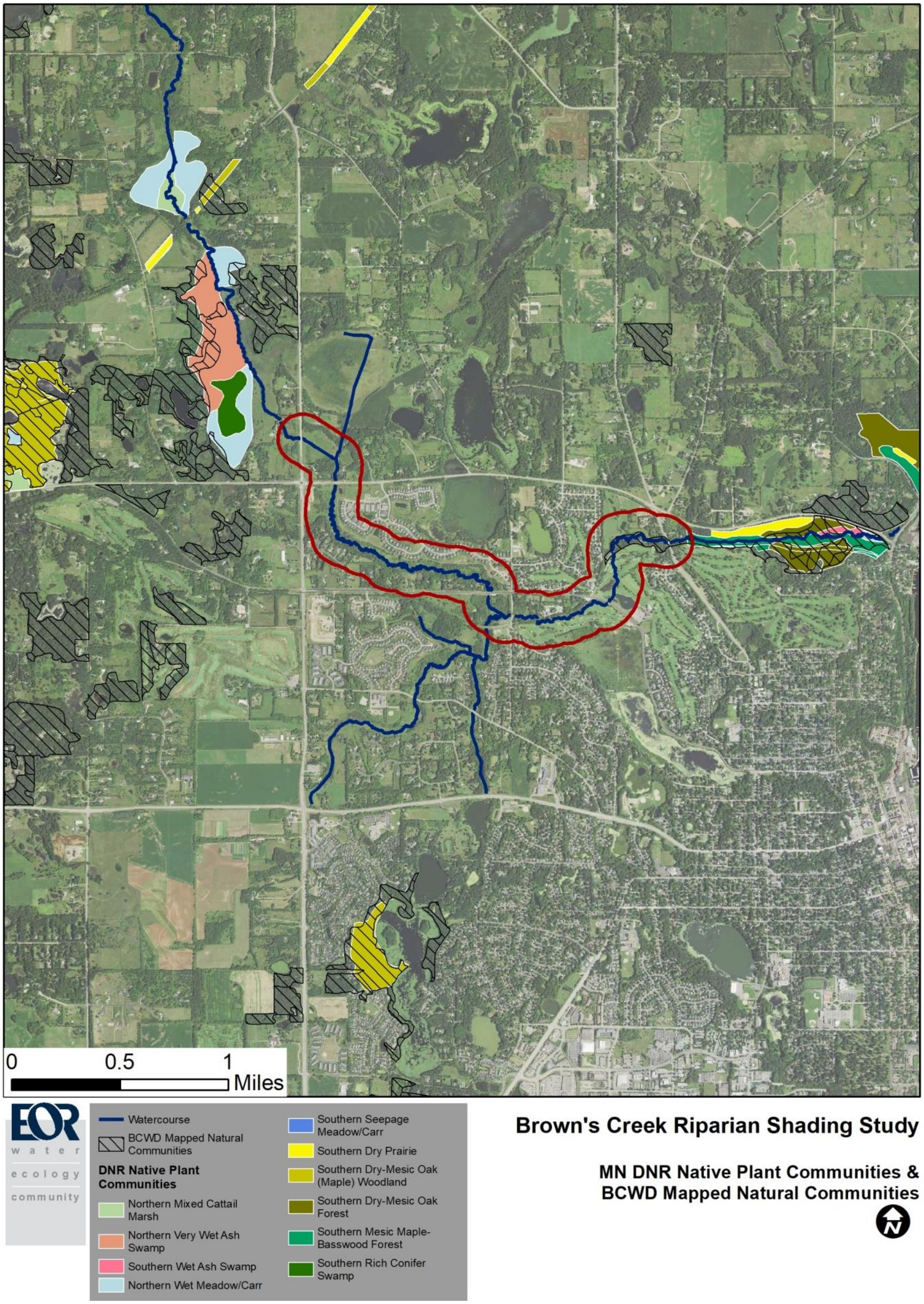


Figure 20. Existing Native and Natural Plant Communities

3.7. Floodplain, Upland, and Wetland Wildlife

The SBPM Subsection is home to 149 Species of Greatest Conservation Need (SGCN), including 74 state or federally endangered, threatened, or of special concern. The study area falls within a township identified as having 51-100 SGCN records and SGCN richness of 31-50. Habitat loss and degradation, invasive species and completion, and pollution are identified as the greatest problems for SGCN in the Subsection. Prairie, oak savanna, grassland, and stream habitats, among others, are all considered key habitats within the Subregion. MN DNR recommended stream habitat actions include:

a) Maintain good water quality, hydrology, geomorphology, and connectivity in priority stream reaches
b) Maintain and enhance riparian areas along priority stream reaches
c) Provide technical assistance and protection opportunities to interested individuals and organizations

The BCWD inventoried unique species in the headwater region and middle reach of Brown's Creek in 2015. The natural communities along the creek provide significant habitat and form a wildlife corridor through the watershed. The unique species identified in the two regions are illustrated in Figure 15 and Figure 16.

The mosaic of wetlands, forest, and grassland communities support a variety of animals. In particular, there are records of the Blanding's turtle (a state-listed threatened species), Red-shouldered hawk (a state-listed species of special concern), and Hooded warbler (classified as a "Rare Regular" species by the Minnesota Ornithologists Union) in the headwaters region. In addition, large wetlands in the headwaters region support healthy populations of painted and snapping turtles in addition to several species of frogs and toads. Due to the quality and size of the wetland communities, the potential for additional rare species is high (Emmons & Olivier Resources, 2017).

The wetland and shrub-carr communities in the middle reach of Brown's Creek provide important breeding and foraging habitats for many resident and migratory species of birds, such as Ring-necked duck, Mallard, Broad-winged hawk, Killdeer, Pileated woodpecker, Chimney swift, Alder flycatcher, Great-crested flycatcher, and Barn swallow. In addition, common herpetile species such as Common garter snakes, Green frogs, Western chorus frogs, and Northern leopard frogs are most likely to be prevalent within this somewhat developed reach of Brown's Creek (Emmons & Olivier Resources, 2017).

3.8. Aquatic Biota

Ultimately, the purpose behind strategies to decrease stream temperatures is to support healthy coldwater fish assemblage in Brown's Creek. Brown trout have been stocked yearly since 1958 in Brown's Creek. The DNR typically stocks between 800 and 1,000 yearlings, but sometimes stocks several size classes. Historically, fish surveys did not report many trout, sometimes fewer than 20 individuals, and the trout were primarily young-of-year (YOY) which indicated possible natural reproduction in Brown's Creek. Still, long-term fish survey data indicated that brown trout were not establishing well in Brown's Creek. From 1998-2004, stream habitat improvement projects in conjunction with lower water temperatures lead to higher trout populations in the creek. However, fish surveys conducted from 2004 to 2007 showed a decline trout population. Natural reproduction was confirmed sporadically (1966, 1976, 1989, and 1998-2001) but not consistently enough to maintain a sustainable population. Native brook trout, another coldwater fish species historically found in Brown's Creek, were not found in the 2000, 2005, and 2008 MNDNR surveys (Emmons & Olivier Resources, 2012).

Recent surveys at different locations along Brown's Creek have provided useful data to better understand the health and stability of the brown trout community in Brown's Creek. On September 13, 2016, a fish survey conducted by the Minnesota DNR in the Oak Glen Golf Course between the crossings of Brown's Creek State Trail and the second cart path found eight adult trout that had survived since the previous stocking in 2014 (Figure 21). Although their findings did not indicate natural reproduction had occurred, it seemed imminent since the large females captured were of the size and age that could reproduce. On September 30, 2016, EOR captured a young-of-year brown trout while conducting a macroinvertebrate survey in the gorge downstream of the Oak Glen Golf Course (Figure 22). This was an indication that natural reproduction of brown trout had occurred since the previous year's stocking.

Figure 21. Adult Brown Trout Caught in Oak Glen Golf Course on Sept. 13, 2016 (Photo Credit: MN DNR)

Figure 22. YOY Brown Trout Caught in Brown's Creek Gorge on Sept. 30, 2016 (Photo Credit: Mike Majeski, EOR)

More recently in 2017, a complete fish community survey was conducted in the lower, middle, and headwater reaches of Brown's Creek. The middle reach of Brown's Creek was surveyed north and south of the Highway 96 crossing east of Highway 15. The survey results indicated that the middle reach of Brown's Creek contained an IBI score of zero or "Very Poor" due to the lack of detectable presence of coldwater species such as rainbow darters and brown trout. The fish community found in the middle reach was more consistent with a cool or warmwater system than a coldwater system. Survey samples were also conducted in June between the Stonebridge Trail and Highway 95 crossings in the lower (gorge) reach of Brown's Creek. A total of 140 brown trout were collected in the gorge, of which nearly half were considered young-of-year, indicating good natural reproduction occurred in 2016. The frequencies of observed fish lengths are summarized in Figure 23. The size of the young-of-year brown trout captured in June as part of this study indicated that the fish were not part of the 100 brown trout stocked by a Stillwater High School in May of 2017. Four rainbow darters were also captured in the lower reach. Overall, the fish community survey resulted in an IBI score of 30 or "Fair" ranking for the lower reach indicating that the stream has experienced moderate degradation of biotic integrity. The four rainbow darters indicate a significant increase relative to previous surveys but still indicate a critically small and restricted population (Lallaman, 2017).

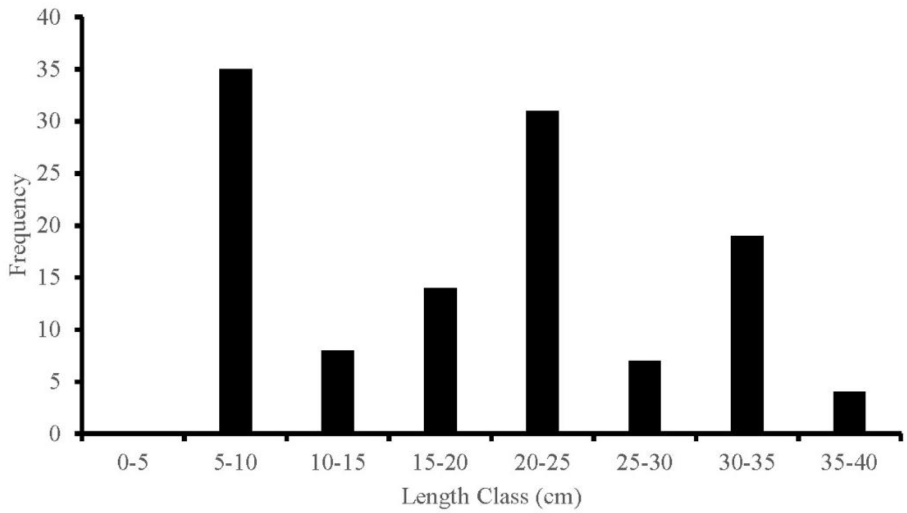


Figure 23. Length-Frequency Distribution of Brown Trout Captured in Brown's Creek Gorge (Lallaman, 2017)

Coldwater fish populations are supported by environmental conditions and the macroinvertebrate community which can also be assessed for indications of biotic health. As such, the BCWD has also conducted macroinvertebrate surveys from 2015 to 2017 in the lower, middle, and upper reaches of Brown's Creek. Over the three years of monitoring, all three reaches were found to contain similar taxa that were consistent with the previous years' surveys. All sites contained taxa with both high and low pollution tolerance levels, indicating some level of urbanization impacts, but also ample oxygen levels and good habitat. These results indicate good water quality and stable conditions in Brown's Creek over the last 3 years (Rufer, 2017).

The Minnesota Pollution Control Agency (MPCA) will conduct a watershed assessment in 2020, with the Intensive Watershed Monitoring program beginning in 2019, to re-evaluate the status of biotic health in Brown's Creek using all monitoring data collected as part of the Brown's Creek Impaired Biota TMDL study and recent biological surveys. Brown's Creek will be removed from the impaired waters list when the IBI score meets the threshold for southern coldwater streams (ranking of 45 +/- 13) and when instream TSS meets the state's numeric standard for class 2A coldwater streams (10 mg/L) (Emmons & Olivier Resources, 2012).

In addition to aquatic biota, beavers are also common in the middle reach of Brown's Creek. They are active in the stream, building dams which cause ponding into the floodplain that can also result in tree mortality under the sustained inundation.

4. LITERATURE REVIEW SUMMARIES

The purpose of the riparian shade review in Appendix A was to identify the best-suited methods for comparing shade provided by grassy and woody riparian vegetation. There are few studies in North-Central America which have quantitatively assessed grassy riparian shade and none using rigorous field measurements. The review found that hemispherical photography is the best-suited method for comparing shade provided along small streams by grassy vegetation to woody vegetation. In addition, direct measurements of shade using arrays of pyranometers or other light sensors are useful in validating indirect measurements of shade from hemispherical photography. Canopy cover and closure are not acceptable surrogate measurements for shade because they do not vary based on the position of the sun in the sky. In addition to shade, ancillary data on the physical characteristics of the stream and vegetation should be collected in order to diagnose differences in shade at multiple monitoring locations and assess which variables can be used to predict shade.

The second literature review in Appendix B was conducted to seek out the most recent information regarding the comparative benefits of grassy and woody riparian buffers with respect to their environmental functions. These environmental functions included sediment control, phosphorus control, increasing dissolved oxygen, supporting aquatic fauna, and maintaining groundwater inputs to the creek. All of these functions are relevant to the watershed management objectives and priorities of the BCWD. The review was conducted to support the well-informed riparian management decisions primarily focused on stream temperature management from this study with a full view of the potential trade-offs with other watershed management objectives. Overall, the most relevant trade-offs of establishing forested streams was the resulting changes that occur in the channel morphology and resulting loss of trout habitat. Streams with woody riparian vegetation typically are wide and flat, whereas streams with grassy buffers are deep and narrow along with overhanging banks. The latter is considered to be more optimal for supporting trout and other wildlife, although there must be a balance with regards to opening the canopy to the extent that incoming solar radiation radically increases stream temperature. Multiple other factors are considered in Appendix B. The practical implications for these trade-offs is that both grassy and woody riparian vegetation provide necessary benefits to coldwater stream systems and riparian management strategies should use a balanced, mosaic approach to a variety of vegetation types. This means that multiple benefits could arise from thinning out over-forested buffers while others could arise from sporadic tree plantings in open meadows. The specific take-away for the riparian shading study is that a widespread tree-planting approach to increase shade would likely result in several detrimental impacts such as increased erosion of the streambanks. The Riparian Shading Study should assess and propose measures to increase shade while mitigating the potential detrimental impacts of changes to the riparian buffers.

5. RIPARIAN SHADE ANALYSIS

Existing riparian shade in the study area was analyzed using hemispherical photographs to address the limitations of LiDAR identified in the Brown's Creek Thermal Study. Further steps were taken to understand where plantings would be most effective and to define a targeted shade restoration scenario.

5.1. Existing Conditions

5.1.1. Method

Data Collection

The study area was limited to Brown's Creek between the Stonebridge Trail and Highway 15 / Manning Avenue. Reaches within the study area were selected for monitoring based on their unique vegetation composition, estimated shade, and channel geometry. The representative reaches included three un-shaded areas identified by Herb and Correll (2016) as having less than 20% shade. In addition, a reference reach with established woodlands was selected to represent the maximum attainable shade and the recently restored location in lower Oak Glen Golf Course was selected to represent improved conditions 5-years post construction. The geometry of these reaches was assessed using the Rosgen Classification system in the Brown's Creek Stream Classification Study (2007), which identified unique E4, E5, C3, and C4 classifications within the study area. The criteria for these classifications and the stages of channel adjustment are illustrated in Figure 24 and Figure 25. The characteristics of the representative reaches are listed in Table 5 and the locations are illustrated in Figure 26. The selection of representative reaches based on these characteristics facilitated comparisons of shade provided by different vegetation and at locations with different channel geometry.

Table 5. Preliminary Identification of Representative Reaches in the Study Area

Representative Reach ID	Rosgen Classification	Estimated Shade	Vegetation	Reach Length (m)
1	E5	41-60%	Shrub Carr	291
2	C3	61-80%	Woodland & Lawn	159
3	E4/5	0-20%	Sedge Meadow	396
4	C4	61-100%	Woodland	222
5	C4	21-40%	Woodland & Sedge Meadow	197
6	E4	21-40%	Woodland	194
7	C4c	0-60%	Mixed	395
			Total:	1,855

A portion of each representative reach was monitored to assess the riparian shade. The necessary sample reach length was estimated by multiplying the average wetted width of the stream by 40 (Dent et al., 2000). For this study, the average wetted width of Brown's Creek was approximately 3 m and the resulting sample reach length was 120 m. The distance between transects was calculated by dividing the sample reach by ten (Dent et al., 2000), resulting in 11 evenly spaced transects (12 m apart) to be monitored in each sample reach. A total of 77 transects (i.e. points along the creek) were monitored to evaluate riparian shade in the representative reaches. The above sampling scheme enabled analysis of individual representative reaches, comparison of one reach to another, and analysis of multiple reaches at a watershed scale.

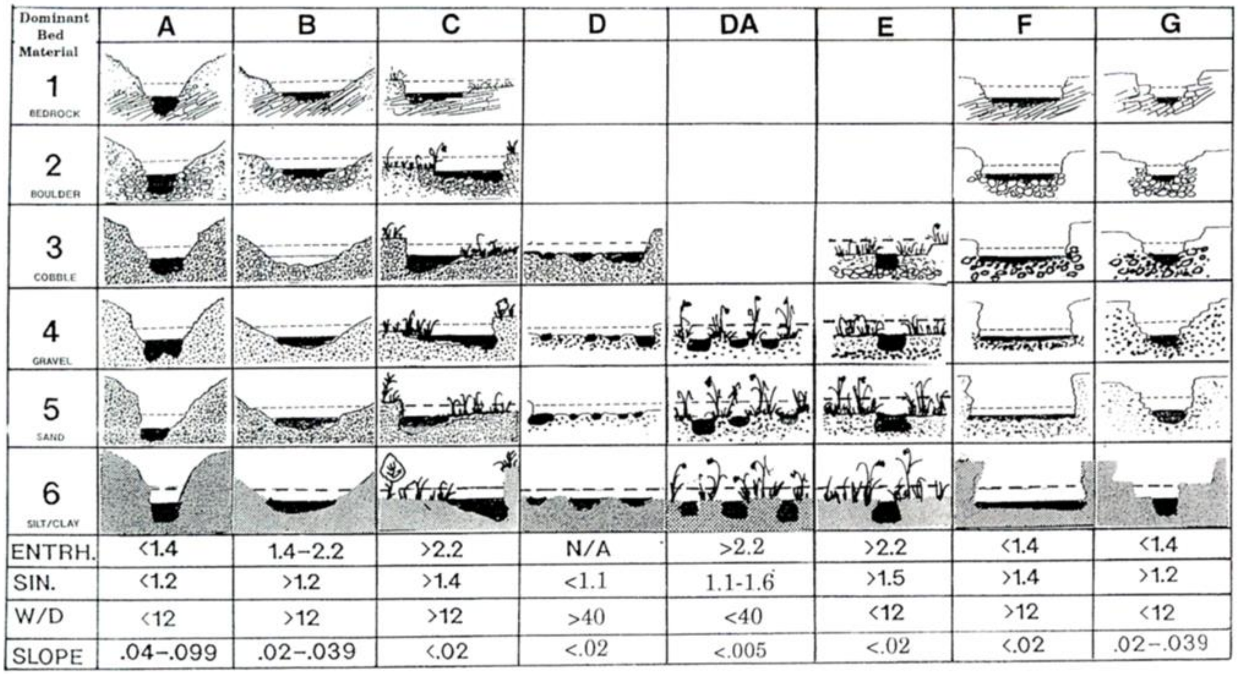


Figure 24. Illustrative guide showing cross-sectional configuration, composition and delineative criteria of major stream types (Rosgen, 1994) [3]

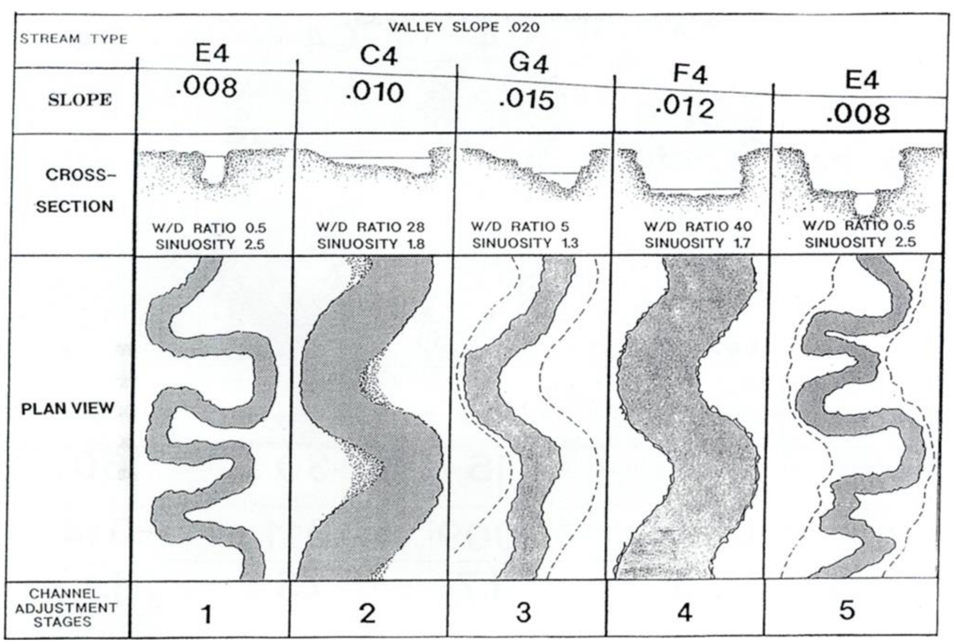


Figure 25. Evolutionary stages of channel adjustment (Rosgen, 1994)

[3] ENTRH = Entrenchment Ratio = Flood prone width / Bankfull width
SIN = Sinuosity = Channel length / Valley length
W/D = Width to Depth Ratio

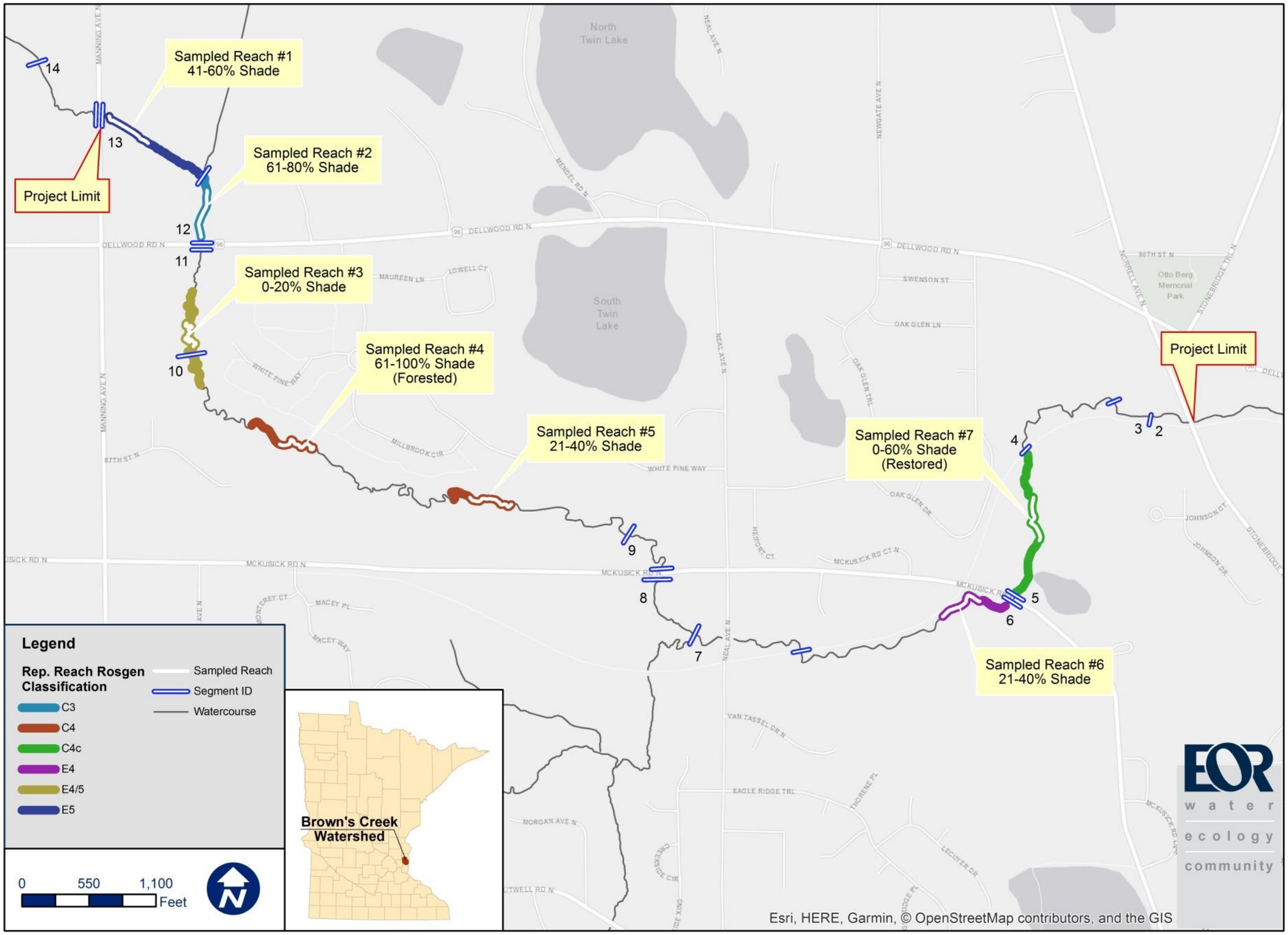


Figure 26. Location of Representative and Sampled Reaches

Hemispherical (fisheye) photographs were collected at each transect in the study area between July and September of 2017 using a Sony Alpha 6000 (ILCE-6000) camera with a fisheye lens mounted by a self-leveling apparatus developed by Regent Instruments, Inc. attached to the ballhead of a Benro TAD28AIB2 Adventure Aluminum Tripod and with the lens facing skyward (Figure 27). The tripod was adjusted to lower the camera as close as possible to the stream surface without risking water damage to the equipment. A tape measure was used to set up and collect three photos across each transect at the center, left, and right[4] (Figure 28). Transect locations were recorded using a GeoExplorer 6000 handheld global positioning system (GPS) and, where accuracy was low, marked using flagging tape.

Figure 27. Setup for Center Photograph

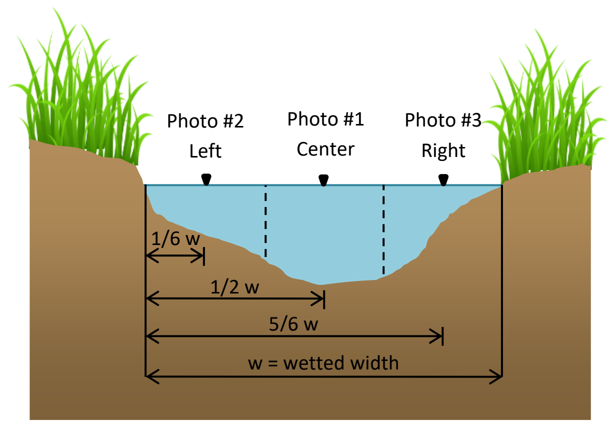


Figure 28. Example Transect with Photograph Locations

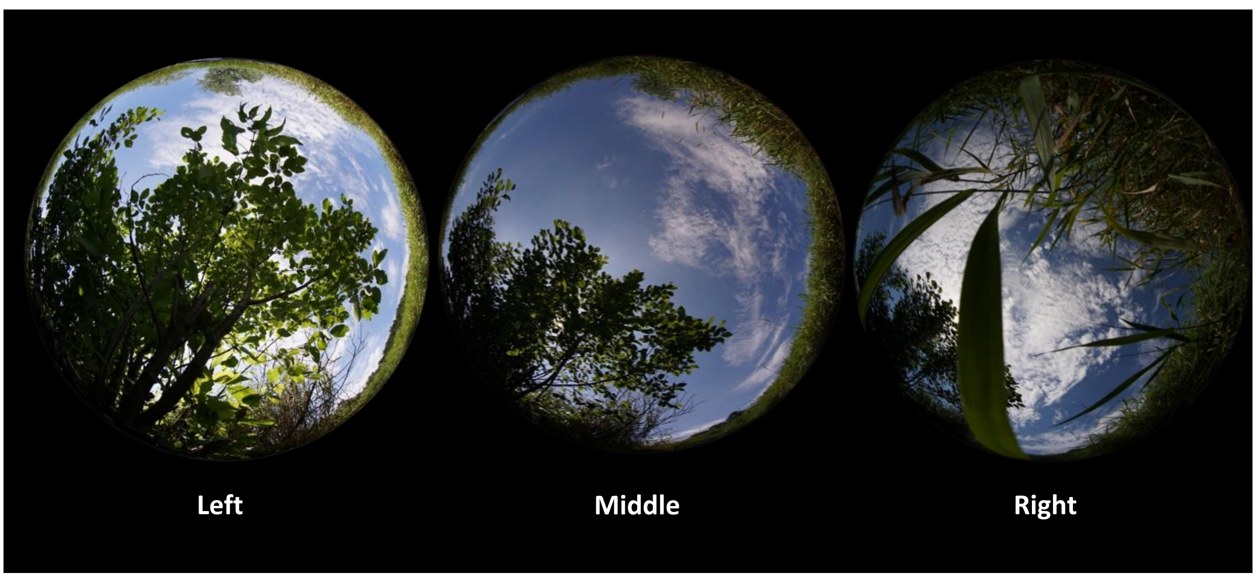


Figure 29. Example of Hemispherical Photographs (Reach 3, Transect 7)

The photos were collected during baseflow conditions in the creek because this flow condition has been demonstrated to be a critical time of temperature stress for aquatic organisms in Brown's Creek

[4] The left and right sides of the transects were identified when looking downstream.

and it is the condition when stream shade is most essential to control stream temperature. Of the 77 transects, two were visited twice to test for variability in shade caused by vegetation growth and senescence later in the season (Reach 3 Transect 6 and Reach 4 Transect 5). The remaining 75 transects were visited once during the monitoring period.

The physical characteristics of each transect were also collected to account for factors that may influence shade, including vegetation and channel characteristics. Where feasible, past studies and datasets were referenced to supplement field data from this study. Only the herbaceous vegetation immediately adjacent to the water's edge were characterized, in addition to woody vegetation that could be seen while standing in the creek at the transect. The physical characteristic assessment included the following:

Channel characteristics:

- *Wetted width*: The width of the wetted surface, subtracting mid-channel point bars and islands that are above the bankfull depth, measured using tape.
- *Thalweg depth*: The deepest part of the channel measured with a surveyor's rod.
- *Stream azimuth*: The direction that the stream is flowing relative to due north. Measured by orienting a compass downstream with the direction of the meander.
- *Classification of valley type, valley width and constraint ratio* [5]: Rosgen Stream Classification.
- *Bankfull width* [3]: Width of the channel at the average annual high water mark.
- *Gradient* [3]: Slope of the channel.
- *Sinuosity* [3]: Ratio of the channel length to the valley length.
- *Substrate* [3]: The percent of channel bed composed of each size class of material (i.e. bedrock, bolder, cobble, gravel, sand or fines).

Riparian vegetation characteristics:

- *Dominant overstory species*: The species of woody (tree or shrub) which dominates the stand (i.e. the tallest, and/or greatest in number).
- *Dominant herbaceous species*: The most common herbaceous species.
- *Species composition*: Other species.
- *Height of vegetation above river*: Maximum height of herbaceous vegetation measured in field, mode height of herbaceous vegetation measured in field, and maximum height of vegetation above the water surface estimated using 2011 LiDAR.
- *Buffer width*: Width of uninterrupted native vegetation averaged over the representative reaches.
- *Activities within the riparian area:* Document other factors influencing composition of plant species, such as beavers, grazing, mechanical disturbance, harvesting, development, fire, restoration, or recreational activities.

One of the steps in the riparian shade analysis was extrapolate the findings at each of the 77 transects to estimate shade in the rest of the study are that was not monitored. Two additional locations were monitored in the study area that were separate from the 77 transects in the sample reaches. The field

[5] Channel characteristic were determined using past studies, surveys, and other monitoring work by BCWD.

data at these two locations were needed to validate the predictive model for shade in un-monitored parts of the study area. These two locations are referred to as Reach 2 Transect 0 and Reach 6 Transect 0.

Several additional days at the end of the monitoring period were spent collecting data at four transects selected to represent the range of vegetation types and stream orientations in the study area (Table 6). The same procedure for collecting photographs as outlined above was used except that five photos were taken at each position (center, left, right) across the transect instead of one. The camera was set at varying heights above the water surface for each of the five photos. The process was repeated with a pyranometer to measure solar radiation below the canopy at five stages at the three positions across each transects. These photos were collected to evaluate the variability in shade due to camera lens height above the water surface under controlled vegetation type and stream orientation. The solar radiation measurements were collected to validate the results of the hemispherical photograph analysis.

Table 6. Transects Selected for Stage-Shade and Validation Monitoring

Vegetation	Stream Orientation	
	East	South
Grassy	Reach 3 - Transect 9	Reach 3 - Transect 6
Woody	Reach 4 - Transect 5	Reach 2 - Transect 0

In total, 297 photos were collected across the study area in addition to characterizing the channel dimensions and vegetation at 79 transects.

Data Analysis

The hemispherical photographs were analyzed using the software WinSCANOPY (Regent Instruments, Inc.) in multiple steps illustrated in Figure 30. First, the position of magnetic north in each photo was identified using the red LED northfinder from the equipment. Second, the colors in the photo were grouped based on a user-defined legend. Third, the groupings were then used to classify which areas of the photo were canopy and which were sky. An intermediate, fourth, step was sometimes taken to edit the legend or add masks to the image where the sunblock apparatus had been used in the field. The fifth and final step to the photo analysis was to simulate the sunpath at each time step over the course of the defined analysis period.

The analysis settings used for all photos are summarized in Table 7. These settings defined how the position of the sun and solar radiation were calculated. The program specifications for the camera, lens, and hemisphere were provided by Regent Instruments, Inc., the developers of WinSCANOPY and supplier of the camera, lens, and mount equipment. Color classes and masks were defined for each photograph and are saved in the project files.

The main output from WinSCANOPY used in this study is the *total site factor*, which is the ratio of average daily direct and indirect solar radiation under and over the canopy during the simulation period (i.e. the growing season). Average shade throughout the growing season was then calculated as 1 minus the total site factor. Average transect shade was calculated as the average of the center, left and right shade results. Average reach shade was calculated as the average of all transect shade levels in each reach.

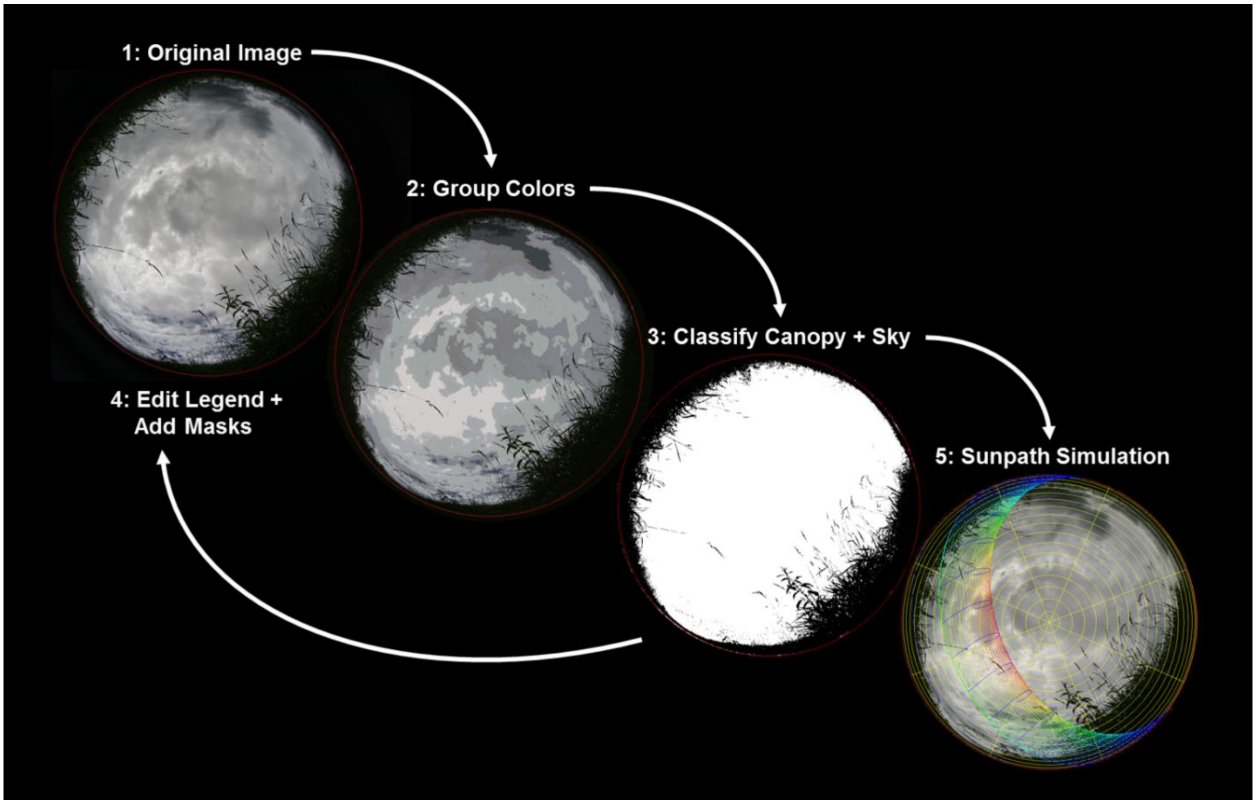


Figure 30. Steps of Hemispherical Photographs Analysis

Table 7. WinSCANOPY Settings

Parameter	Setting
Analysis type	Fish-eye (Wide FOV)
Masks resolution	Low
Filters	None
Diffuse radiation distribution	Standard Overcast Sky (SOC)
Growing season (on/off)	On
Simulation Period (Direct radiation: growing season)	May 1, 2017 to September 30, 2017
Direct radiation: frequency of suntrack creation	5 days
Direct radiation: frequency of sun position calculation	3 minutes
Direct radiation: time zone	-6
Radiation units	Energy (Joules)
Solar constant	1370
Atmospheric transmissivity	0.6
Radiation to PAR conversion factor	1.0 (i.e. PAR results not needed)
Diffuse radiation fraction of direct radiation	0.15
Sun size	1 pixel
Canopy detection based on	Color analysis
Channels for canopy detection	Grey, red, green, and blue
Scale of canopy detection	Log

In addition to the *total site factor*, two other results from the WinSCANOPY analysis were recorded: the *total hemisphere gap fraction* and the *total hemisphere openness*. These parameters indicate how much of the sky above the stream is blocked by vegetation and topography using different approaches. The total hemisphere gap fraction is the ratio of the number of pixels in the photograph classified as sky to the total number of pixels in the photograph. As such, the total hemisphere gap fraction does not account for the projection of the lens onto the plane of the photograph, and so it does not reflect the real canopy above the lens. In comparison, total hemisphere openness accounts for the hemispherical projection of the open sky regions projected onto the photograph. Both parameters are independent from the position of the sun. These results were recorded from the WinSCANOPY analysis because they relate to canopy cover and closure, which are commonly used when discussing shade although they cannot be used as a surrogate for shade (See Appendix A). Total hemisphere gap fraction is similar to 1 minus canopy cover. Total hemisphere openness is similar to 1 minus canopy closure. WinSCANOPY provides many other results that were not utilized in this study, such as leaf area index.

Shade-stage curves were developed for the four transects where photos were taken at five different heights above the stream surface. It is assumed that baseflow conditions were consistent during the period of these photos (September 10 to 13, 2017). A factor was developed using these curves to correct shade to a consistent elevation immediately above the stream surface. Corrections for other variables, such as herbaceous vegetation growth, were not implemented but will be assessed further in the main author’s thesis.

The last piece of the shading data analysis effort was to examine methods for extrapolating the shading results from the monitored reaches to unmonitored reaches in order to create an updated version of the existing shading conditions initially developed in the Brown’s Creek Thermal Study. First, a regression analysis was conducted to assess the correlation of the transect characteristics (e.g. stream azimuth, vegetation height, etc.) with the resulting average transect shade. Second, the WinSCANOPY analysis results were extrapolated to other areas of the creek, relying on the original results of the ArcMap solar radiation analysis of LiDAR data conducted in the Brown’s Creek Thermal Study (hereafter referred to as “LiDAR analysis” and “LiDAR-based shade”, familiarity with the study area and best judgement informed by the WinSCANOPY results.

5.1.2. Results

The full record of data collected in this study is provided in Appendix C which is organized by the channel characteristics, vegetation characteristics, and results of the photo WinSCANOPY analysis. Over 130 plant species were identified adjacent to the stream in the study area as detailed in Table 22 of Appendix C, including native, invasive, exotic, and ornamental species. Eleven invasive or exotic species were identified at the study area transects, including Amur maple, common burdock, birds-foot trefoil, common buckthorn, Canada thistle, glossy buckthorn, garlic mustard, honeysuckle (*Lonicera* spp.), purple loosestrife, reed canary grass, and watercress. At least one of these invasive/exotic species were identified at each transect. The most common invasive species identified were reed canary grass (152), glossy buckthorn (58), Canada thistle (17), and common buckthorn (15). Plants were only identified if they could be seen while standing in the creek at each transect.

The stage-shade curves in Figure 31 indicate that shade did not change significantly with lens height in forested reaches, but it was a significant factor in grassy reaches where shade typically increased as the camera was lowered towards the stream. These curves were used to develop a correction factor for any photos collected in transects with grassy to mixed riparian vegetation. The correction factor was the most significant for reaches with north-south orientation, and resulted in, for example, an incremental increase in shade of 20% where the lens was 0.4 m above the water surface. On average, the correction factor resulted in 7% more shade in grassy reaches.

The final shade results from the WinSCANOPY analysis, including the correction for lens height above the stream, are illustrated in Figure 32 for every transect in the study area. These results illustrate that the shade at each position across a transect typically varies more in grassy reaches than in forested reaches. As such, photos need to be collected at multiple positions across the transect instead of taking a single photo from the middle of the stream in order to estimate shade across the entire transect. Average transect shade (i.e. the purple line in Figure 32) ranged from 8% to 97% in each sampled reach with a mean value of 61%.

A regression analysis of the correlation between multiple independent variables (i.e. the channel and vegetation characteristics) and average shade identified many potential correlations (Figure 33 and Figure 34). Regression analysis is a set of statistical modeling processes for estimating the relationships between variables. Two of the most highly correlated variables with transect shade (*shade.avg*) were the type of vegetation (*veg.code.avg*) and shade estimated using LiDAR in the Brown's Creek Thermal Study (*shade.lidar.leafoff.dsm*). The regression analysis was unsuccessful in developing a reliable predictive model for shade using the physical characteristics of each transect. The range of average transect shade at locations with various levels of woody vegetation is illustrated in Figure 35 and demonstrates the lack of certainty in predicting shade simply using the type of vegetation.

Another regression analysis was more successful in developing a predictive model to correct the results of the LiDAR analysis with the WinSCANOPY-based shade. LiDAR-based shade is compared to WinSCANOPY-based shade spatially (Figure 36), averaged by transect (Figure 38), and averaged by reach (Figure 39). As part of the Brown's Creek Thermal Study, the LiDAR-based shade were revised to calibrate the stream temperature model. The calibrated shade is illustrated in comparison to the WinSCANOPY results in Figure 37. The lognormal relationship between LiDAR and WinSCANOPY-based average transect shade (Figure 38) resulted in an R^2 value of 0.54. Looking at the results on an average reach basis (Figure 39) was more successful with an R^2 value of 0.76. Both of the regression models used a lognormal relationship such that the predicted shade was not less than zero percent or greater than 100% given the range of inputs to the model (i.e. the original LiDAR-based shade from the Brown's Creek Thermal Study). In addition, the shade results for Reach 7 were not included in the regression analysis since the LiDAR data was collected before the 2012 restoration of Oak Glenn Golf Course and the hemispherical photographs used in the WinSCANOPY analysis were collected after the restoration project.

The existing conditions riparian shade analysis conducted in the Brown's Creek Thermal Study was updated using the WinSCANOPY results applied across the sampled and representative reaches monitored in this Riparian Shading Study. The WinSCANOPY results were aggregated on a 40 m segment basis throughout the monitored reaches. This processing was necessary since the stream temperature model simulates the creek in 40 m segments. In areas that were not monitored in this study, the pre-calibration existing shade estimated using LiDAR in the Brown's Creek Thermal Study was adjusted using the lognormal regression formula shown in Figure 39. Lastly, the areas in the Oak Glen Golf Course that were mowed to the water's edge prior to the 2012 stream restoration project were set to 10% shade such that the existing conditions analysis would represent pre-restoration conditions in 2012. The original and final corrected shade along the profile of Brown's Creek is shown in Figure 40.

In comparison to the mowed grass conditions in 2011/2012 in the Oak Glen Golf Course, the hemispherical photo analysis results for representative Reach 7 indicate that current shading is approximately 46% in the golf course. This is the estimated total shade over an entire growing season (May to October) and is averaged over the length of the stream from McKusick Road at the golf course to the Brown's Creek Trail crossing near Stone Bridge Trail.

Hemispherical photograph analysis is the best-suited method for *indirectly* estimating shade and is less intensive than *directly* measuring solar radiation at multiple sites over a growing season (See Appendix A). The uncertainties in hemispherical photo analysis were identified and mitigated where possible, as follows:

- The horizontal level of the camera can affect the view angle used when capturing the image. This was mitigated for by using an auto-balancing mount for the camera and adjusting the position using small weights to center the bubble level.
- Shade is unevenly distributed across the width of the stream. This was assessed through the sampling design which included multiple photos across the stream width.
- Depending on the wind conditions, the motion of vegetation introduces more potential variability in the shade results. A multi-shutter release was used for several sampled reaches which could be used to assess the impact of this factor on the WinSCANOPY results in the future, however such analysis was not included in this study.
- Randomness and variability of shade at monitoring locations and other locations in the study area was accounted for in the sample design.
- The method used in simulating solar pathway and incoming solar radiation in WinSCANOPY has several known limitations such as underestimating the radiation reflected through the canopy by leaves. This was mitigated for by directly measuring solar radiation at four transects in order to validate the WinSCANOPY results. Further review and processing of the solar radiation measurements will be conducted as part of the main author's thesis.

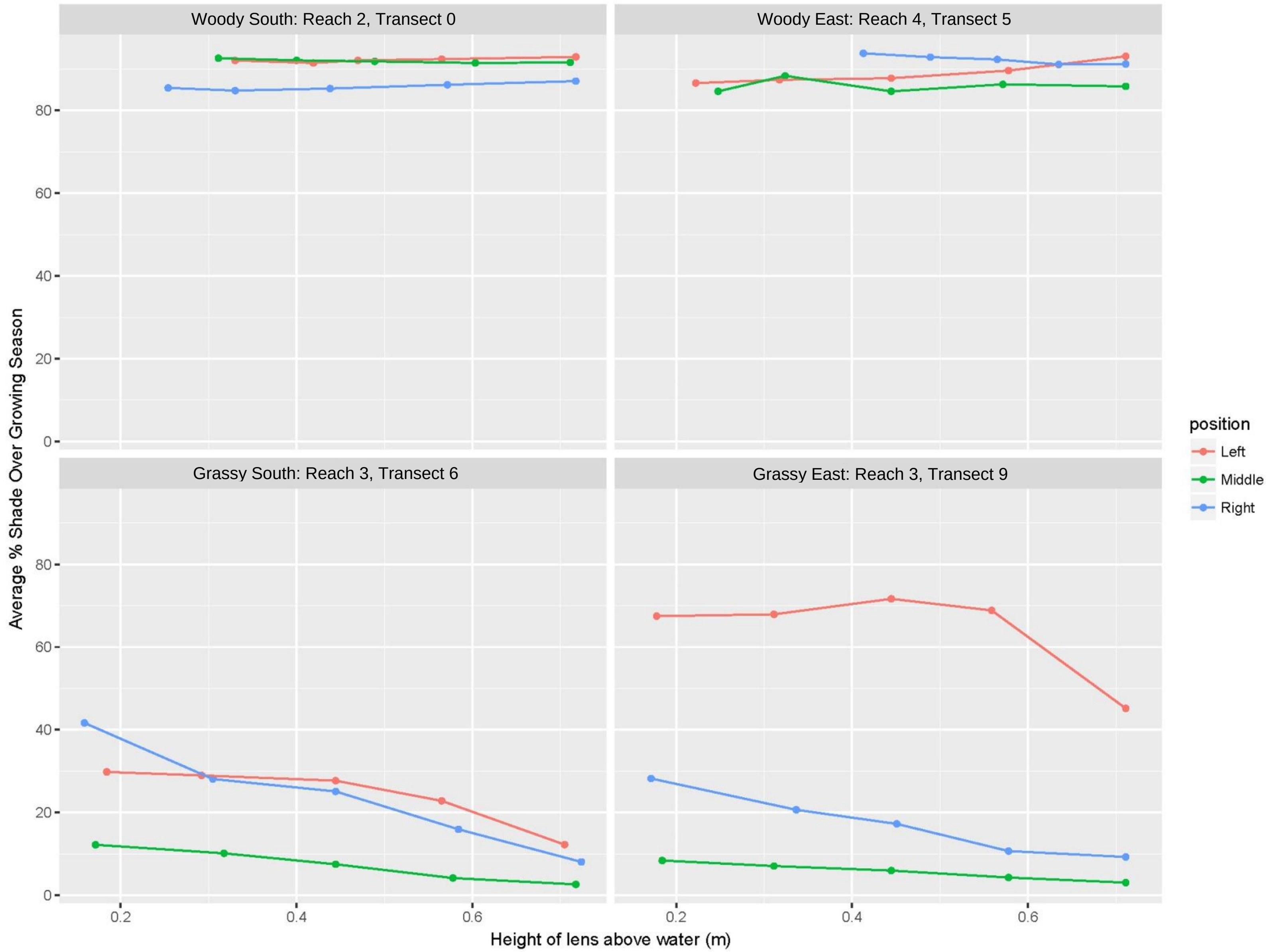


Figure 31. Stage-Shade Curves at Forested and Grassy Transects

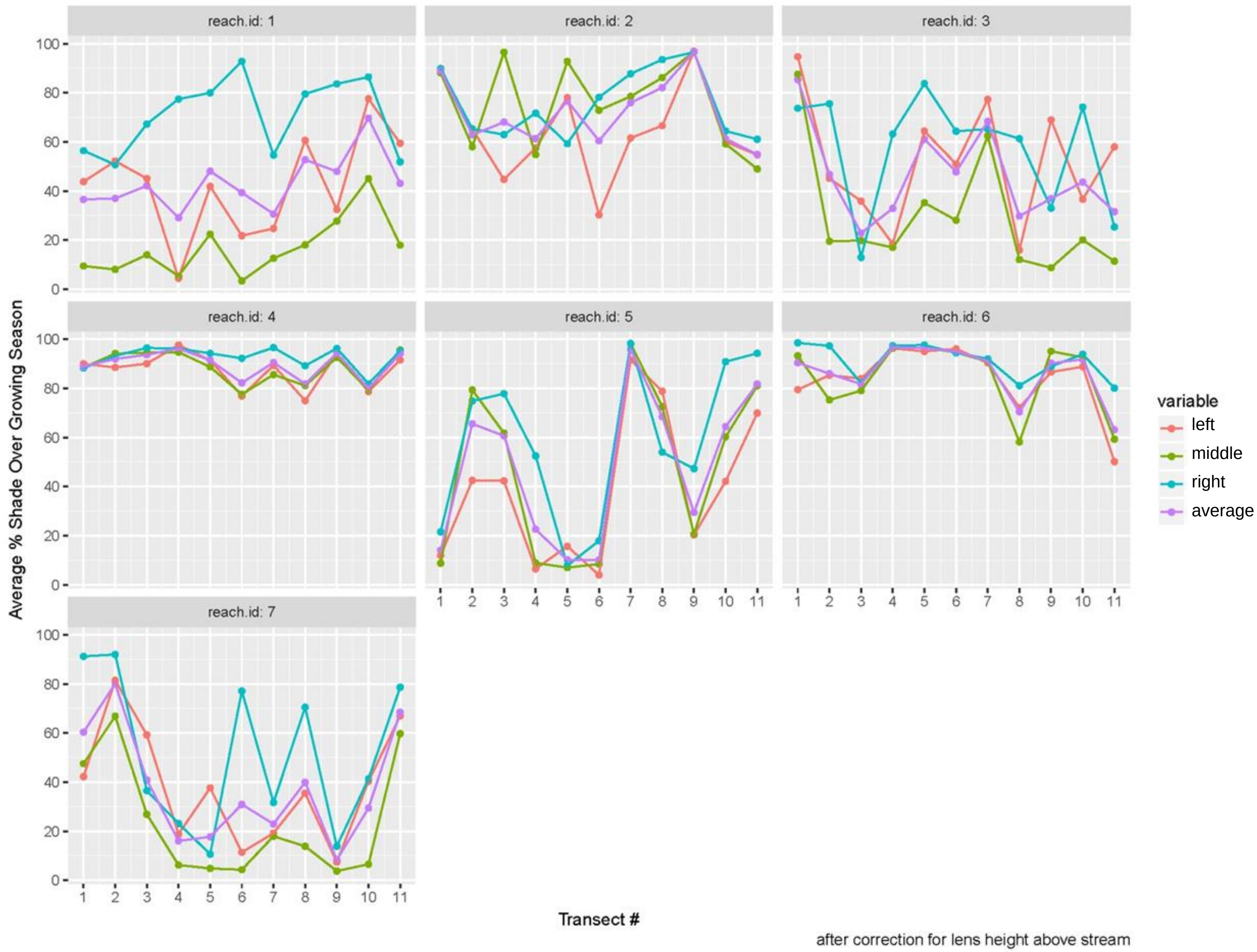


Figure 32. Transect Shade Estimated with WinSCANOPY on Average and at Positions

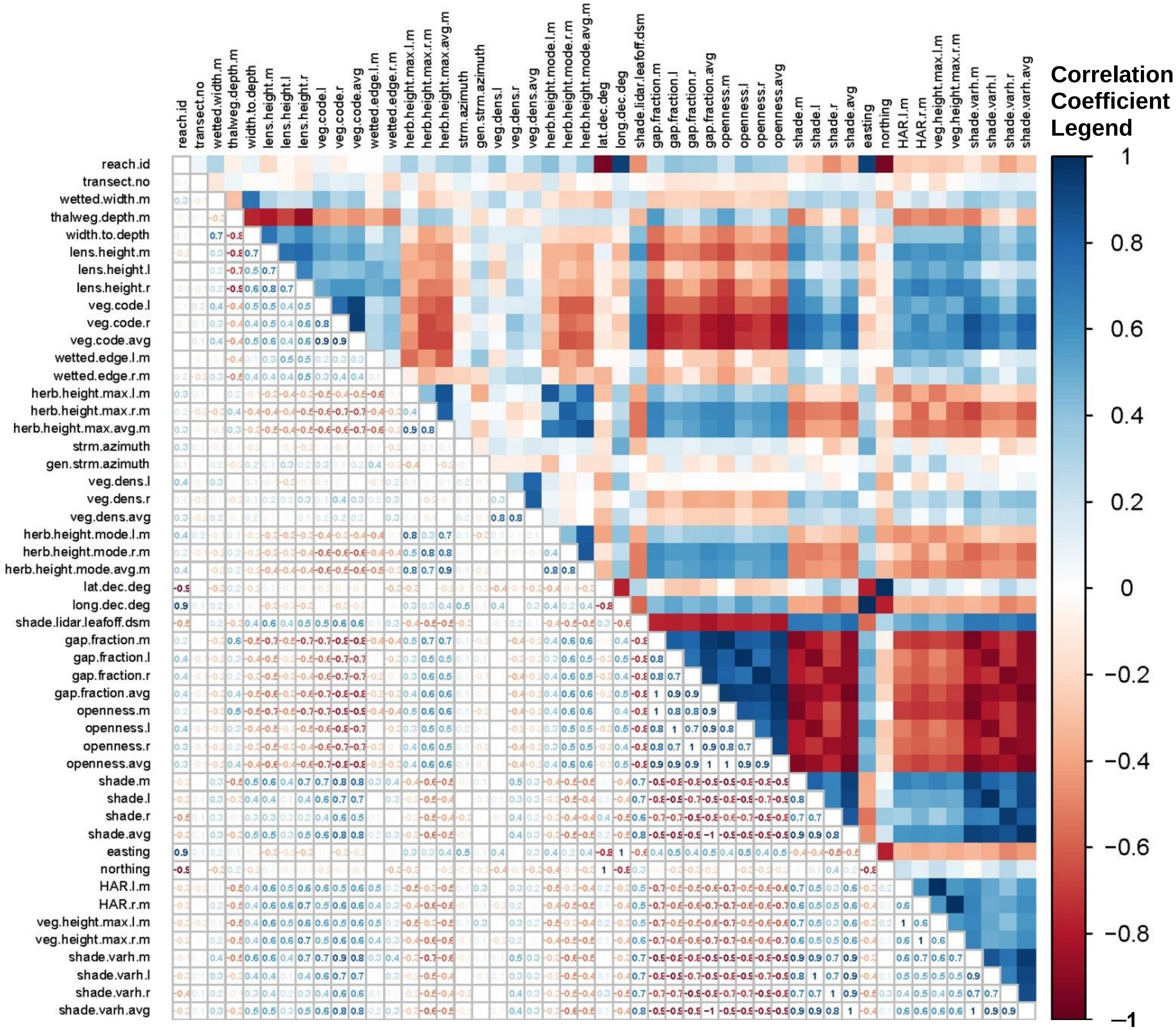


Figure 33. Correlation Coefficients of Independent and Dependent Variables

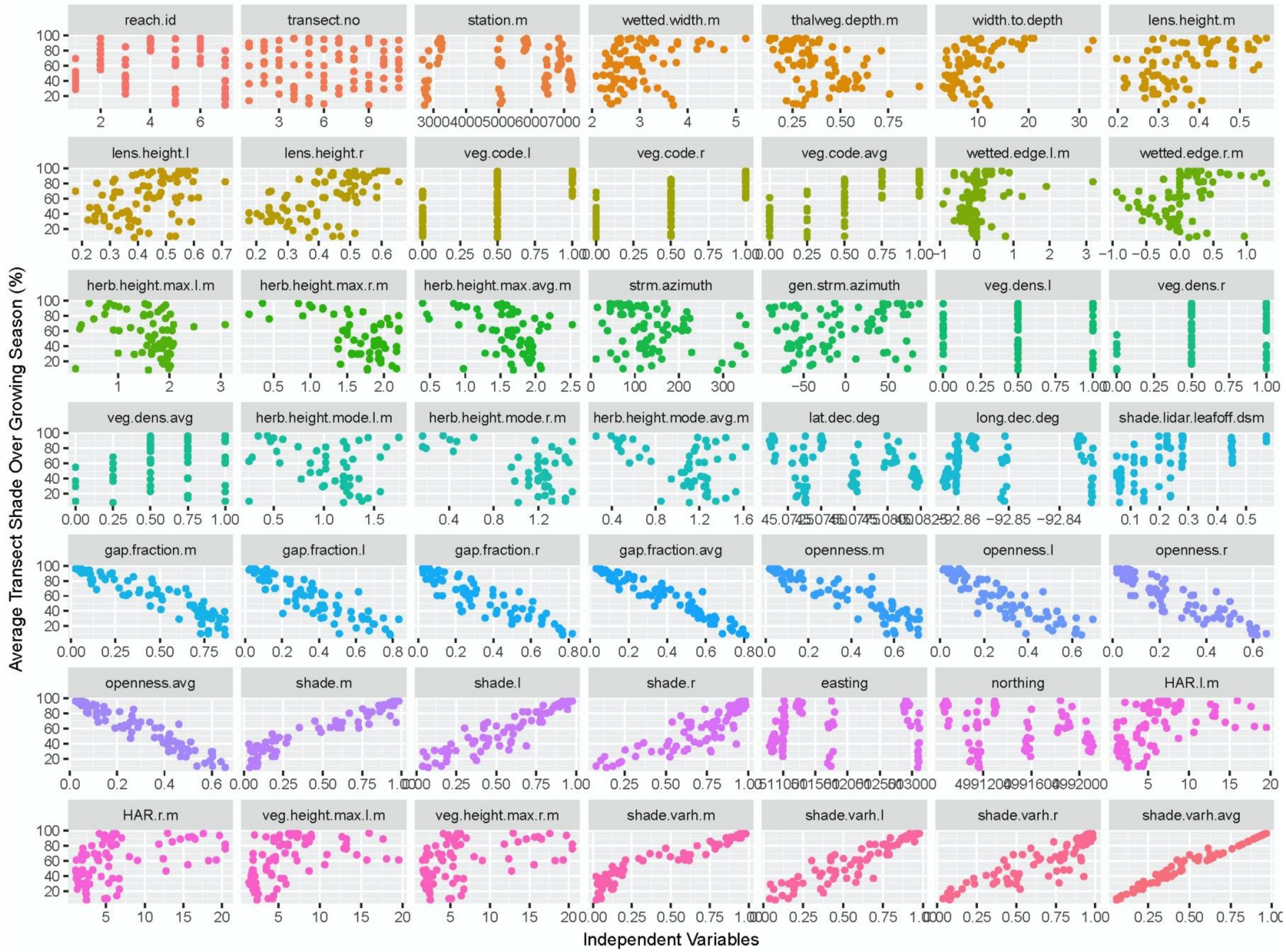


Figure 34. Independent Variables vs. Average Transect Shade

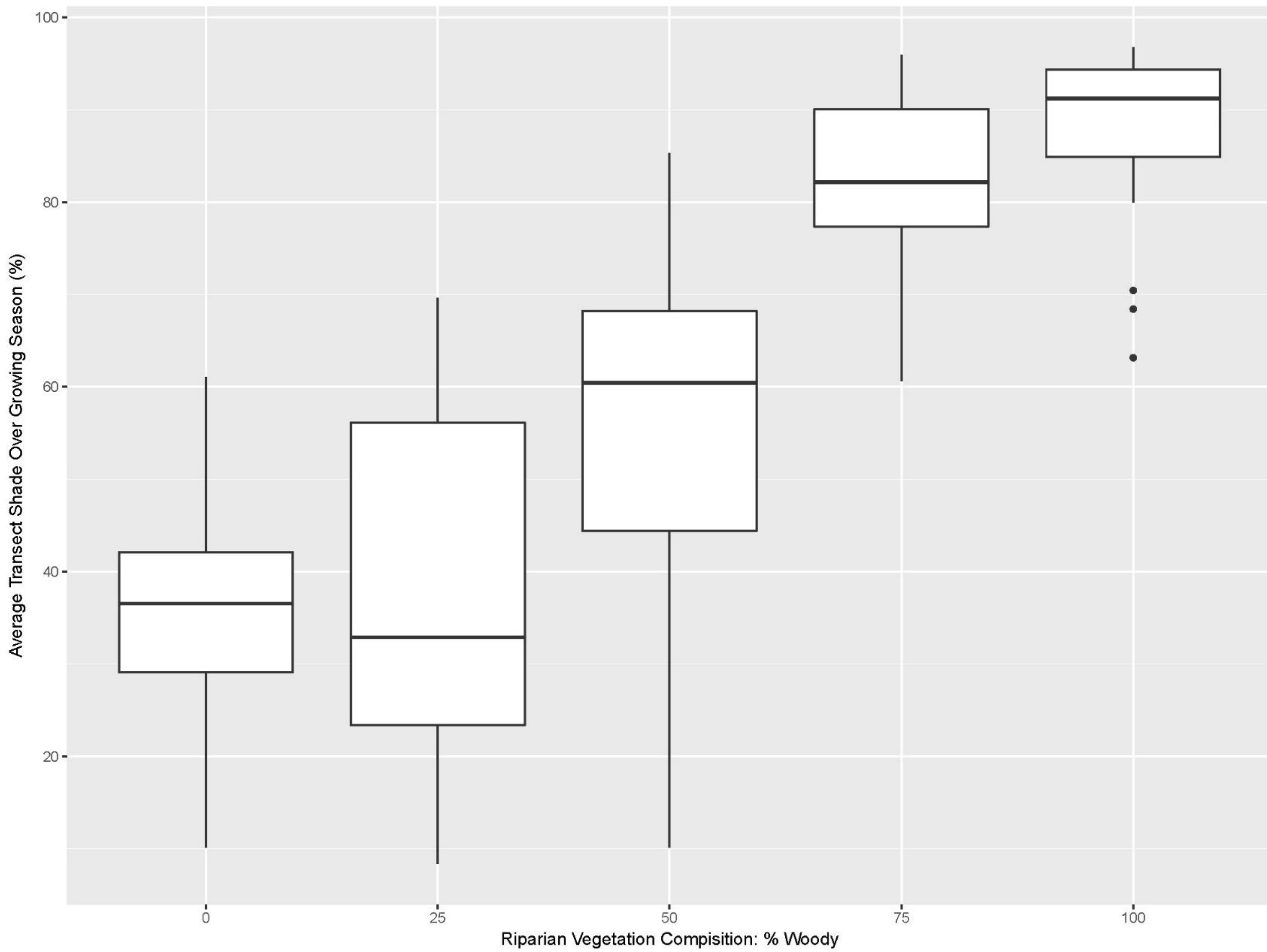


Figure 35. Variation in Transect Shade (WinSCANOPY) Based on Woody Riparian Vegetation Composition

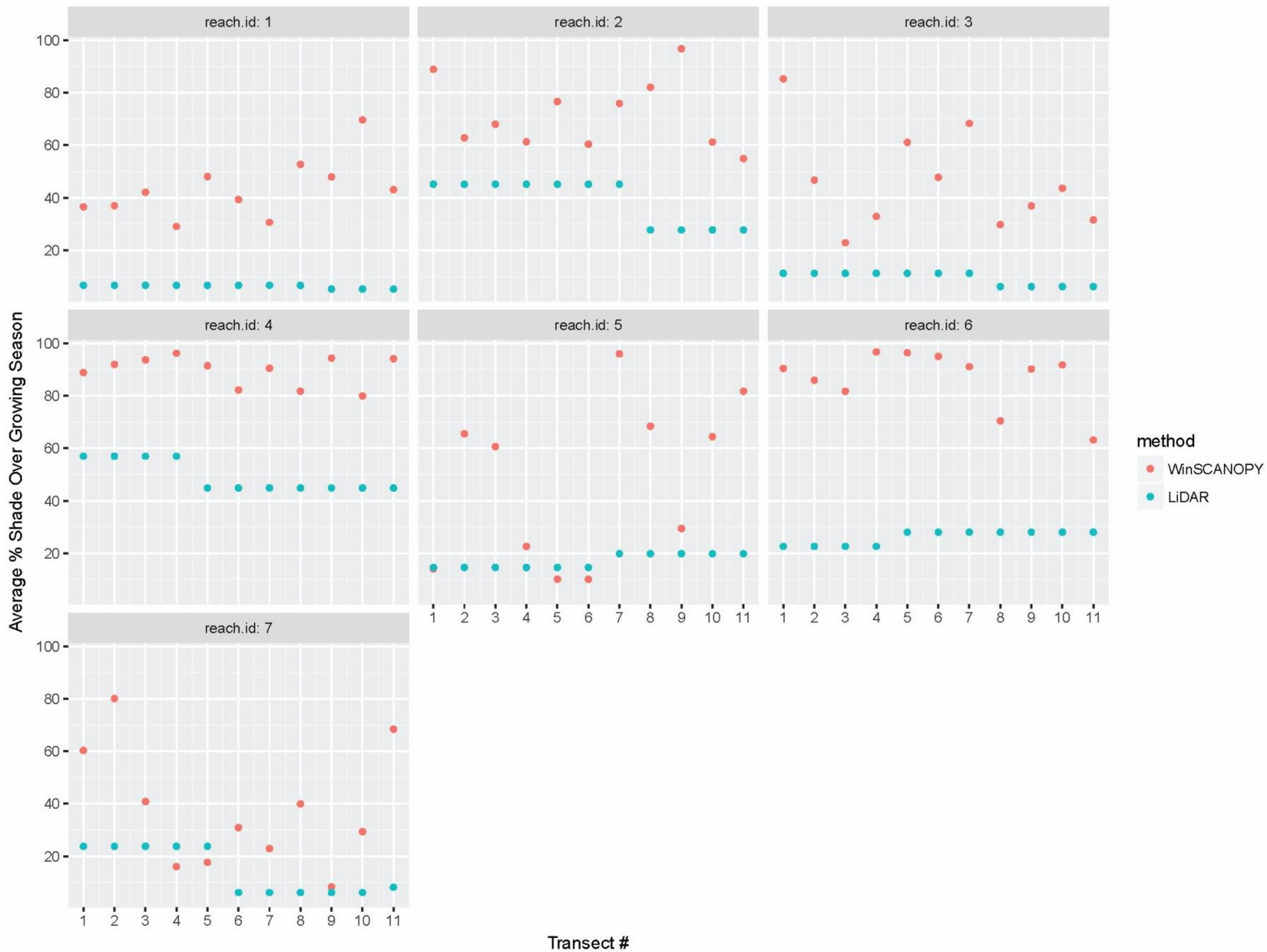


Figure 36. Transect Shade Estimated using WinSCANOPY in Comparison to Shade Estimated from LiDAR

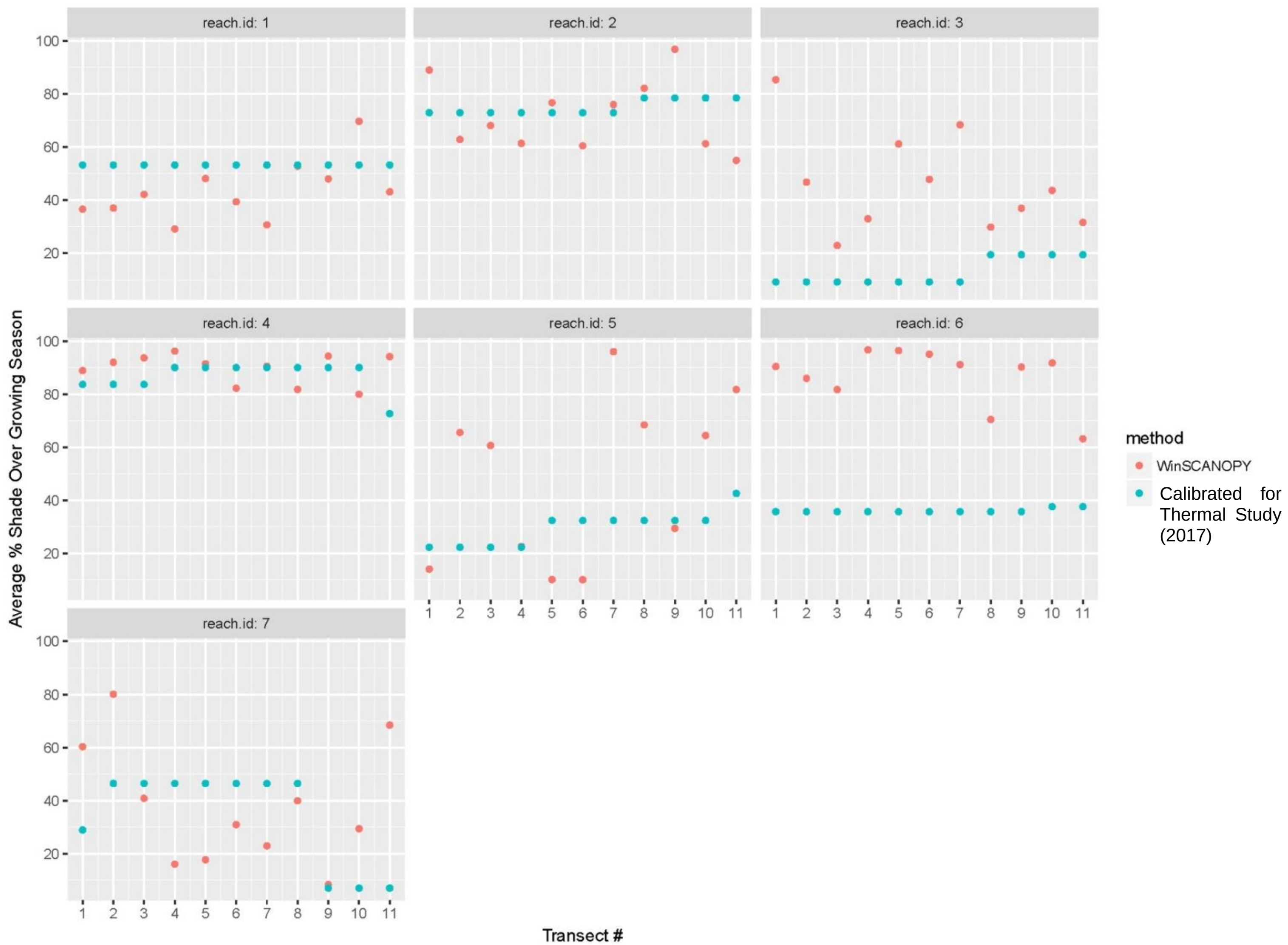


Figure 37. Transect Shade Estimated using WinSCANOPY in Comparison to Shade Calibrated in Brown's Creek Thermal Study

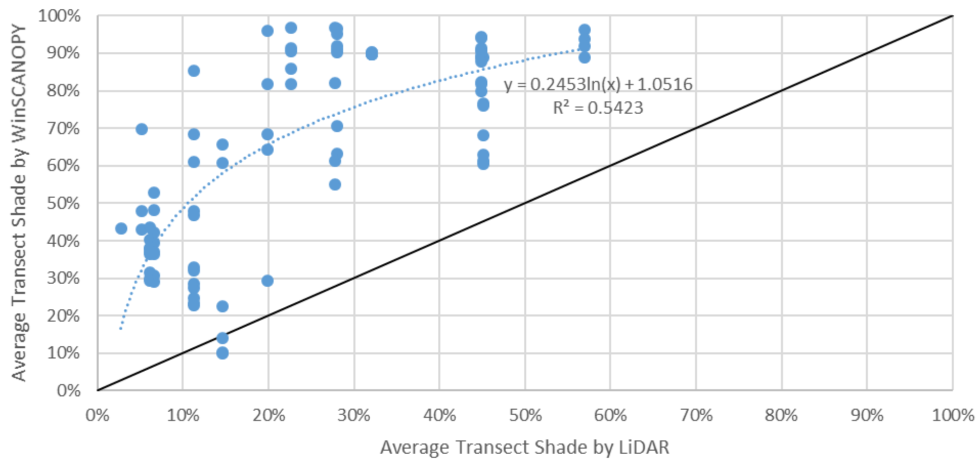


Figure 38. Average Transect Shade Estimated using LiDAR and WinSCANOPY (Omitting Reach 7)

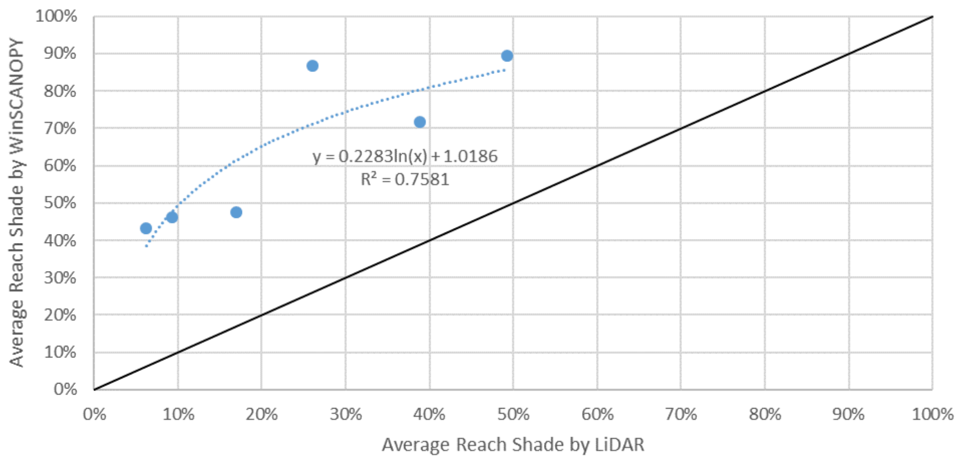


Figure 39. Average Reach Shade Estimated Using LiDAR and WinSCANOPY (Omitting Reach 7)

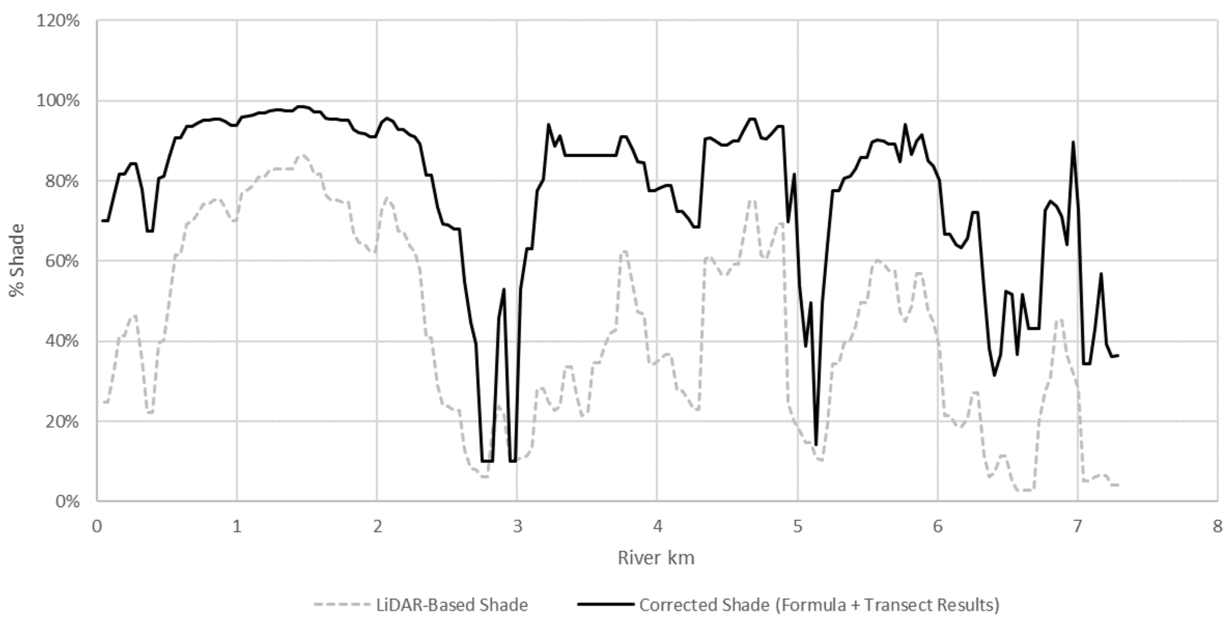


Figure 40. Profile of Existing Conditions Riparian Shade along Brown's Creek

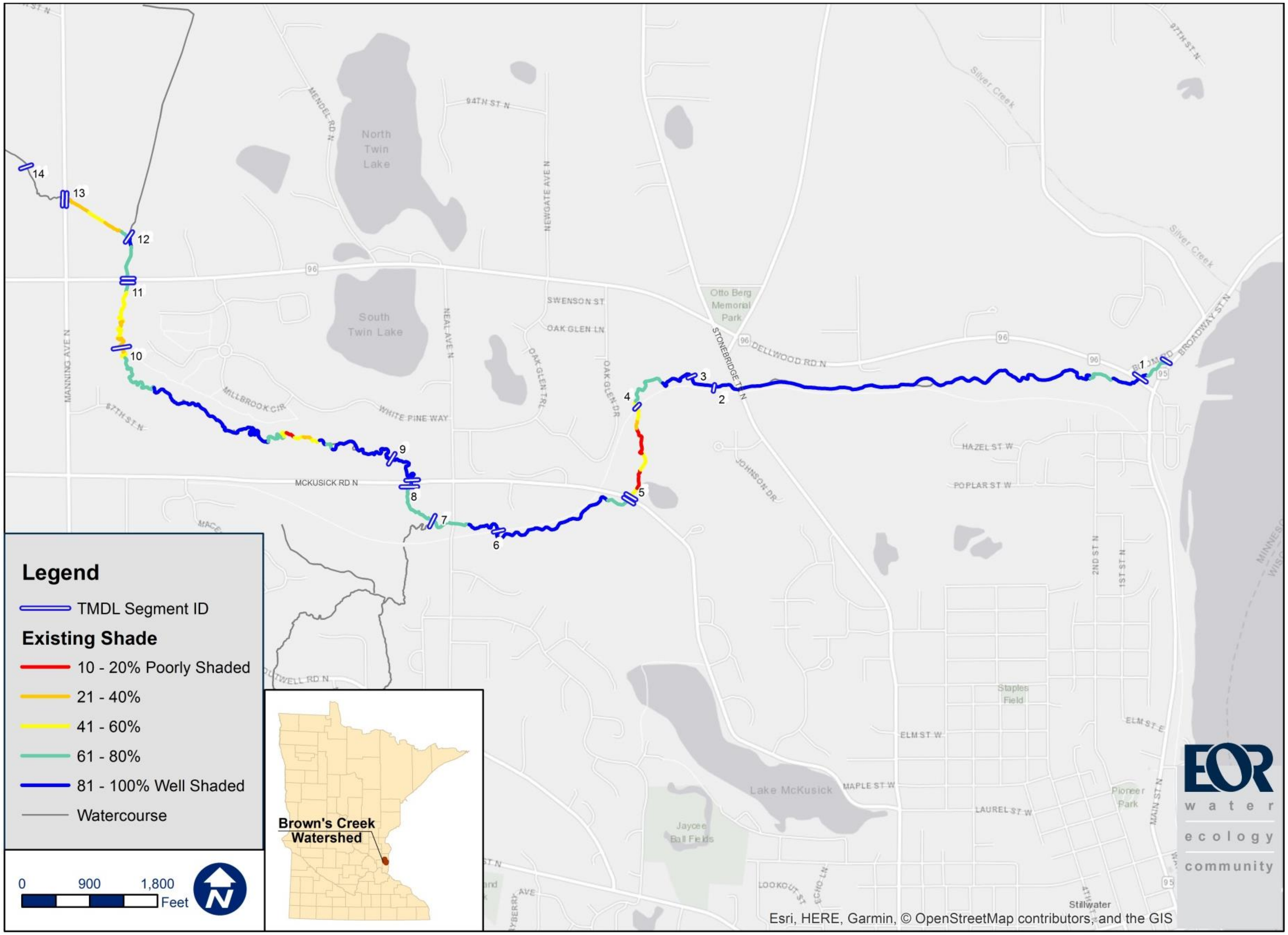


Figure 41. Updated Riparian Shade Analysis using WinSCANOPY (Shade Conditions in Year 2011)

- The canopy structure changes over the growing season. The implication of this variable with respect to the timing of photograph collection was tested by collecting repeated photos at three transects at different times during the monitoring period. The resulting shade estimated using mid-summer (July/August) and late summer (September) photos indicated that some locations have more variable shade from senescence late in the summer than others which have consistent shade (Figure 42). However, there was an insufficient number of re-sampled locations to determine a trend and adjust other results accordingly.

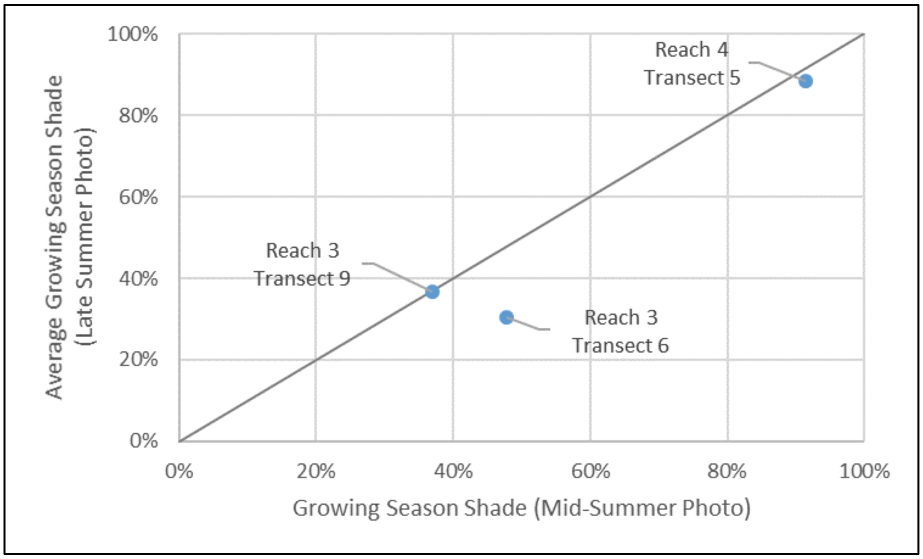


Figure 42. Growing Season Shade Estimated in WinSCANOPY using Hemispherical Photographs from Mid-Summer and Late Summer

- Categorization of canopy and sky areas in photographs is affected by resolution of photos and by user-defined color classification. This was mitigated by using a camera with high resolution photos and by repeating the analysis of several photos by a second person. User error in WinSCANOPY appears to be minor based on the repeated analysis conducted for two of the study area transects. On average for each transect, the difference in shade estimated by two different users ranged from -0.3% to -0.2% (Table 8).

Table 8. Evaluation of User Error in WinSCANOPY Analysis

Reach and Transect	Difference in Shade			
	Left	Middle	Right	Average
Reach 4, Transect 5	-1%	-1%	0.3%	-0.3%
Reach 1, Transect 5	1%	-2%	1%	-0.2%

- Variable depth of flow and height of lens above water surface were accounted for by monitoring only during baseflow conditions and assessing the sensitivity of shade to lens height above the water surface. The first transects were monitored in July when flows were in the mid-range flow regime but otherwise activities were limited to dry conditions or low flows (Figure 43).

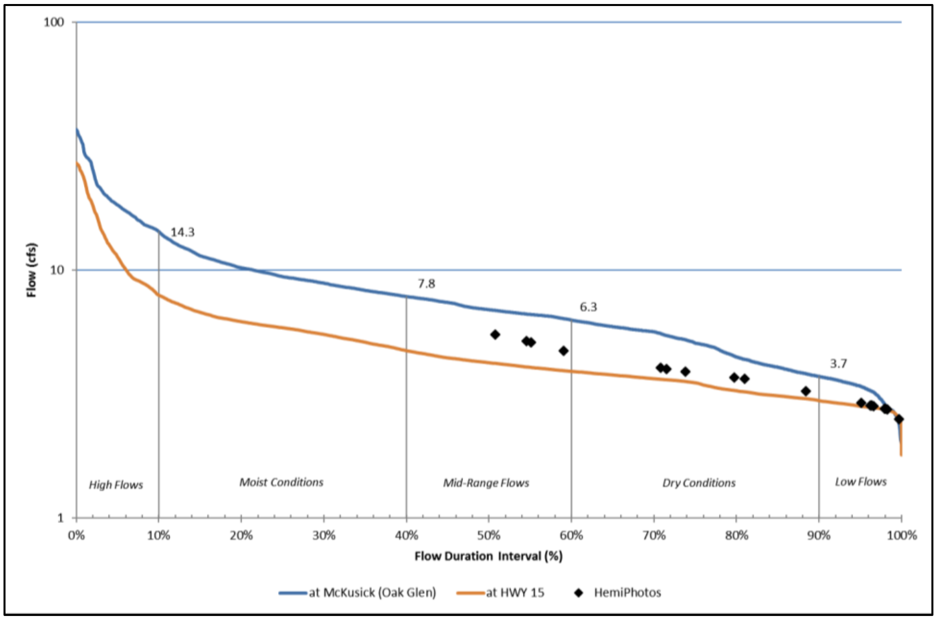


Figure 43. Flow Duration Curve at Highway 15 and at McKusick (Oak Glen) from April to October 2017

5.1.3. Discussion

Comparing shade estimated using ArcMap solar radiation analysis of LiDAR data in the Brown's Creek Thermal Study and to the results of analyzing the hemispherical images indicates that the analysis of LiDAR data frequently underestimated shade. This is likely due to the limitations of the LiDAR data itself, as it was collected in November 2011 after leaf-off and has limited accuracy in identifying small herbaceous vegetation. Correcting the LiDAR-based estimates using the WinSCANOPY results worked well in areas with mixed forested vegetation, perhaps due to the dense coniferous vegetation even after leaf off. However, the corrections did not work well in areas with predominantly deciduous canopy such as the dense willow woodland upstream of McKusick Road North in Oak Glen Golf Course. As of 2011 when the LiDAR was flown, the canopy should have been established since the willows were planted in 1999 during a MNDNR stream restoration project. As such, these results indicate that LiDAR flown after leaf off requires varying corrections based on species composition in woodlands. Overall, the updated existing shade (Figure 41) indicates that Brown's Creek is more shaded than estimated in the Brown's Creek Thermal Study.

Analysis of the hemispherical photographs collected in Reach 7 (the segment of the Oak Glen Golf Course Restored in 2012) indicates that as of 2017, vegetation had established to the point of providing 38% shade across the sampled reach, with the shade at individual transects ranging from 8 to 80%. The un-calibrated shade estimated using 2011 LiDAR data in the Brown's Creek Thermal Study at the same location was an average of 14% and ranged from 6 to 24%. The correction formula for LiDAR cannot be applied to Reach 7 because the input data (LiDAR and hemispherical photographs) were taken under different vegetation conditions. However, the results indicate that the segments of the restoration with young trees have not yet established to provide the expected shade restoration. The herbaceous vegetation is providing approximately 20% shade in this reach.

Continued monitoring of shade at these same locations in Reach 7 will provide the data needed to assess the lag time between plantings to reaching target shade levels.

Riparian shade analyses are commonly conducted to develop inputs for stream temperature models. In the case of this and other studies, those stream temperature models use the same shade value for a segment of the stream and over the course of the entire model period, sometimes up to an entire growing season. While these total growing season shade levels averaged across the length of the stream are useful for stream temperature models, they mask the factors influencing the variability in shade. The existing conditions riparian analysis in this study provides useful insight into some of those factors by using hemispherical photography. The WinSCANOPY results in Figure 32 illustrate how much riparian shade can vary across the stream width and along the length of the stream. In addition, the stage-shade curves illustrated that shade estimated with hemispherical photographs in grassy reaches varies significantly based on the height of the camera lens above the stream surface. The WinSCANOPY results shown are total shade over the growing season which is calculated on a sub-daily time step basis to consider the variability in the position of the sunpath and the intensity of sunlight over the growing season. The remaining factor potentially resulting in further temporal variation in shade is vegetation growth. It was assumed in this study that collecting the hemispherical photographs in July, August, and early September captured typical vegetation conditions when shade is critical to stream temperature control. This assumption could not be comprehensively assessed within this study due to the limited occurrences of baseflow conditions and the time required to complete each sampled reach. As such, monitoring each transect monthly was not feasible given the time constraints.

The stage-storage curves were also useful in identifying the significant shade (close to 70%) that can be provided by overhanging herbaceous vegetation on the north bank of an east-west oriented stream (see the bottom right panel of Figure 31). In comparison, similar vegetation on a north-south oriented stream (see the bottom left panel) provides consistently low shade of 30 to 40%. While these results may be specific to the two transect monitored, the results reinforce the findings from other studies in grassy streams: that shade is more challenging to attain in north-south oriented reaches than east-west. Even further, there would seem to be much more potential to add shade on the south bank in the east-west stream through plantings.

The updated shade analysis also refines our understanding of the length of unshaded areas along the creek (less than 55% shade) which was previously estimated to be 3 km (1.9 miles) but with the refined shade analysis, there is only 1.3 km (0.8 miles) unshaded. Increasing the threshold of what is considered "low" shading in the mitigation scenarios would target additional areas up to a total of 3.7 km (2.3 miles) if anything less than 85% shade was considered for implementation activities.

Developing a predictive model for shade using the physical characteristics of each transect proved difficult in this study. Part of the challenge is the vast number of spatiotemporal variables influencing shade, including channel characteristics (e.g. width, depth, azimuth, and slope), upland topography, and vegetation structure (e.g. height, width, distance from stream, species, and location relative to transect). Assessing the influence of these variables in nature also makes it challenging to control for variability and discern the sensitivity of shade to modifications in individual parameters, although monitoring a single system helped to control the range of some variables to be within the range of a small stream. The challenges faced in the regression analysis indicate that larger sample size is needed within representative reaches to develop a regression model based on physical parameters. However, such a predictive model is not required when trying to assess existing shade conditions because hemispherical photographs themselves provide the data needed to assess existing shade levels and validate LiDAR-based estimates. Although the hemispherical photography equipment and analysis software was expensive, gathering the field-based physical data for a hypothetical predictive model would also require considerable cost in labor. Beyond assessing existing shade, a predictive model would be helpful in assessing the canopy structure required to attain target shade levels in the future, or optimize plantings where they will provide the greatest increase in shade. These topics are addressed in the next section on assessing future shade conditions.

In hindsight, the monitoring program for this study could have been strengthened by consistently collecting the following data:

- Width of overhanging bank
- Height of bank adjacent to stream
- Density of vegetation (i.e. high, medium, low or on a scale of 1 to 0)
- Mode vegetation height
- LiDAR data collected in the summer with a sub-1 m resolution
- Additional representative reaches with mixed or shrubby vegetation

5.2. Sensitivity Analysis

Gaining insight into the shade provided by understory in comparison to tree canopy is essential for this study to guide future riparian management decisions, such as long term investment in expanding the riparian tree canopy or quickly enhancing riparian shrubs and grasses. After the existing conditions riparian shading analysis (Section 5.1) and trade-offs assessment (Appendix B), three critical questions remained to be addressed in order to develop a targeted plan for riparian shade restoration in Brown's Creek:

1. Under what conditions can herbaceous riparian vegetation sufficiently shade Brown's Creek?
2. How far can woody vegetation be planted away from the stream while sufficiently increasing shade for Brown's Creek? A horizontal separation of tree plantings from the creek will help sustain the integrity of terrestrial resources (e.g. sedge meadows), improve the survival rate of tree plantings where they can be located in non-hydric soils, and provide stream shade while maintaining herbaceous cover on the streambank in order to prevent streambank erosion.
3. Under which physical conditions will plantings be most effective (i.e. provide the greatest increase in shade)?

The above questions were assessed using a sensitivity analysis of the range of physical structure of Brown's Creek and its riparian vegetation found in the study area.

5.2.1. Method

The regression analysis using physical characteristics of the study area transects was unsuccessful in developing a predictive model for shade. As such, the sensitivity analysis used a theoretical model to test the impact of physical characteristics on shade. The algorithm developed to predict shade in the SNTEMP model (Theurer, Voos, & Miller, 1984) was programmed into a spreadsheet to simulate instantaneous and daily shade based on the following variables:

1. Stream azimuth: orientation of stream measured as angle from facing due south (e.g. south-east and north-west oriented streams would both have an azimuth of -45°).
2. Stream width: width of baseflow.
3. Height of vegetation.
4. Crown measurement: diameter of canopy from bird's eye view, which influences if vegetation overhangs across the stream's surface.
5. Vegetation density: thickness of canopy.
6. Vegetation offset: distance from stream centerline to plant's stem or trunk.

A sensitivity analysis was conducted to assess the effect of changing the input parameters listed above on simulated instantaneous and daily total shade. A base scenario was defined to represent the average conditions identified in grassy reaches within the study area, as summarized in Table 9. Additional scenarios were developed to calculate shade when individual parameters were changed from the base scenario within the minimum and maximum range of what was observed in the study area (Table 9). The values for stream azimuth, stream width, vegetation height, vegetation crown, vegetation density, and vegetation offset were each modified from the base scenario. All simulations were run to represent the summer solstice conditions on June 22, 2017 (i.e. when the sun reaches the highest altitude in the sky and riparian shading is at its lowest). The simulation calculated instantaneous shade at regular intervals throughout the day between sunrise and sunset. The sensitivity of shade to stream width was tested under the base scenario stream azimuth (0°) to represent a north-south oriented stream in addition to a second series of models for when stream azimuth is east-west (90°). The results of each model simulation included a time series of instantaneous shade in addition to the total daily shade.

Table 9. Range of Physical Characteristics at Grassy Study Area Transects

Parameter	Grassy			Woody
	Base Scenario	Minimum	Maximum	Optimized
Stream Azimuth (°)	0	-90	90	-90 to 90
Stream Width (m)	2.6	2.3	3.6	2.3
Height of Vegetation (m)	1.08	0.16	2.17	18.3
Crown (m)	0.9	0	1.8	13.7
Vegetation Density (%)	90	50	100	90
Vegetation offset (m)	0	0	3.2	10

Three additional scenarios were developed after the sensitivity analysis to represent the following inputs under the full range of stream azimuth:

1. Parameters for grassy vegetation that maximizes shade.
2. Parameters for woody vegetation (mature black willow) offset from the stream centerline (Table 9).
3. Combination of the above two scenarios with tree offset optimized to provide shade while not being located immediately adjacent to stream.

The sensitivity analysis was limited in that it did not consider the following:

- topographic shade (which determines the local time of sunrise and sunset).
- multi-day or full season simulation.
- plant growth.
- variability of incident radiation based on time of day.
- Validation to measured radiation or other shade prediction methods (e.g. WinSCANOPY).

5.2.2. Results

The results of the sensitivity analyses are illustrated by the time series plots on the following pages. Each plot shows the instantaneous shade simulated throughout the day on June 22, 2017 and the total daily shade is labeled below the legend. The results of the base scenario are illustrated in Figure 44. The results of modifying individual parameters from the base scenario within the range observed in the study area are illustrated in Figure 45 to Figure 51. The sensitivity of shade to stream azimuth under optimal grassy conditions is shown in Figure 52. The time series shown in Figure 53 illustrate the instantaneous shade provided by trees offset from the stream. Lastly, Figure 54 illustrates shade provided by optimal grassy conditions in addition to trees offset from the stream.

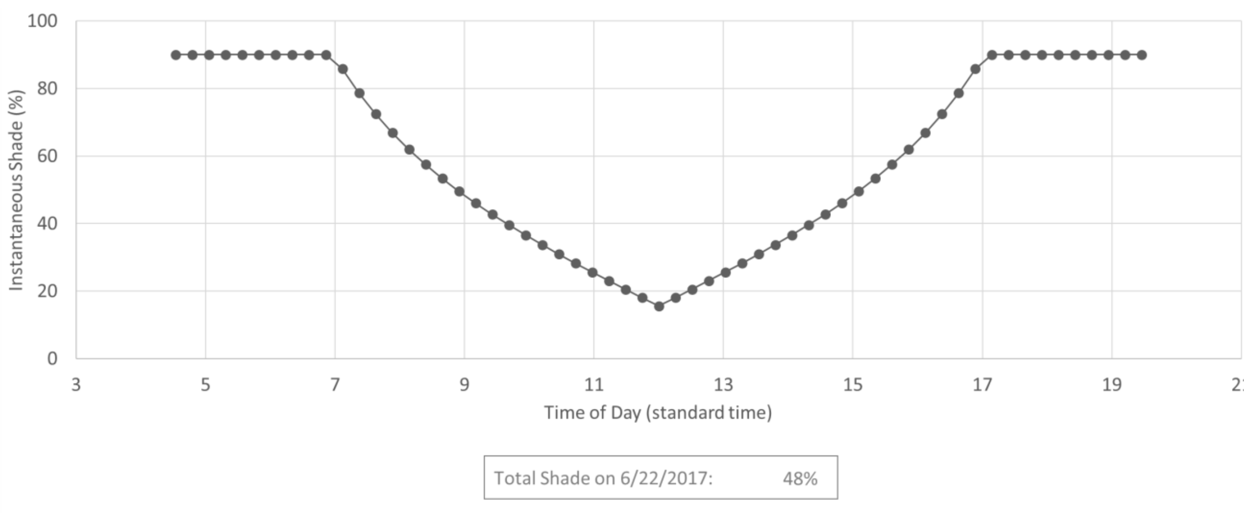


Figure 44. Base Scenario of Sensitivity Analysis

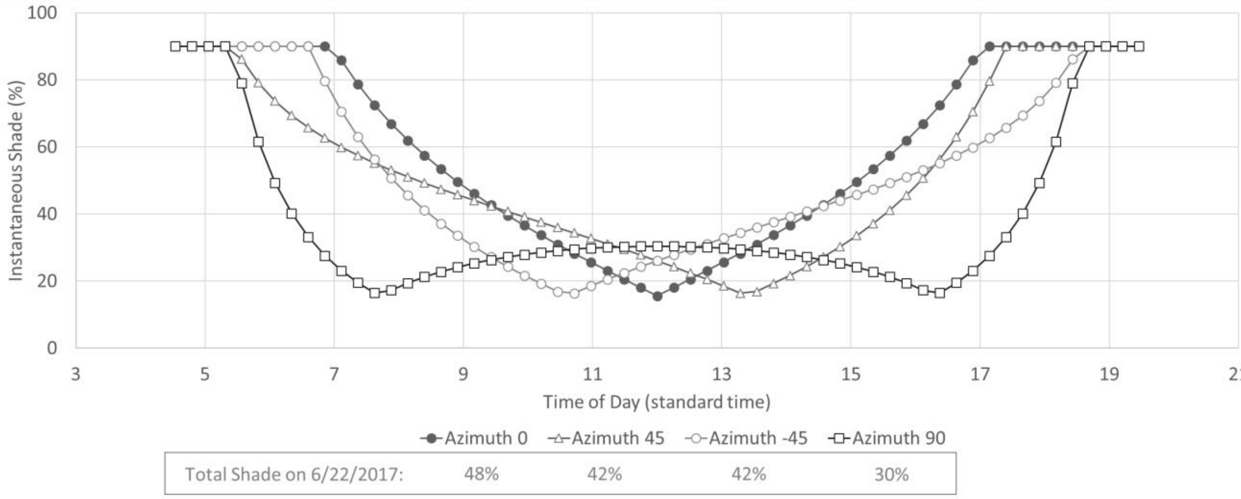


Figure 45. Sensitivity Analysis of Modeled Shade to <u>Stream Azimuth</u>

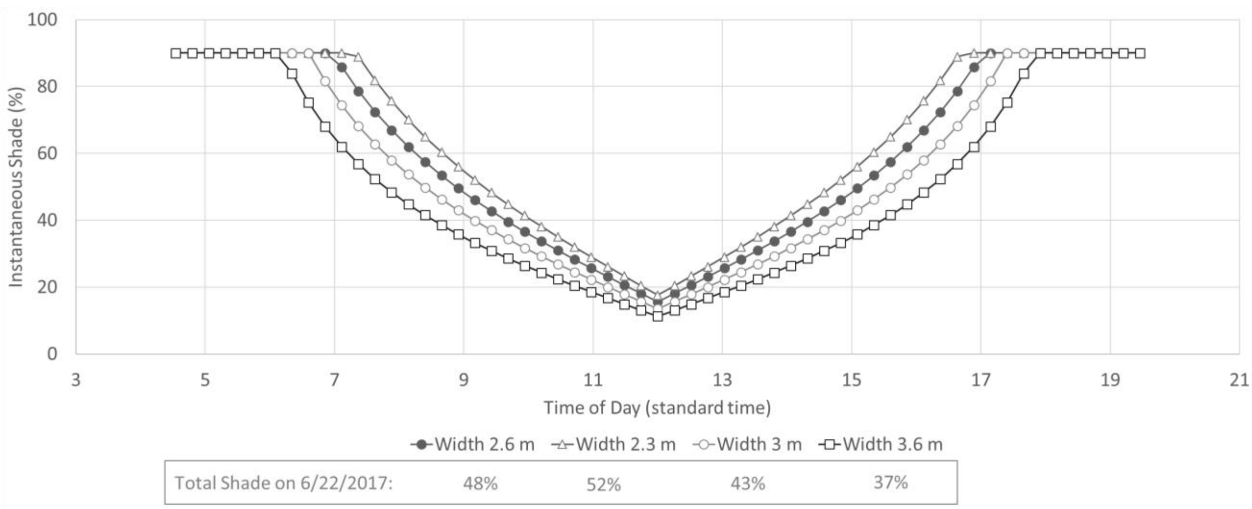


Figure 46. Sensitivity Analysis of Modeled Shade to <u>Stream Width (0° Azimuth)</u>

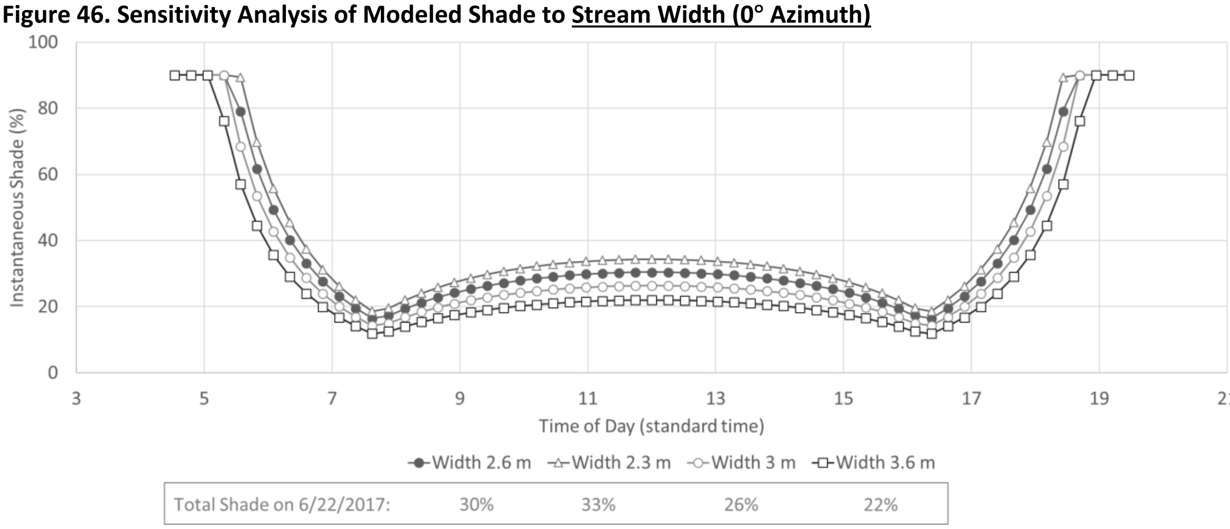


Figure 47. Sensitivity Analysis of Modeled Shade to <u>Stream Width (90° Azimuth)</u>

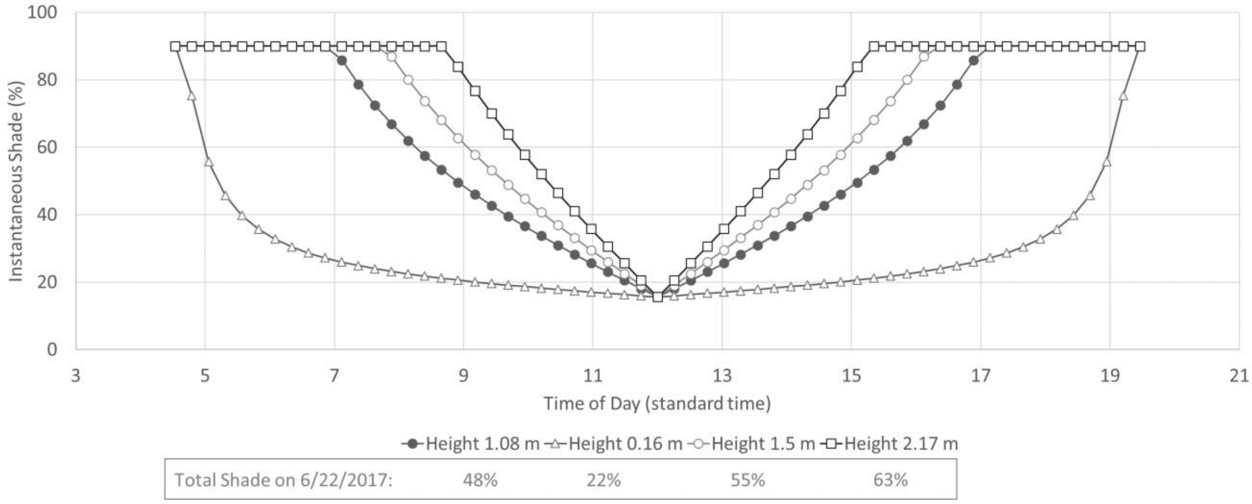


Figure 48. Sensitivity Analysis of Modeled Shade to <u>Vegetation Height</u>

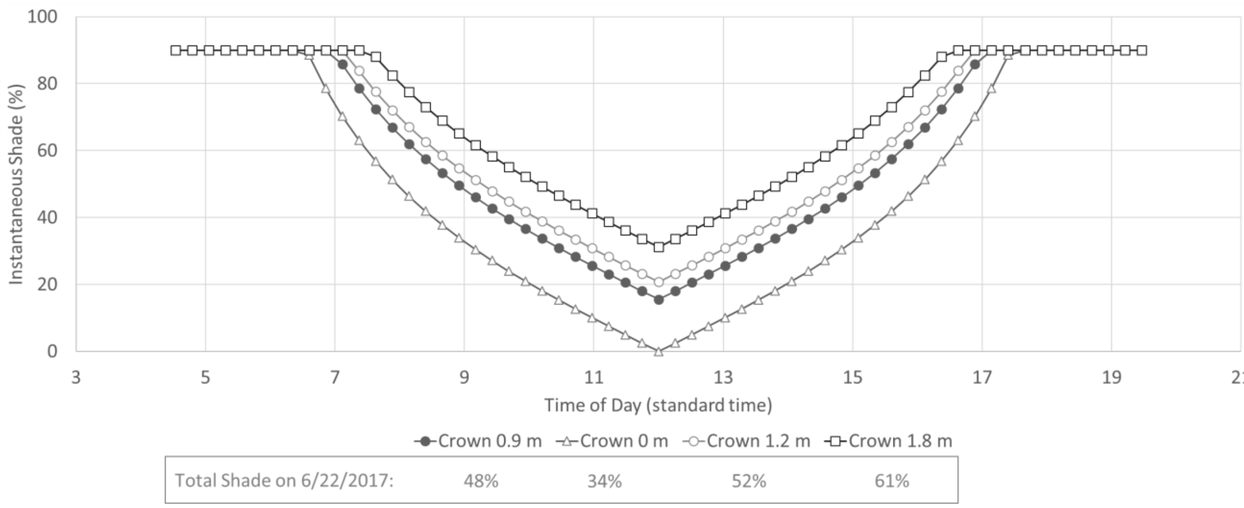


Figure 49. Sensitivity Analysis of Modeled Shade to <u>Vegetation Crown (Diameter)</u>

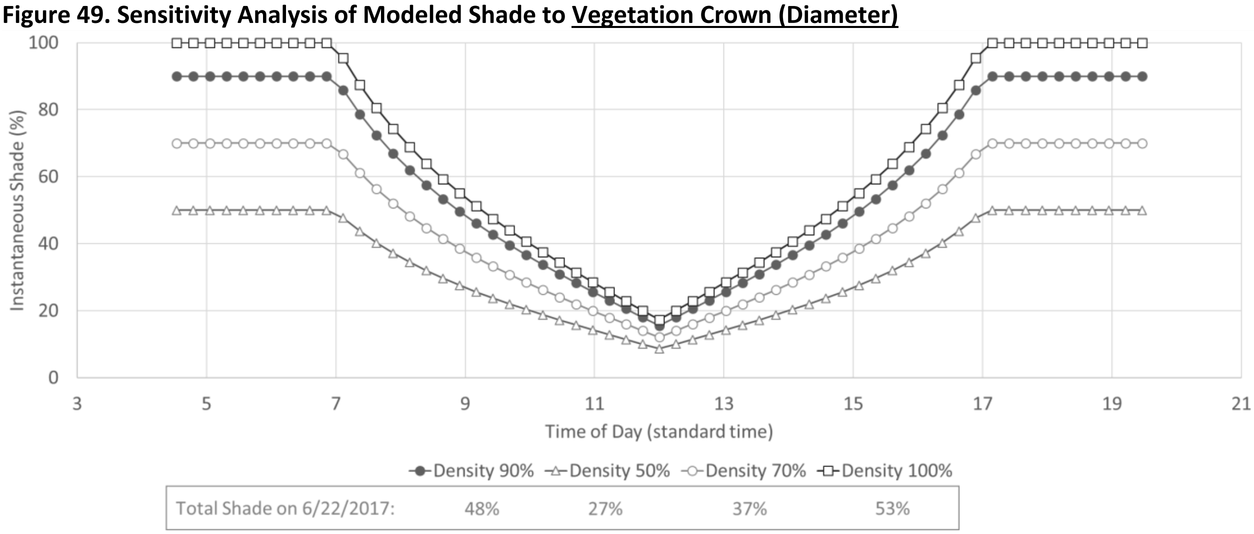


Figure 50. Sensitivity Analysis of Modeled Shade to <u>Vegetation Density</u>

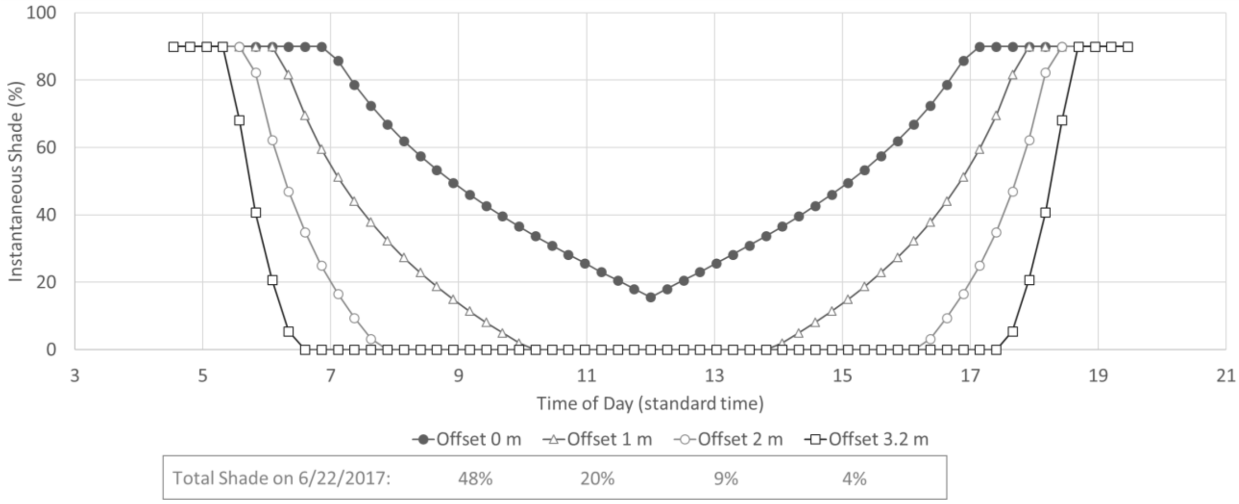


Figure 51. Sensitivity Analysis of Modeled Shade to <u>Vegetation Offset</u>

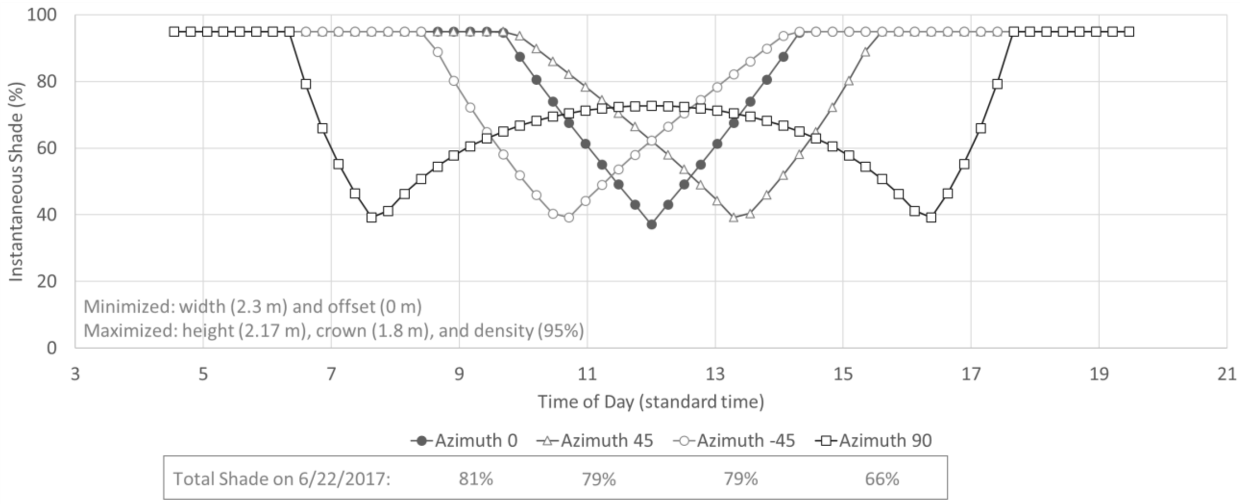


Figure 52. Sensitivity Analysis of Modeled Shade to <u>Azimuth under Optimized Grassy Conditions</u>

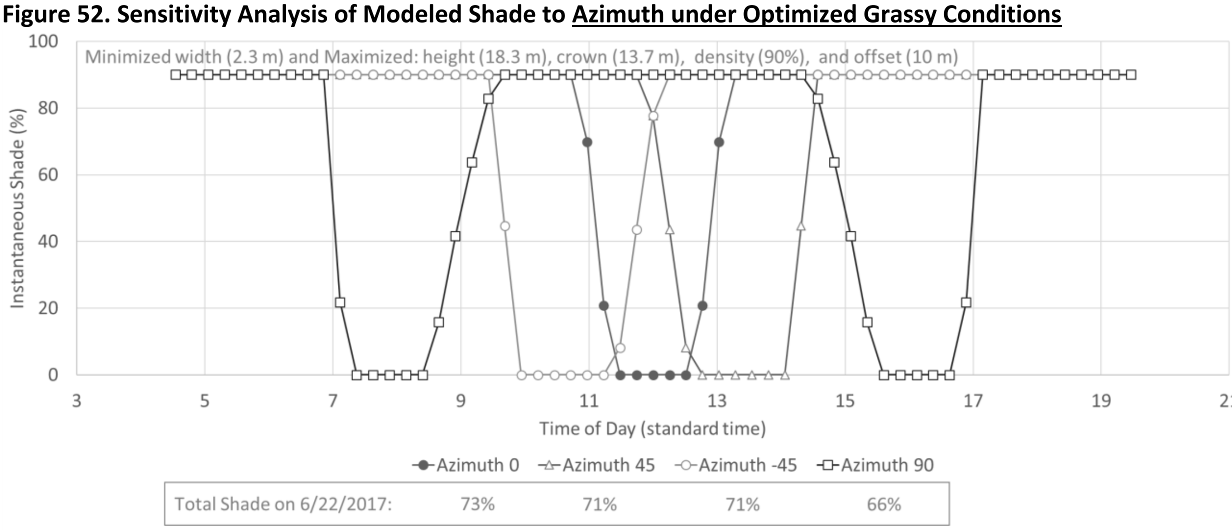


Figure 53. Sensitivity Analysis of Modeled Shade to <u>Azimuth under Offset Woody Conditions</u>

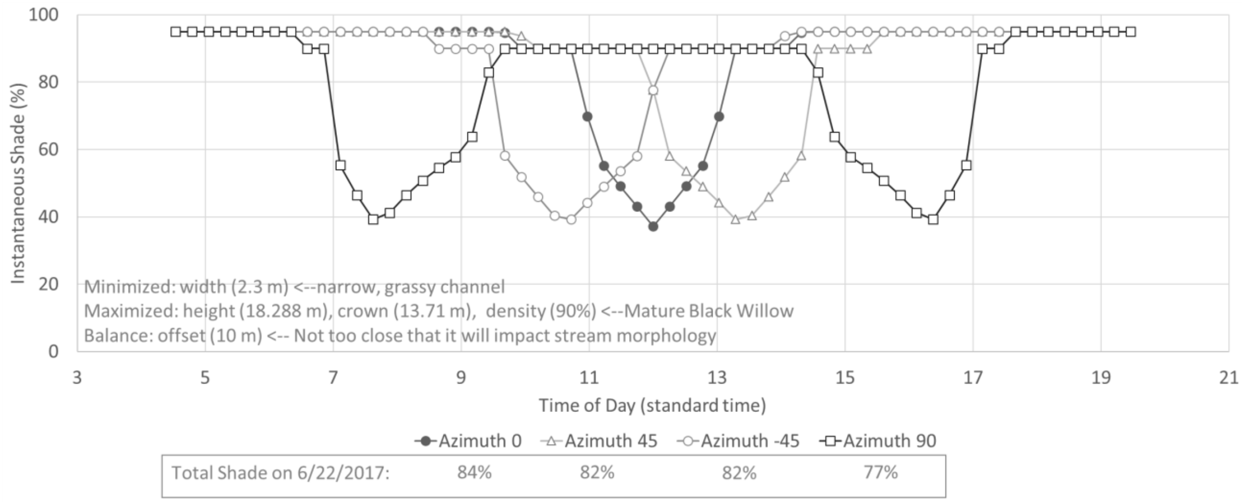


Figure 54. Sensitivity Analysis of Modeled Shade to Azimuth With Optimized Grassy and Woody Vegetation

5.2.3. Discussion

Further review of the trends in simulated daily shade illustrated in Figure 55 highlight the sensitivity of the model to each parameter. The sensitivity analysis identified the following trends in shade provided by grassy vegetation when individual parameters were modified:

- Least shade provided when banks were exposed (i.e. large offset distance), plants were short, and when the stream was wide on east-west branches.
- Most shade provided when vegetation was tall and when there was significant vegetation overhanging the stream.
- Shade was least sensitive to changing stream width.
- Shade was most sensitive to how much bank was exposed (i.e. offset distance) and height of vegetation.

Simulated daily shade in the grassy scenarios ranged from 4% to 63%. The scenarios with grassy conditions optimized for shade (i.e. by minimizing width and offset while also maximizing height, overhang, and density) resulted in simulated daily shade between 66 to 81%. This indicates that modifying grassy conditions could provide an incremental increase in shade of 3% (the minimum increase) or up to 77% (the maximum increase). The minimum increase would occur if existing vegetation was already at the maximum possible height.

Simulated daily shade in the combined scenario of optimal grassy conditions with offset tree plantings was between 77 and 82%, with the lowest occurring on the east-west aligned stream segment. In comparison to optimal grassy conditions alone (66 to 81% shade), these results indicate that tree plantings could incrementally increase shade by 11% in east-west oriented streams or by 3% in streams with orientations between southeast, south, and southwest.

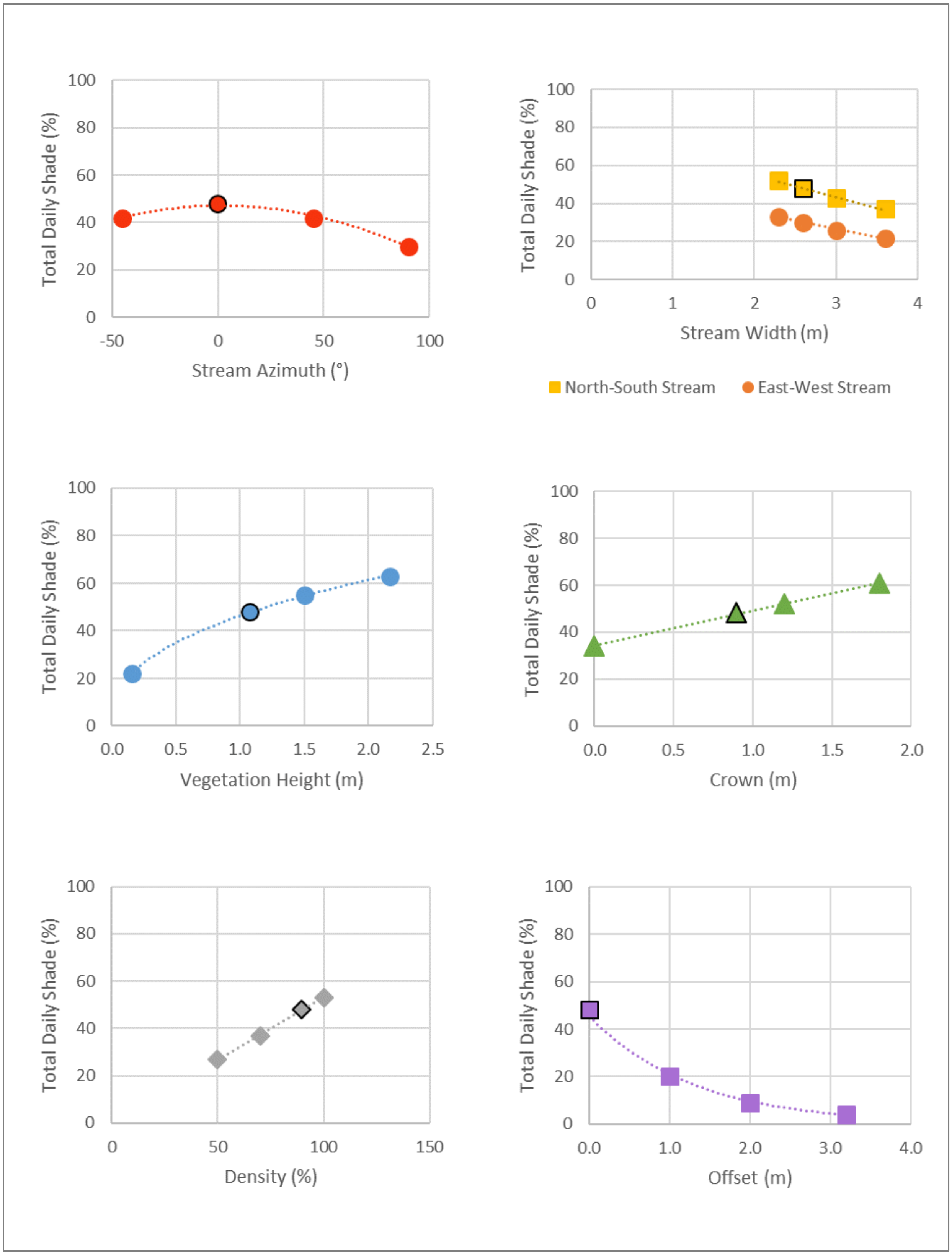


Figure 55. Summary of Simulated Total Daily Shade from Variables Modified in Sensitivity Analysis

These results address the original questions behind the sensitivity analysis, as follows:

1. *Under what conditions can herbaceous riparian vegetation sufficiently shade Brown's Creek?*
   The greatest grassy shade is provided in Brown's Creek when the following conditions occur in the channel and riparian zone:

   - Stream width is minimized to 2.3 m
   - Vegetation is established on the streambank and there is no exposed bank
   - Vegetation height is maximized to 2.17 m
   - Vegetation overhang is maximized to 0.6 m
   - Vegetation density is maximized to 95%

   The optimal conditions are within the range observed in the study area. Simulating these conditions resulted in total shade on the summer solstice of 81% in a north-south oriented stream, 79% in a southeast or southwest oriented stream, and 66% in an east-west oriented stream. Conditions for shade throughout the study area could be optimized by managing riparian vegetation, such as introducing tall herbaceous species, or by restoring the channel morphology, such as the narrowing of the creek that occurred through the Oak Glen Golf Course after the 2012 restoration project. Even further, the above simulations did not include topographic shade and so could be enhanced on sites with overhanging stream banks and adjacent valleys or other topographic features.

   With a target for shade between 75 to 85% in Brown's Creek, these results indicate that optimal grassy vegetation can meet the District's shade target where the stream orientation is between 320° to 45° or between 135° to 225° as measured using a compass relative to due north.

2. *How far can woody vegetation be planted away from the stream while sufficiently increasing shade for Brown's Creek?*
   The sensitivity analysis indicates that woody vegetation can be planted approximately 10 m away from the stream and increase the shade sufficiently to meet the District's shade target.

3. *Under which physical conditions will plantings be most effective (i.e. provide the greatest increase in shade) for Brown's Creek?*
   Tree plantings would be most effective and provide the greatest increase in shade when located on the south bank of an east-west oriented segment. This trend compliments the trend in grassy shade, where the least shade is provided in east-west branches.

5.3. Future Conditions

This section describes the concept plans developed for riparian shad improvements in the unshaded areas of the creek. These concept plans were then used to estimate the future shade along the study area with these improvements as well as estimating the time to maturity of shade.

5.3.1. Method

High Priority Segments for Shade Restoration

Areas requiring shade restoration were first prioritized where the existing conditions riparian shade analysis (Figure 41) indicated less than 80% shade is currently provided. Segment 5 is located downstream of McKusick Road through Oak Glen Golf Course was also identified as having shade below the 80% threshold but has already been restored and so was not included in the shade restoration plan. The priority areas include the following creek segments[6]:

- Segment 13, downstream of Manning Ave/Highway 15
- Segment 12, upstream of Highway 96
- Segment 11, downstream of Highway 96
- Segment 10 (upper and middle section), south of Millbrook Development
- Segment 8, upstream of Neal Avenue
- Segment 6 (lower section), upstream of McKusick Road at Oak Glen Golf Course
- Segment 4 (upper section), downstream of Brown's Creek State Trail and Golf Course

Further review of the above short-list helped differentiate levels of priority. Upper Segment 10, Segment 8, lower Segment 6, and upper Segment 4 are relatively short segments featuring relatively well established under and overstory canopies. As such, optimizing the vegetation and channel form for shade in these areas is lower priority than in the long and open segments, such as Segment 13. Focusing on high priority implementation of Segments such as Segment 13 and postponing low priority shade improvements also provides more time in which to monitor Segments 10, 8, and 4 with the WinSCANOPY equipment. These sites were not monitored directly as part of the Riparian Shading Study, however pre-restoration measurements are needed to estimate the stream temperature benefits and develop the concept plans for such improvements. This monitoring effort is included in the recommendations of the study and in Appendix E. The benefits of thinning dense tree canopies, such as those that are overcome with terrestrial invasive species, were not assessed and/or identified in this Study.

The remaining high priority segments for shade restoration are the following locations:

- Segment 13, downstream of Manning Ave/Highway 15
- Segment 12, upstream of Highway 96
- Segment 11, downstream of Highway 96
- Segment 10 (middle section), south of Millbrook Development

These four high priority areas have clear opportunities for improving riparian vegetation to increase shade. Segments 13 and 12 were also identified in the TMDL implementation plan as being high or medium priority for morphology improvements, respectively. Segment 12 has no vegetated buffer on the east bank in some locations and so was also identified as a high priority for buffer width improvements.

[6] Segment numbering is consistent with the TMDL Implementation Plan and as illustrated in Figure 15 and Figure 17.

Targeted Shade Restoration Plan

Concept plans were developed for the four high priority shade restoration segments to illustrate the extents of herbaceous planting/enhancement areas and tree planting locations following the best practices identified in the sensitivity analysis. Where applicable, restoration of the stream meander was also illustrated in the plans.

The soils and hydrology information for these restoration segments were reviewed to assess what types of riparian vegetation could be established and supported by future restoration efforts. The assessment considered pre-settlement vegetation (i.e. oak barrens described in Section 3.6) and considered what current conditions may limit the ability to re-establish certain types of vegetation. For example, certain tree species may have low survival rates in urban wetlands with hydric soils, active hydrology, and subject to pollutants from urban runoff. In addition, existing plant communities surrounding these segments were considered so that plantings for shade restoration would enhance or maintain the quality of the overall plant community. After reviewing these considerations, a preliminary list of grassy to woody plant species was developed (Appendix D) as a reference for designers of shade restoration plans in Brown's Creek. These species are typically suitable for planting in the riparian corridor of Brown's Creek and offer optimized characteristics for shade, such as rapid growth and maximized height. Selection of species for particular locations in each restoration project should be conducted during detailed design in consultation with a landscape architect and ecologist.

Predicted Shade under Restored Conditions

The predictive shade model used in the sensitivity analysis (Section 5.2) was applied again to estimate the increase in shade offered by enhancing herbaceous riparian buffers and targeting tree plantings shown in the concept plans. Typical canopy structure characteristics of the black willow species was used to represent future canopy structure of the restoration projects at maturity. Black willows were selected for this analysis because their fast growth rate relative to other tree species that could thrive in the riparian zones along Brown's Creek. In addition, black willow trees tend to have a broad crown, with branches extending out away from the main trunk, which makes them well-suited to the application of establishing shade along the creek through tree plantings set back from the water's edge. Other tree species suitable to the riparian conditions along Brown's Creek, such as the others listed in Appendix D, may be selected during the design of shade restoration projects to improve the survival rate of tree plantings, especially in areas with known beaver activity. The existing and future characteristics of each segment used in the predicted shade analysis are summarized in Table 10. A correction factor was calculated by comparing the existing conditions results of the predictive model in comparison to the WinSCANOPY results and this factor was applied to the future results.

Table 10. Physical Characteristics Before and After Shade Restoration

Characteristics		Segment 13		Segment 12		Segment 11		Segment 10	
		Existing	Future	Existing	Future	Existing	Future	Existing	Future
Segment Length (m)		304	486	124	157	398	398	310	310
Sinuosity (m/m)		1.04	1.66	1.03	1.30	1.52	1.52	1.56	1.56
Azimuth (°)		-58	-58	6	6	7	7	-90	-90
Stream Width (m)		2.58	2.30	2.75	2.30	2.56	2.30	2.85	2.30
Grassy	Height (m)	1.0 / 1.2	2.2	0.8 / 0.9	2.2	1.3 / 1.6	2.2	1.2 / 1.4	2.2
	Crown (m)	0.9 / 0.7	0.8	0.1 / 0.2	0.8	0.5 / 0.3	0.8	0.1 / 0.1	0.8
	Density	0.9	0.95	0.9	0.95	0.9	0.95	0.9	0.95
	Offset (m)	0	0	0.68 / 0.29	0	0 / 0.02	0	0.13 / 0.31	0
Woody	Height (m)	2.7 / 3.8	2.7 / 18.3	14.5 / 20.0	16.0 / 20.0	2.7 / 3.3	18.3	11.0 / 17.1	11.0 / 18.3
	Crown (m)	2.0 / 2.9	2.0 / 9.1	10.9 / 15.0	10.4 / 15.0	2.0 / 2.5	9.1	7.2 / 9.4	7.2 / 9.1
	Density	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	Offset (m)	105 / 40	105 / 10	9.0	8.5 / 9.0	25 / 30	10	32 / 12	32 / 10

Note: Characteristics that vary on left and right banks (facing downstream) shown with "left / right" format.

In addition to predicting the shade of future restoration activities, another task undertaken was estimating the timing and extent of the shade restoration in Oak Glen Golf Course as tree canopy continues to mature. The predictive spreadsheet model was used again to assess the shade provided at different times throughout the restoration process: pre-restoration (2012), existing conditions (2017), and future conditions at the age of maturity of the tree. The expected time to maturity of black willow trees is between 50 to 70 years (Hardin, Leopold, & White, 2001) and for other species listed in Appendix D, the timing can range from 100 to 200 years. In comparison, forbs, grasses, and other herbaceous species typically concentrate energy into root development in the first two years and then, with the support of proper establishment practices, reach maturity in three to four years after seeding/planting. Managing weeds and assisting native plants in establishing dense cover is essential for the success of an improvement project in the first several years in particular (Minnesota Department of Natural Resources, n.d.). These results were calibrated to the estimated shade in Oak Glen Golf Course before restoration in 2012 (10%) and the latest estimate using hemispherical photos taken in 2017 (46%). The input characteristics are summarized in Table 11.

Table 11. Physical Characteristics of Oak Glen Golf Course Before and After Stream Restoration

Characteristics		Pre-Restoration (2012)		Existing (2017)		Maturity	
		Left	Right	Left	Right	Left	Right
Segment Length (m)		398		398		398	
Sinuosity (m/m)		1.05		1.05		1.05	
Azimuth (°)		3		3		3	
Stream Width (m)		4.13		3.11		3.11	
Grassy	Height (m)	1.1	1.3	1.29	1.25	2.17	
	Crown (m)	0	0	0.16	0.47	0.80	
	Density	1	1	0.9	0.9	0.95	
	Offset (m)	9.4	6.4	0.01	0.01	0	
Woody	Height (m)	3.4	2.7	3.76	2.96	18.30	
	Crown (m)	2.5	2.0	2.82	2.22	9.14	
	Density	0.9	0.9	0.9	0.9	0.9	
	Offset (m)	9	9	9	9	9	

5.3.2. Results

Concept plans for the targeted shade restoration in Brown's Creek are illustrated in Figure 56 to Figure 59. Each concept plan includes a description of the segment and recommended implementation activities. In addition, each concept plan includes a summary of site characteristics, benefits of shade restorations, and costs. The expected future shade from the improvements is summarized in Table 12 and illustrated in Figure 60. The temperature benefits were estimated using the District's stream temperature model and are the results of implementing all shade restoration projects shown in the concept plan (Future Scenario IV of the model). See Section 6.2 for additional detail on the stream temperature modeling.

Table 12. Summary of Existing and Future Shade at Target Shade Restoration Segments

Segment	Average Growing Season Shade	
	Existing (2011)	Future
Segment 13	44%	82%
Segment 12	75%	83%
Segment 11	49%	80%
Segment 10B	56%	84%
Segment 5 (lower Oak Glen Golf Course)	6%	79%
All Segments (Manning Ave to St. Croix River)	76%	84%

The cost of each implementation project is detailed in Table 13. These costs include the enhancement of herbaceous vegetation, planting trees, and restoring the stream morphology where warranted. In addition, the cost of administration and engineering, in addition to a 20% contingency, is included. Property acquisitions or easement costs are not included in the estimates.

Table 13. Estimated Costs of Targeted Shade and Stream Restoration

Segments	Construction/Implementation			Admin. & Engineering	20% Contingency	Total
	Native Herbaceous Community Enhancement	Native Tree Planting	Stream Restoration			
13	$55,500	$3,330	$208,000	$95,000	$83,039	$498,235
12	$18,500	$185	$57,200	$55,000	$29,212	$175,274
11	$49,950	$3,885	$-	$12,000	$15,320	$91,922
10B	$33,300	$3,700	$36,000	$48,000	$27,120	$162,720
Total	$157,250	$11,100	$301,200	$210,000	$154,692	$928,152

1) The following materials & labor are included in the unit NATIVE TREE PLANTING cost: tree (~1" caliper potted stock), herbivore protection, weed barrier, 2-year warranty & associated 2-year maintenance

2) The following materials & labor are included in the unit NATIVE HERBACEOUS PLANT COMMUNITY ENHANCEMENT cost: seed bed and/or invasive treatment preparation; seed, seeding, mulch, select planting (10% of area at 24" on center spacing) of live plants, 2-year establishment maintenance

3) The following materials & labor are included in the unit STREAM RESTORATION cost: all materials, equipment and labor necessary to execute the probable project including 2-year establishment maintenance

4) Cost do not include property acquisitions or easement costs

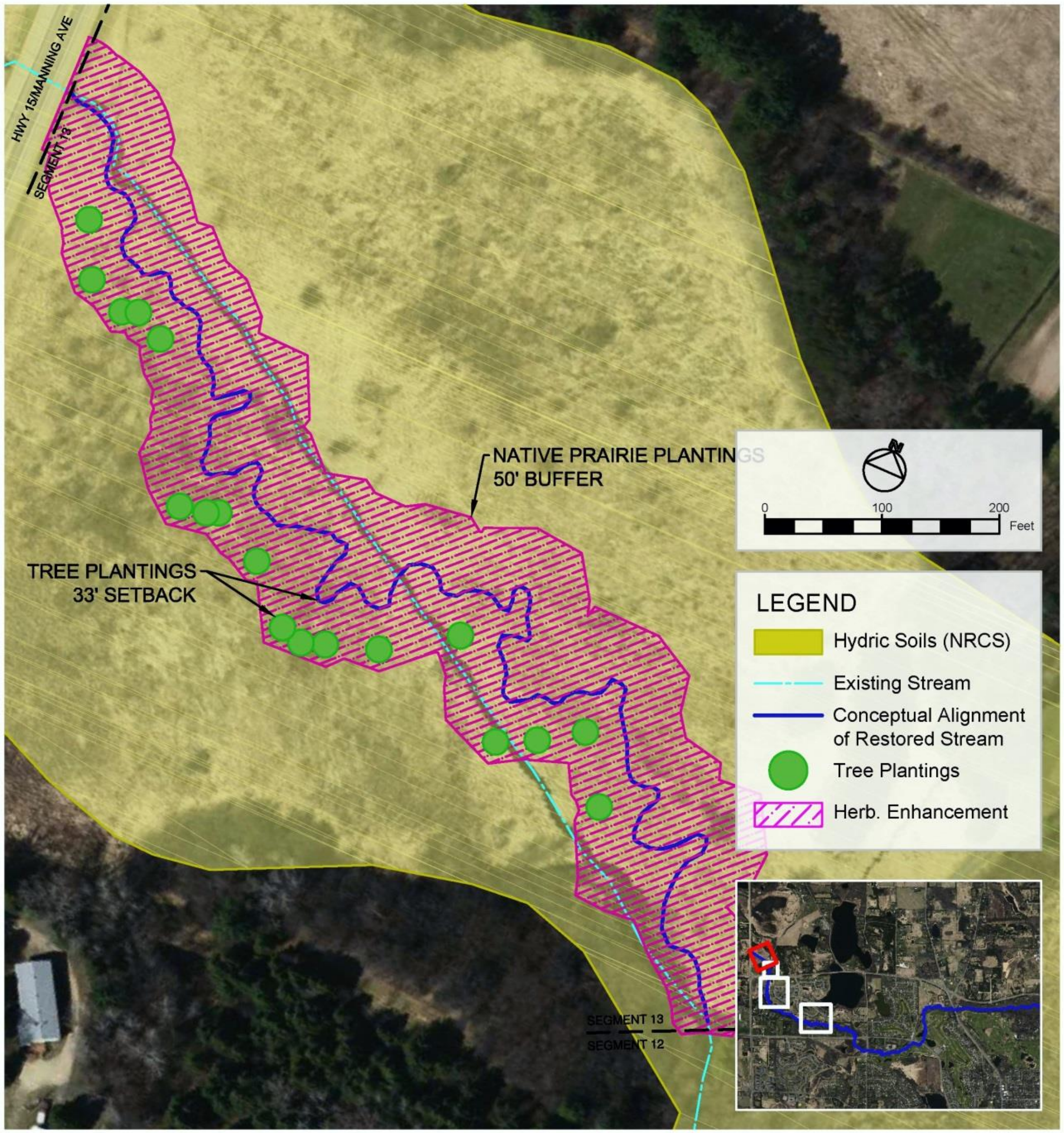
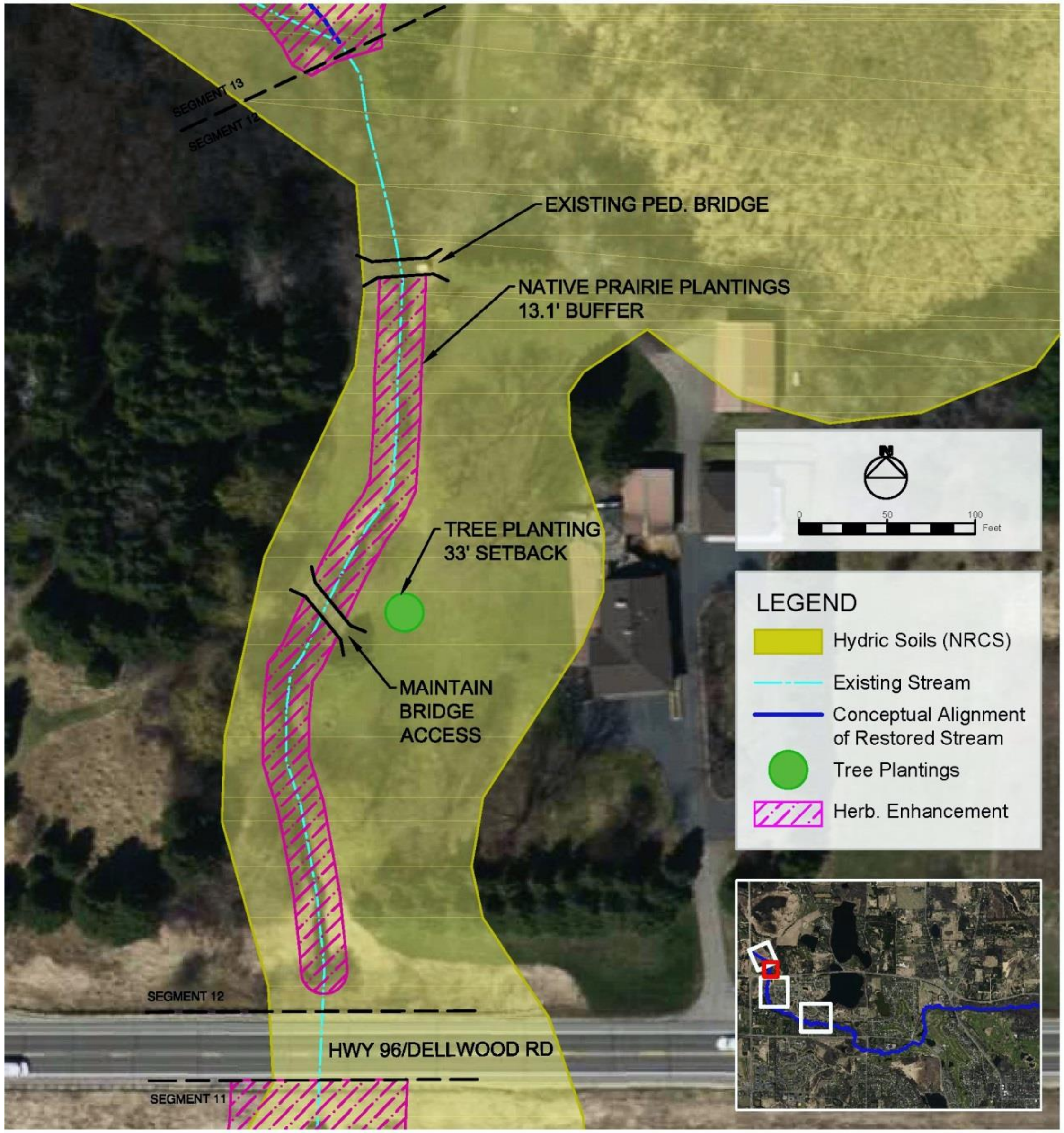


Figure 56. Concept Shade Restoration Plan for Segment 13

Project Description: The alignment of this segment seems to have been straightened historically for drainage efficiency purposes. The segment is surrounded by a shrub-carr wetland. Some dogwood and buckthorn have established on the southwest bank immediately adjacent to the creek in addition to aspen farther to the south. Recommended improvements include restoring sinuosity, narrowing the channel width, enhancing native herbaceous vegetation, and planting woody vegetation on the south banks to enhance the woody community and provide shade.

Segment Characteristics	Existing Left / Right	Future Left / Right
Segment Length (m)	304	486
Sinuosity (m/m)	1.04	1.66
Stream Width (m)	2.6	2.3
Height of Herb. Veg. (m)	1.03 / 1.18	2.17 / 2.17
Width Veg. Over Stream (m)	0.43 / 0.36	0.40 / 0.40
Vegetation Density (%)	0.90	0.95
Distance from Herb. Veg. to Stream (m)	0.00 / 0.00	0.00 / 0.00
Height of Woody Veg. (m)	2.69 / 3.83	2.69 / 18.30
Distance from Woody Veg. to Stream (m)	105 / 40	105 / 10
Growing Season Shade	44%	82%
Implementation Details		
Capital Cost		$ 498,235
Lag Time for Herbaceous & Geomorph. Maturity		1-4 yr
Lag Time for Tree Maturity		50-150 yr
Recommended Year for Implementation		2021



Project Description:
Historically this segment has been straightened and the channel's banks and vegetation have been maintained by the landowner. A mixed woodland is located west of the northern edge of the segment. Recommended improvements include restoring sinuosity, narrowing the channel width, restoring diversity in the channel profile, and establishing native vegetation to enhance shade. All improvements should be designed in partnership with the landowners.

Segment Characteristics	Existing Left / Right	Future Left / Right
Segment Length (m)	124	157
Sinuosity (m/m)	1.03	1.30
Stream Width (m)	2.8	2.3
Height of Herb. Veg. (m)	0.77 / 0.92	2.17 / 2.17
Width Veg. Over Stream (m)	0.00 / 0.00	0.40 / 0.40
Vegetation Density (%)	0.90	0.95
Distance from Herb. Veg. to Stream (m)	0.68 / 0.29	0.00 / 0.00
Height of Woody Veg. (m)	14.49 / 20.00	16.00 / 20.00
Distance from Woody Veg. to Stream (m)	9.0 / 9.0	8.5 / 9.0
Growing Season Shade	75%	83%
Implementation Details		
Capital Cost		$ 175,274
Lag Time for Herbaceous & Geomorph. Maturity		1-4 yr
Lag Time for Tree Maturity		50-150 yr
Recommended Year for Implementation		2022

Figure 57. Concept Shade Restoration Plan for Segment 12

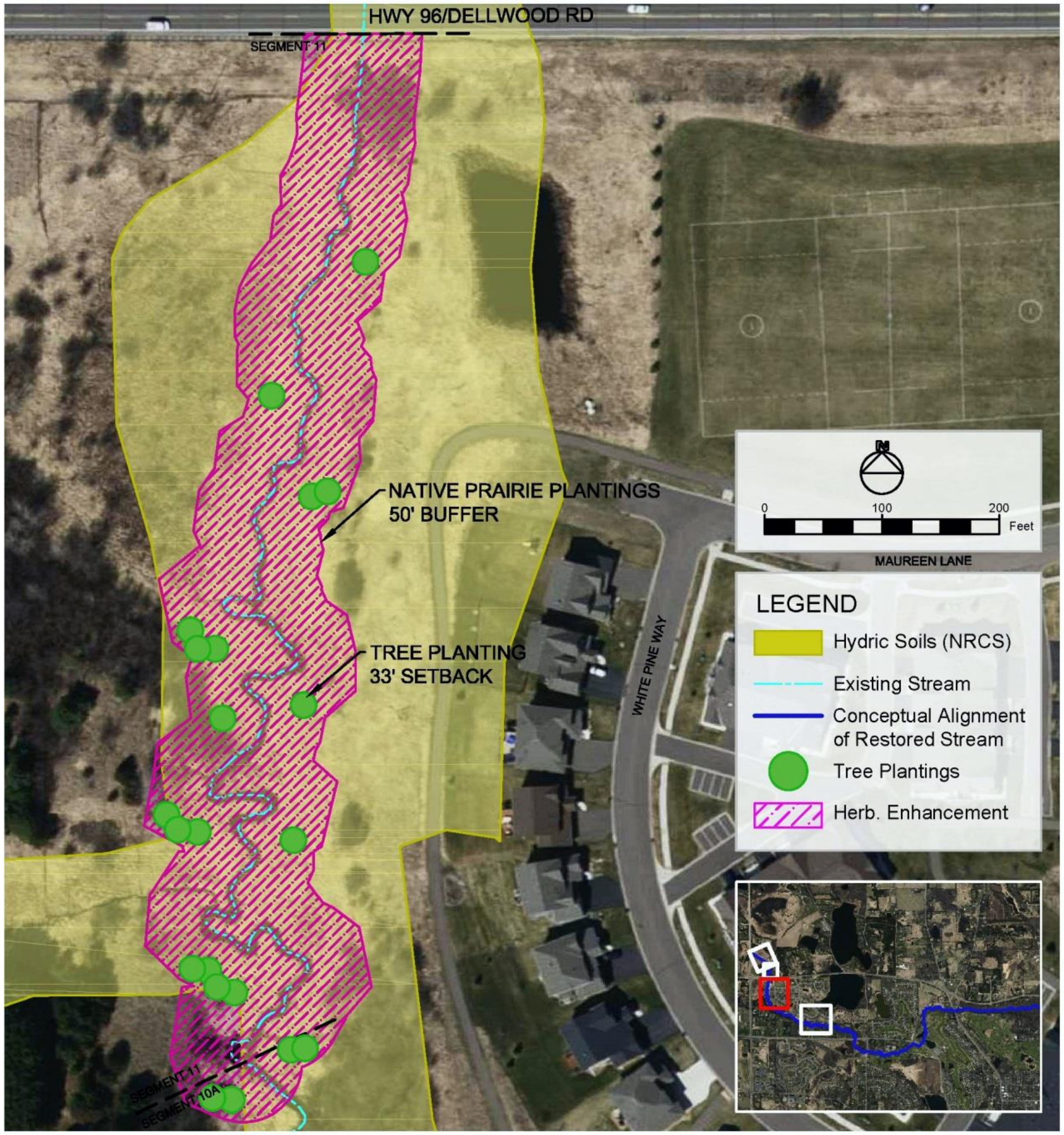
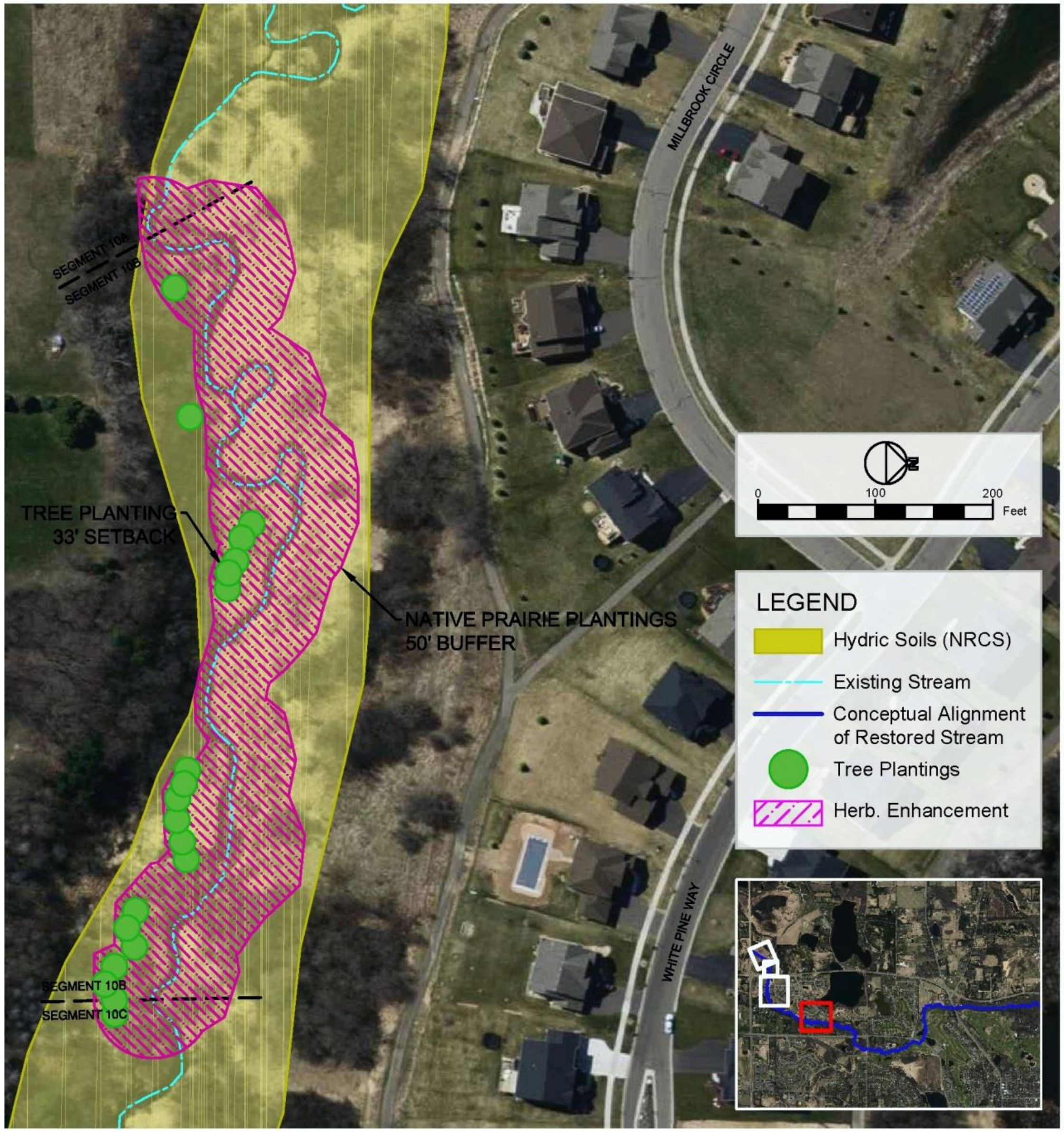


Figure 58. Concept Shade Restoration Plan for Segment 11

Project Description:
The segment winds through a sedge meadow with some woody vegetation located typically 50 to 100 feet upland until it enters a more narrow forested valley in Segment 10A towards the south of this map. Recommended improvements include establishing tall and native herbaceous cover adjacent to the stream in addition to planting woody vegetation on the south banks to enhance shade. Diversifying the channel profile and narrowing the cross section are passive objectives of this restoration effort.

Segment Characteristics	Existing Left / Right	Future Left / Right
Segment Length (m)	398	398
Sinuosity (m/m)	1.52	1.52
Stream Width (m)	2.6	2.3
Height of Herb. Veg. (m)	1.27 / 1.57	2.17 / 2.17
Width Veg. Over Stream (m)	0.23 / 0.12	0.40 / 0.40
Vegetation Density (%)	0.90	0.95
Distance from Herb. Veg. to Stream (m)	0.00 / 0.02	0.00 / 0.00
Height of Woody Veg. (m)	2.72 / 3.32	18.30 / 18.30
Distance from Woody Veg. to Stream (m)	25 / 30	10 / 10
Growing Season Shade	49%	80%
Implementation Details		
Capital Cost		$ 91,922
Lag Time for Herbaceous & Geomorph. Maturity		1-4 yr
Lag Time for Tree Maturity		50-150 yr
Recommended Year for Implementation		2020



Project Description:
This segment and the reach immediately upstream has experienced a recent reduction in sinuosity (stream length) via the "cut-off" of a number of channels. This change is thought to have been caused in part by beaver activity. A sedge meadow is located on the north bank. Improvements will include restoring sinuosity, narrowing the channel width in predominantly herbaceous areas, and planting woody vegetation on the south bank to extend the woodland towards the creek.

Segment Characteristics	Existing Left / Right	Future Left / Right
Segment Length (m)	310	310
Sinuosity (m/m)	1.56	1.56
Stream Width (m)	2.9	2.3
Height of Herb. Veg. (m)	1.16 / 1.40	2.17 / 2.17
Width Veg. Over Stream (m)	0.00 / 0.00	0.40 / 0.40
Vegetation Density (%)	0.90	0.95
Distance from Herb. Veg. to Stream (m)	0.13 / 0.31	0.00 / 0.00
Height of Woody Veg. (m)	11.03 / 17.10	11.03 / 18.30
Distance from Woody Veg. to Stream (m)	32 / 12	32 / 10
Growing Season Shade	56%	84%
Implementation Details		
Capital Cost		$ 162,720
Lag Time for Herbaceous & Geomorph. Maturity		1-4 yr
Lag Time for Tree Maturity		50-150 yr
Recommended Year for Implementation		2019

Figure 59. Concept Shade Restoration Plan for Segment 10B

Figure 60. Targeted Shade Restoration Scenario IV

The estimated shade provided by vegetation over time in Oak Glen Golf Course is illustrated by the blue line in Figure 61 using the typical characteristics of a black willow tree under the future scenario 60 years after the restoration. This indicates that 75% shade may be achieved approximately 42 years after the planting. In comparison, other trees listed in Appendix D grow more slowly and so would not reach 75% shade for approximately 80 years, as shown by the orange line. The pivot point in both curves is based on the WinSCANOPY analysis in Reach 7 showing 46% shade in 2017. The steepness of the curve before this pivot indicates that early on after a stream restoration projects, there will be a rapid increase in shade in the first 5 years due to channel narrowing, herbaceous vegetation establishment, and the small canopy of the young tree.

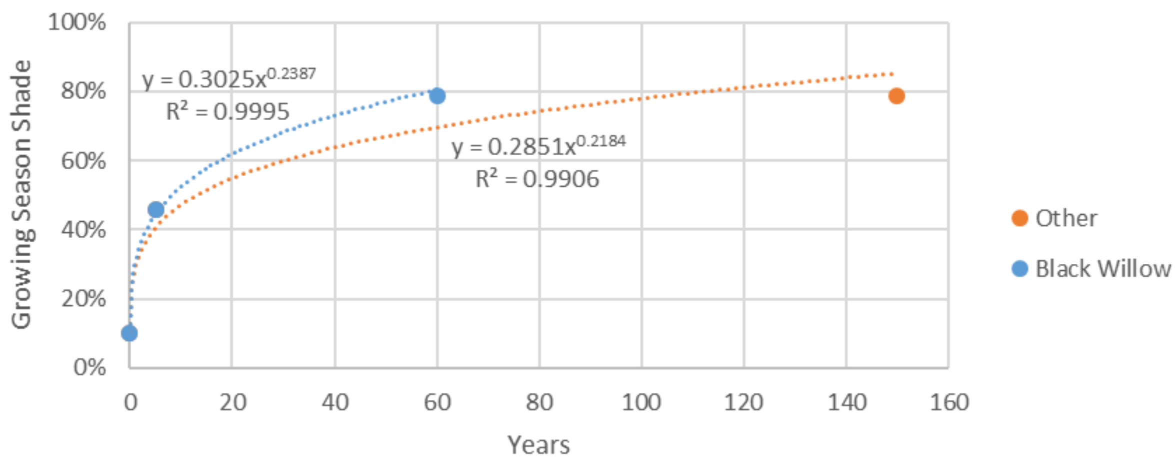


Figure 61. Estimated Shade Over Time as Vegetation Establishes in Oak Glen Golf Course Restoration

5.3.3. Discussion

Targeting shade restoration at four high priority segments of Brown's Creek in addition to previous restoration efforts in the Oak Glen Golf Course is expected to increase the average shade between Manning Avenue to the St. Croix from 76% to 84%, which is an 8% increase in shade overall. Based on the growth rate of vegetation expected to be used in these restoration efforts, approximately 2 to 4% of the shade increase is expected to be provided by mature grassy vegetation and young woody vegetation within 5 to 10 years of planting. The remaining 4 to 6% shade increase overall will be provided once the woody vegetation reaches maturity, which varies based on species between 50 to 150 years.

In terms of reducing heat load to the stream, the shade restoration efforts overall would provide an 8% increase in shade over the growing season, which can also be looked at as an 8% reduction in heat load from solar radiation to Brown's Creek. The total heat load to the creek includes many other heat sources, such as stormwater. The District's Impaired Biota TMDL study identified the need for a 6% reduction in heat load to the creek to lower stream temperatures below the threat temperature for brown trout (18.3°C). The stream temperature model developed by the District since the TMDL study was updated to assess the potential stream temperature benefits in Section 6.

The estimated costs for the targeted shade restoration improvements are $928,152 in total capital costs, including two years of inspection and maintenance of vegetation. These improvements are included in the Higher Priority Implementation Plan and Thermal Improvement Activities in the

District's 2017-2026 WMP, in addition to other stream restoration needs. Reordering the timing of these thermal improvement implementation activities based on priorities for shade restoration is warranted in light of the lag-time in realizing the shade benefits, even for grassy vegetation. Section 7 includes recommendations for a new order of implementing the thermal improvements, pending the willingness of the property owners of the land surrounding Segments 13 and 12.

Further detailed design of each shade restoration improvement will be necessary, especially on Segments 13 and 12 where the recommended improvements include a restored stream meander and where the design needs to be informed by land owner preferences. Public outreach will also be useful for the residents adjacent to Segments 10 and 11 in the Millbrook development. In addition, detailed planting plans will be informed by ecological site assessments in order to maintain or enhance the vegetative communities adjacent to these segments. Cost-savings may be realized by reducing the size of vegetation (i.e. shrubs and grasses instead of trees), although the placement of these species relative to the stream will need to be optimized for shade enhancement without detrimental impacts to streambank erosion. The benefits realized by the restoration efforts may also be accelerated where shrubs and grasses may be used to establish shade faster than tree canopy.

The sensitivity analysis in Section 5.2 and the timing of shade restoration estimated above indicates that optimizing grassy buffers can provide significant and relatively rapid increase in shade. As such, grassy riparian buffers on Brown's Creek should be both maintained and restored to maximize height of vegetation and minimize exposed banks, which are the two parameters to which shade is most sensitive. The concept plans for shade restoration address how this approach can be applied to complete segments. In addition, this approach should be considered during maintenance and ongoing activities, such as:

- Removal of invasive woody species should be accompanied with herbaceous plantings to enhance understory cover, height, and minimize exposed banks.
- District and consulting field staff should watch for and record the locations of areas in the creek that have stunted grassy vegetation, emergent vegetation, or exposed banks. The district should allocate annual funding for maintenance of these small sites, including erosion control blanket, planting plugs, and seeding during appropriate times of year (e.g. late spring or summer when there are stable flows) to enhance grassy vegetation and shade.

This Riparian Shading Study has provided much insight into shade conditions in Brown's Creek and has familiarized the District with useful tools in assessing shade in the field and estimating the timing and extent of future shade. The District has the opportunity to continue advancing the knowledge around riparian management in small, urbanizing, coldwater prairie streams as they look to implement the improvements by monitoring the timing and extent of shade before and after these improvements using the hemispherical photography analysis method. Additional data over time will also help improve the predictive shade model as well as provide insights into how shade varies over a single season. Such monitoring will help the district continue to evaluate progress towards shade restoration and ultimately restoration of aquatic health in Brown's Creek. In addition, continued monitoring will provide insights applicable to other stream systems and buffer restoration efforts across Minnesota and North-Central America. The recommended monitoring plan for the District's shade improvements is detailed in Appendix E.

6. STREAM TEMPERATURE MODEL

The stream temperature model was assembled based on the United States Army Corps of Engineers (USACE) model, CEQUAL-W2 by William Herb (Saint Anthony Falls Laboratory, University of Minnesota) as part of the Brown's Creek Thermal Study in 2016. CEQUAL-W2 is a two-dimensional (2-D) model for flow, temperature and nutrient transport which can be applied to lakes, rivers, and reservoirs. For modeling a well-mixed stream such as Brown's Creek, the 2-D capability of the model over the stream wise distance and depth is not needed, but this feature may be useful in the future for modeling in-stream ponds due to beaver dams. The CEQUAL package simulates flow and temperature with high resolution in time, such as hourly time steps. An alternative stream temperature modeling package developed at the United States Geological Service (USGS), SNTEMP, was considered during the Brown's Creek Thermal Study, however, SNTEMP is not well suited for modeling the propagation of heated stormwater pulses through a small stream because it is limited to daily time steps. Development of the Brown's Creek model described further in the Brown's Creek Thermal Study. The following section describes the updates made to the model as part of this study and the new results of shade restoration scenarios.

6.1. Existing Conditions

The existing conditions scenario of the stream temperature model was updated with the refined riparian shade analysis results of this study. In addition, the detailed channel characteristics monitored during the study were used to update the width of the channel in the model. The updates to the model increased the average shade across all segments from 61% to 76% (Figure 62) and widened the stream from a constant width of 1.6 m to the average observed width of 3.4 m. A few of the modeled segments near Stonebridge Trail became hydrodynamically unstable with the increased width and so it was limited to 2.5 m in these segments so that the model could run successfully. All other model inputs were the same as was modeled in the Brown's Creek Thermal Study.

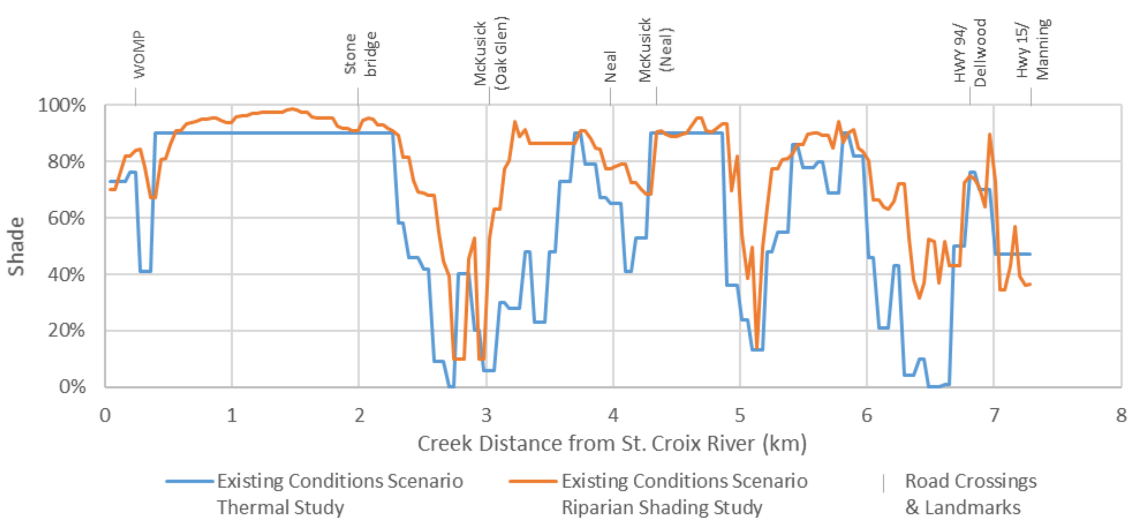


Figure 62. Shade Inputs to Existing Conditions CE-QUAL-W2 Models in Thermal and Riparian Shading Studies

100% Shade means no solar radiation will reach the water surface.

The model was run for the same simulation periods in 2012 and 2014 (April through October) as the Brown's Creek Thermal Study. The increased shade resulted in cooler water temperatures in the updated simulation. This modification was partially offset by the widening of the stream, which increased the water surface area subject to solar radiation and decreased the depth of the stream. The model was re-calibrated to observed temperatures at the three monitoring stations (WOMP, Stonebridge, and McKusick/Oak Glen) using groundwater temperature as the calibration parameter. Adjustments to the wind sheltering coefficient were also tested but the model was less sensitive to this parameter and so the input was left at a constant coefficient of 0.3. In order to calibrate the model of 2012 (the warm and dry year), groundwater temperatures in the upper branches of the model (Manning Avenue to Stonebridge Trail) were increased by 3.8°C on average and the lower branch (Stonebridge Trail to the St. Croix River) was increased from a constant temperature of 9°C to 10°C. Calibration of the model to observations in 2014 (the cool and wet year) was performed by increasing the constant groundwater temperature in the lower branch from 9°C to 12°C.

The observed and simulated stream temperatures under existing conditions in 2012 are shown in Figure 63 and Figure 64 for daily average and maximum temperatures, respectively. Similar comparisons are provided for 2014 in Figure 65 and Figure 66. Overall, temperature simulations were somewhat better in 2014, the wetter and cooler year. The root-mean-square error (RMSE) is a measure of the typical error in simulated temperature values versus observed temperatures, and is calculated as follows on a daily basis:

$$RMSE = \sqrt{\frac{\sum_i^n (Ts_i - To_i)^2}{n}}$$

where Ts_i and To_i are the simulated and observed temperature at the *i*th day, respectively, and *n* is the total number of days. The RMSE for the daily mean and maximum temperatures at each monitoring location are summarized in Table 14 for both the full simulation period (April to October) and the typically warm months of the year (July and August). Overall, the RMSE was better (smaller) during the months of July and August than when looking at the full simulation period. The RMSE values also indicate that the simulated stream temperature had a better fit with observed daily mean temperatures than with daily maximum temperatures. In addition, the RMSE was typically lower in the 2014 simulation than in 2012. Looking at the months of July and August, the RMSE for mean temperatures was between 1.4 and 2.0°C in 2012 at each of the monitoring locations and in 2014 was between 0.5 to 0.6°C. This level of calibration is consistent with the level of calibration achieved in the Brown's Creek Thermal Study which focused on the WOMP monitoring station.

Table 14. RMSE of 2012 and 2014 Existing Conditions Simulations

Year	Period	RMSE (°C)					
		WOMP		Stonebridge		McKusick	
		Mean	Max	Mean	Max	Mean	Max
2012	April to October	1.4	1.4	2.0	2.0	1.7	1.7
	July and August	1.2	1.2	1.2	1.8	1.1	1.8
2014	April to October	0.9	2.2	0.9	1.1	0.8	1.3
	July and August	0.6	1.4	0.5	0.8	0.5	1.1

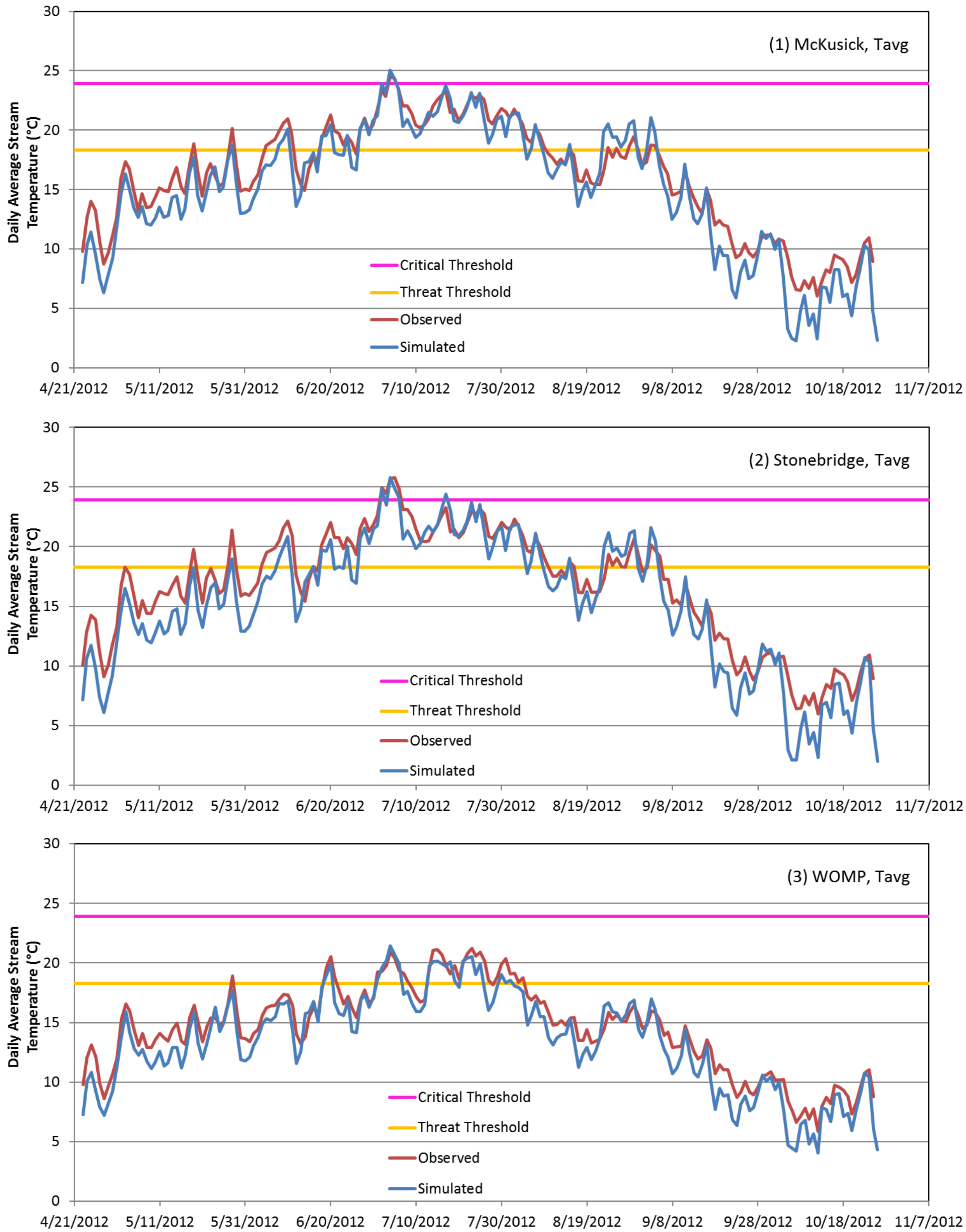


Figure 63. Simulated and Observed Daily Average Stream Temperature in 2012 at the McKusick (Oak Glen), Stonebridge, and WOMP Monitoring Stations

Similar to the results in the Brown's Creek Thermal Study, the maximum daily temperatures shown in Figure 64 and Figure 66 suggest that the model is over-predicting maximum temperatures on some wet days, particularly in 2014. This could be due to the assumptions made in the routing of stormwater (directly vs. indirectly connected), limitations in the MINUHET simulations of runoff temperature and flow rates from impervious areas, or in the CEQUAL model itself (heat routing during highly transient storm flow).

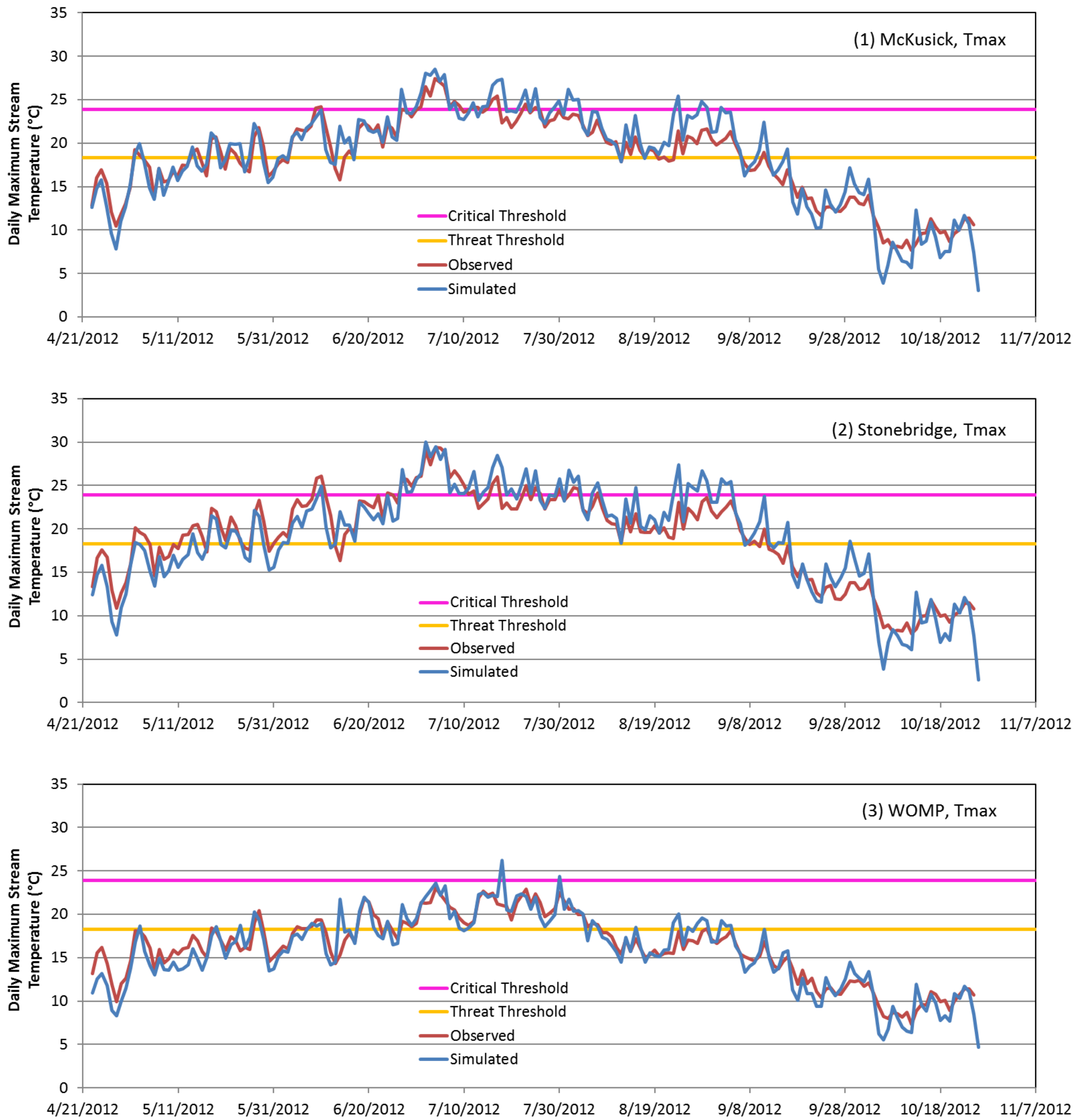


Figure 64. Simulated and Observed Daily Maximum Stream Temperature in 2012 at the McKusick (Oak Glen), Stonebridge, and WOMP Monitoring Stations

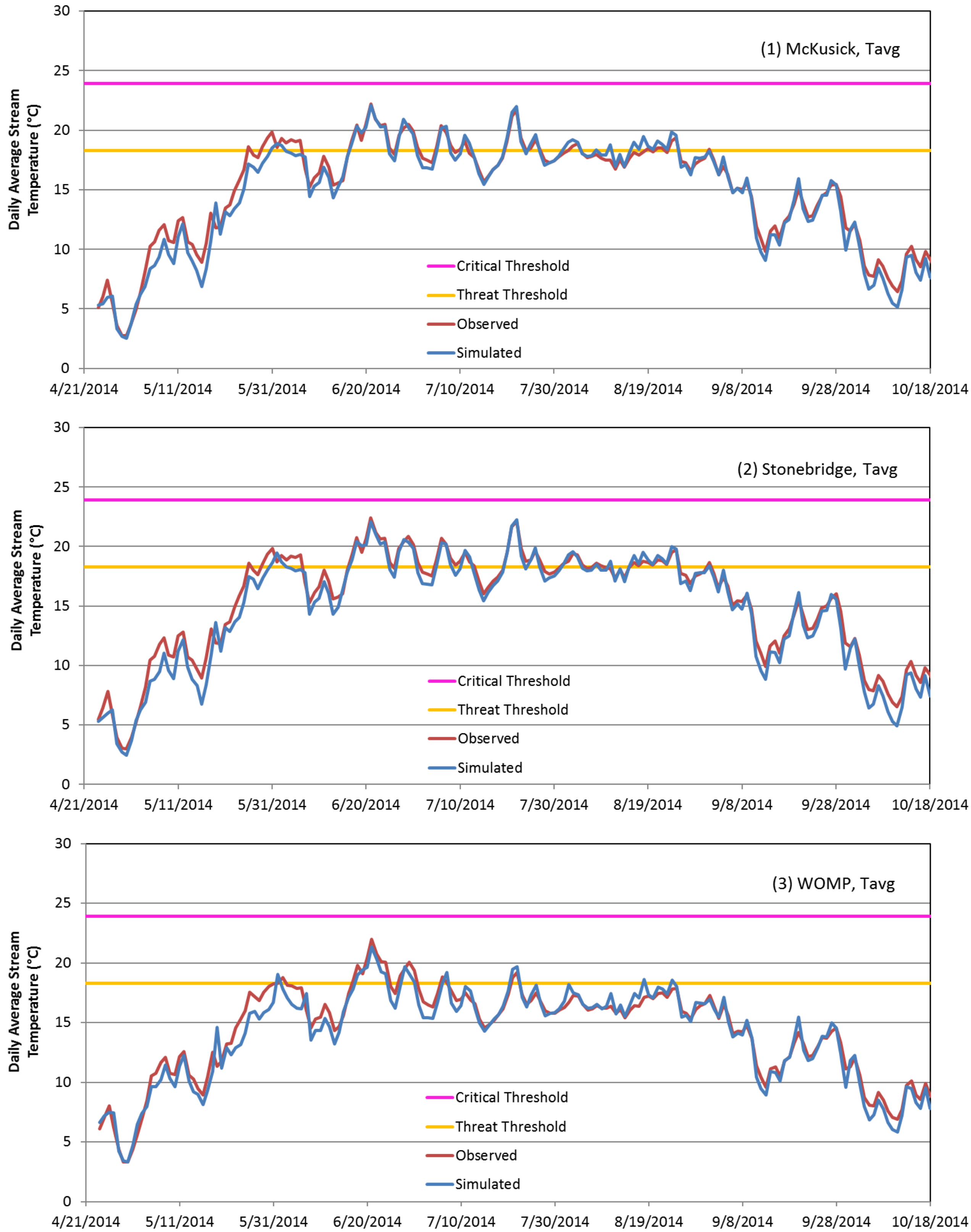


Figure 65. Simulated and Observed Daily Average Stream Temperature in 2014 at the McKusick (Oak Glen), Stonebridge, and WOMP Monitoring Stations

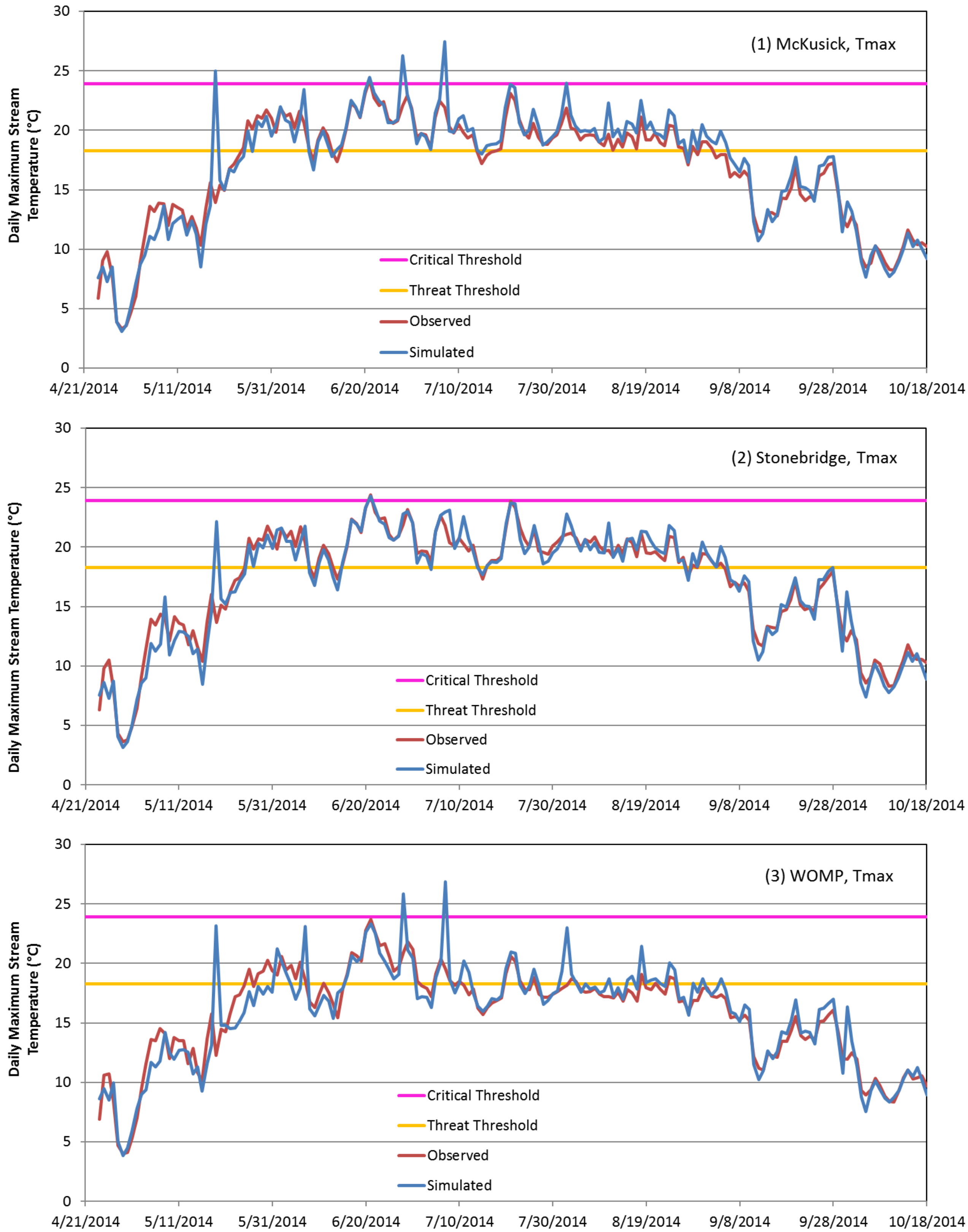


Figure 66. Simulated and Observed Daily Maximum Stream Temperature in 2012 at the McKusick (Oak Glen), Stonebridge, and WOMP Monitoring Stations

6.2. Future Conditions

Four future conditions scenarios (listed below) were developed to estimate the stream temperature reductions resulting from increasing shade to varying degrees. The first two scenarios were updates to the shade restoration scenarios assessed in the Brown's Creek Thermal Study. The stream temperature benefits estimated in this study are different because they are in comparison to the new existing conditions scenario. The shade levels defined in the shade restoration scenarios are shown in comparison to those of the existing conditions scenario in Figure 67.

1. Shade Restoration I: Minimum shade of 50%
2. Shade v II: Minimum shade of 75%
3. Shade Restoration III: Minimum shade of 85%
4. Shade Restoration IV: Targeted shade restoration plan (Figure 60)

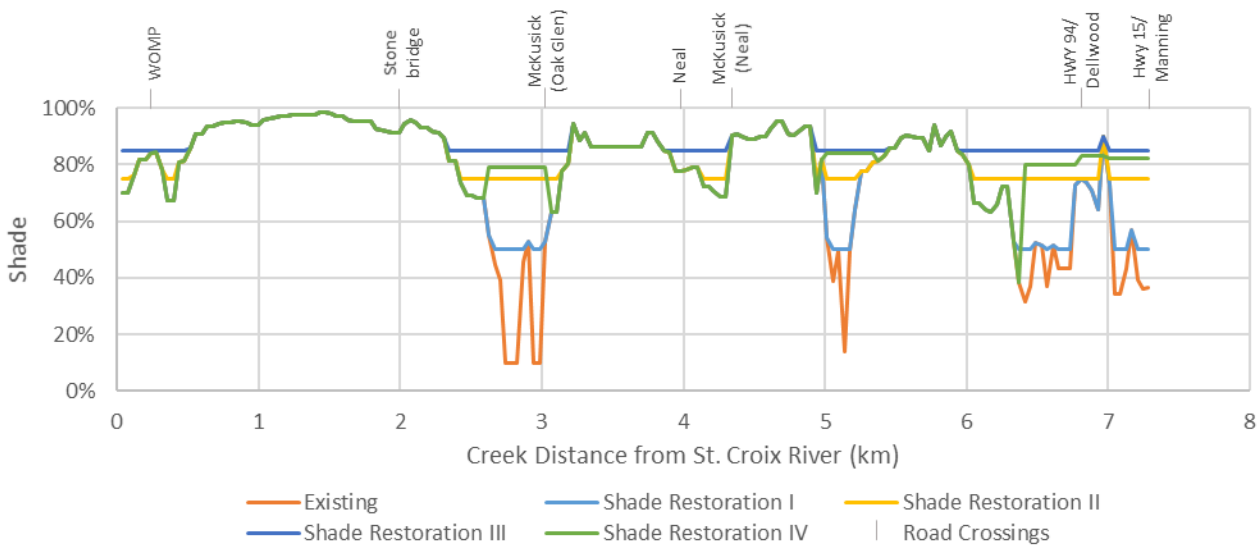


Figure 67. Comparison of Existing Riparian Shading with the Shade Restoration Scenarios

Over the entire length of the modeled stream, the results indicate that monthly mean stream temperatures between June and August will decrease on the order of 0.16 to 0.52°C under the targeted shade restoration scenario. The simulated temperature changes under future scenarios are summarized in Table 15 and are illustrated in Figure 68 and Figure 69 on monthly and daily bases, respectively.

Table 15. Change in Simulated Monthly Mean Stream Temperature between McKusick and WOMP

Month	Year	Change in Monthly Mean Temperature (°C)			
		Scenario I: 50% Minimum	Scenario II: 75% Minimum	Scenario III: 85% Minimum	Scenario IV: Targeted
June	2012	-0.11	-0.41	-0.63	-0.42
	2014	-0.04	-0.15	-0.23	-0.16
July	2012	-0.12	-0.42	-0.65	-0.44
	2014	-0.07	-0.24	-0.37	-0.26
August	2012	-0.14	-0.50	-0.78	-0.52
	2014	-0.05	-0.20	-0.31	-0.21

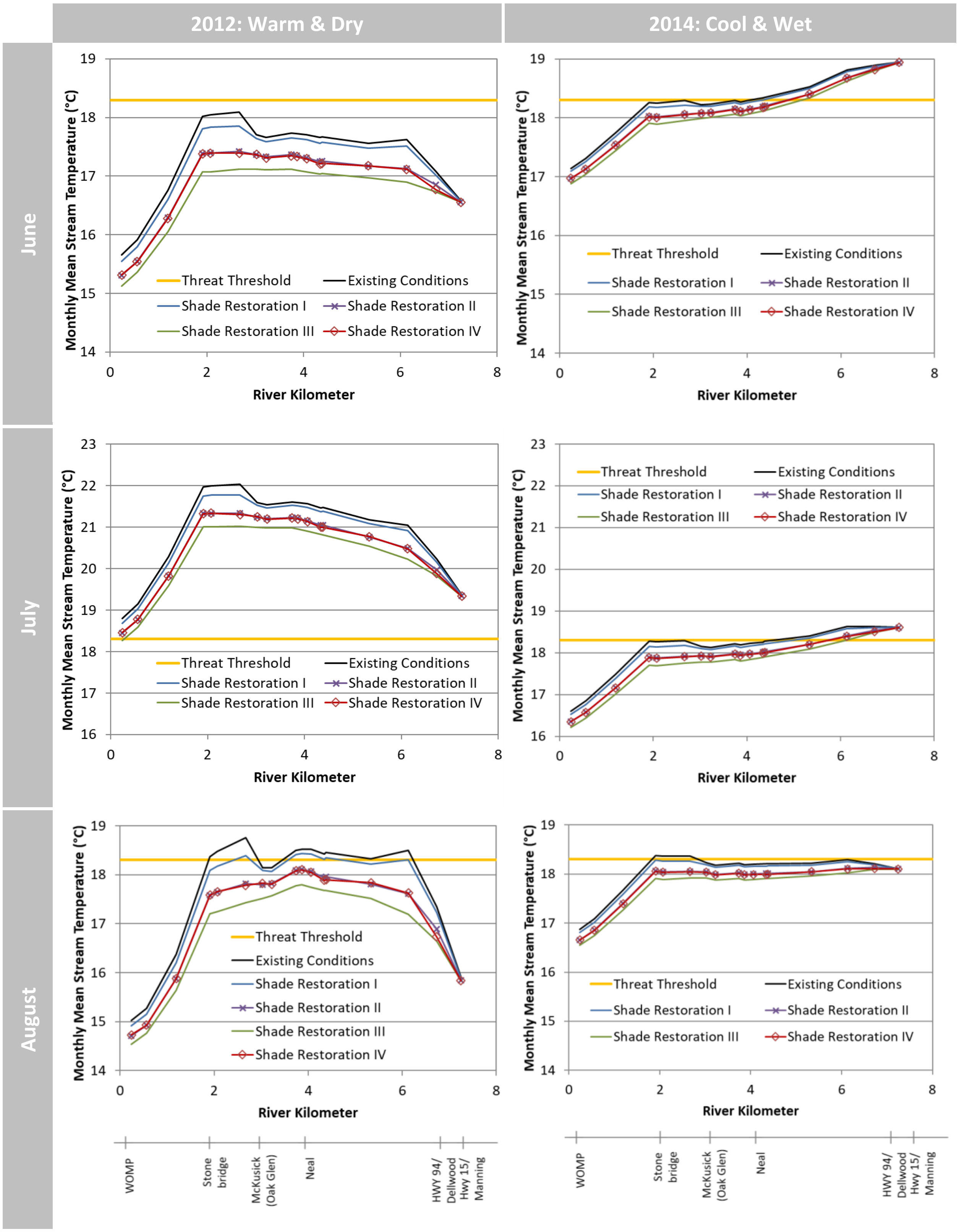


Figure 68. Monthly Mean Water Temperatures in June, July, and August under Existing and Shade Restoration Conditions in 2012 and 2014

Note: The critical threshold temperature for Brown Trout (i.e. when mortality is expected) is 23.9°C.

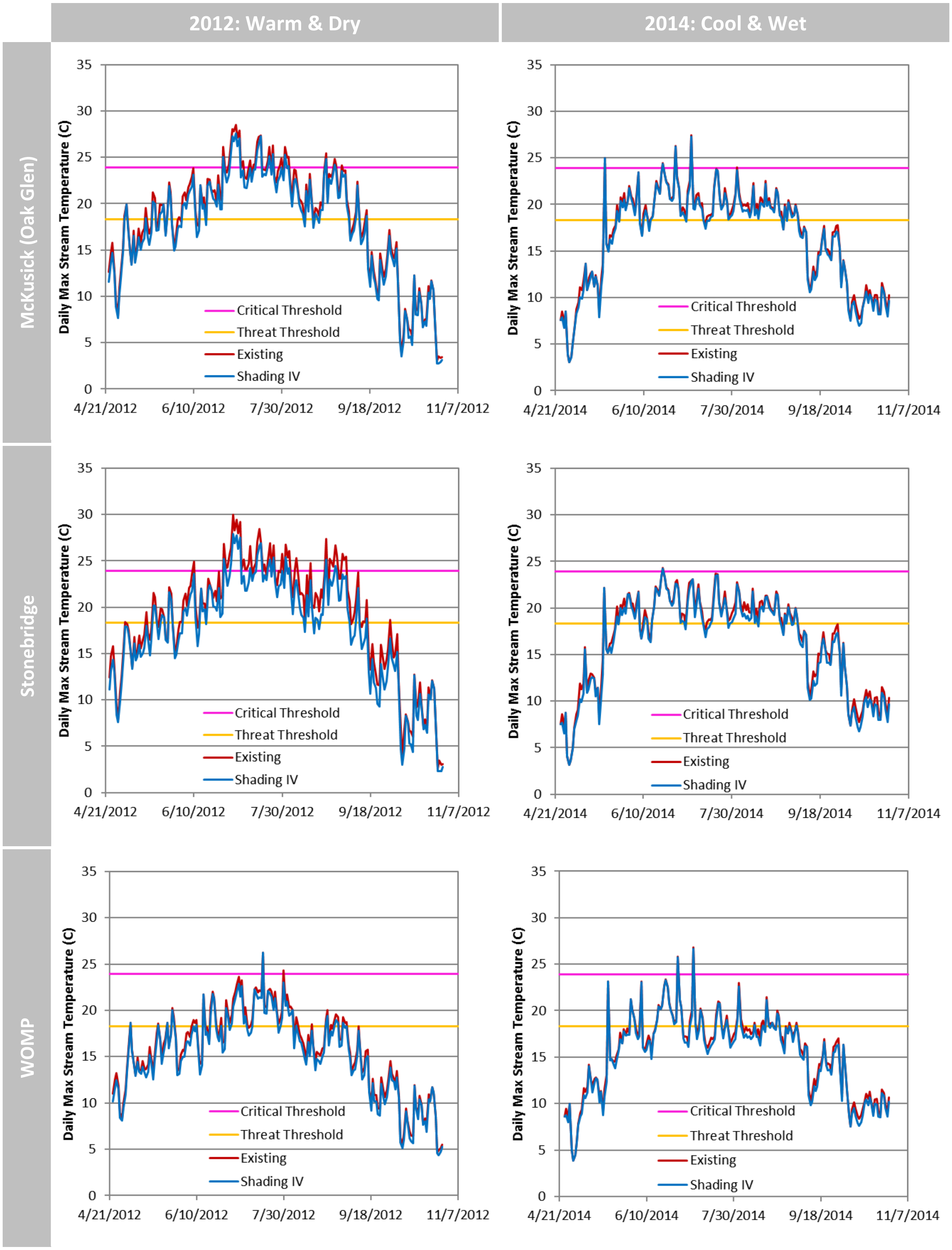


Figure 69. Daily Maximum Water Temperatures at Monitoring Stations under Existing Conditions and Shade Restoration Scenario IV

The number of hours and days each month exceeding the brown trout threat temperature of 18.3°C (65°F) are illustrated in Figure 70 and Figure 71. Similar to the changes in monthly mean temperatures, the shade mitigation scenarios offer modest reductions in exceedance durations.

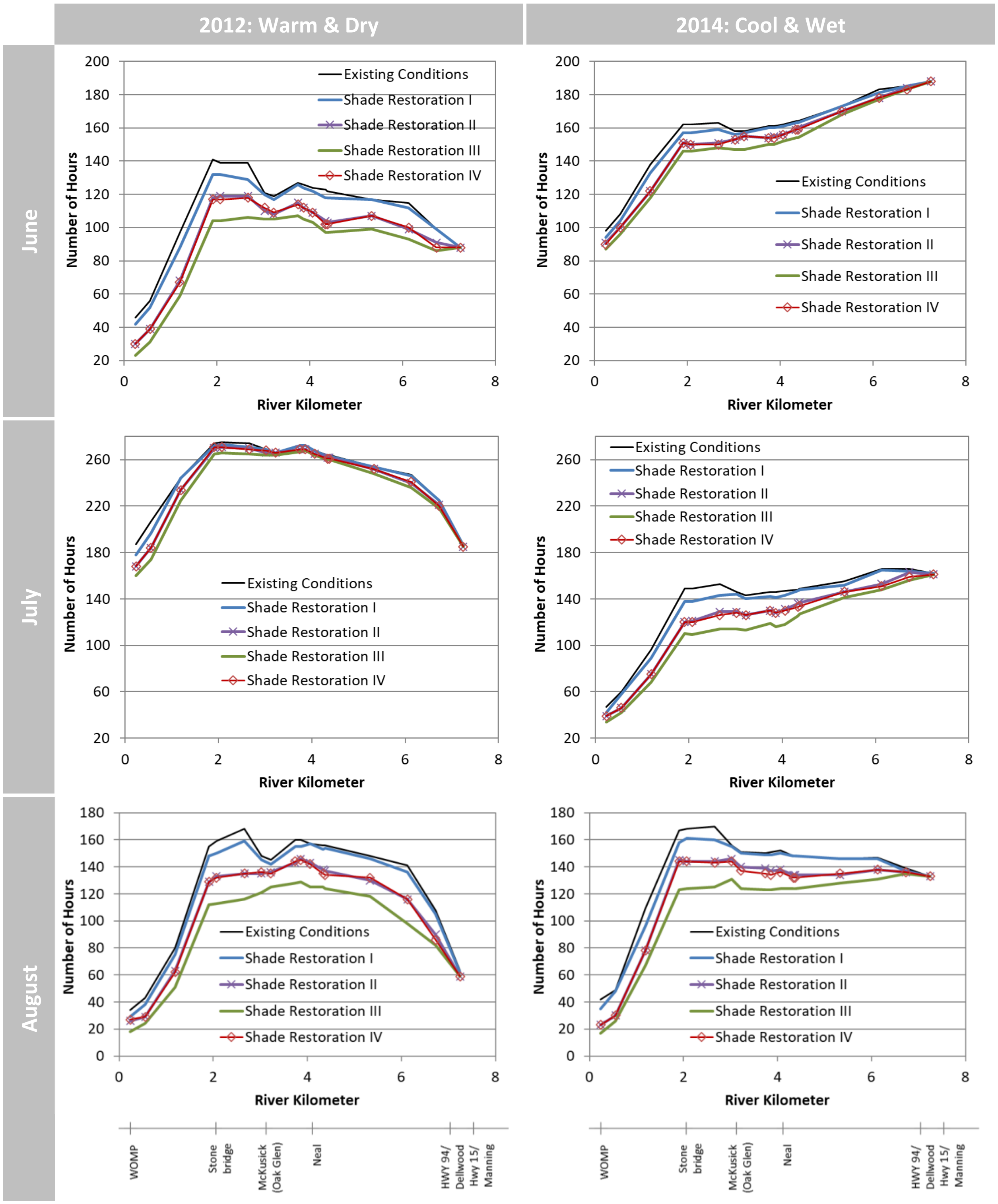


Figure 70. Total Hours Exceeding Threat Temperature

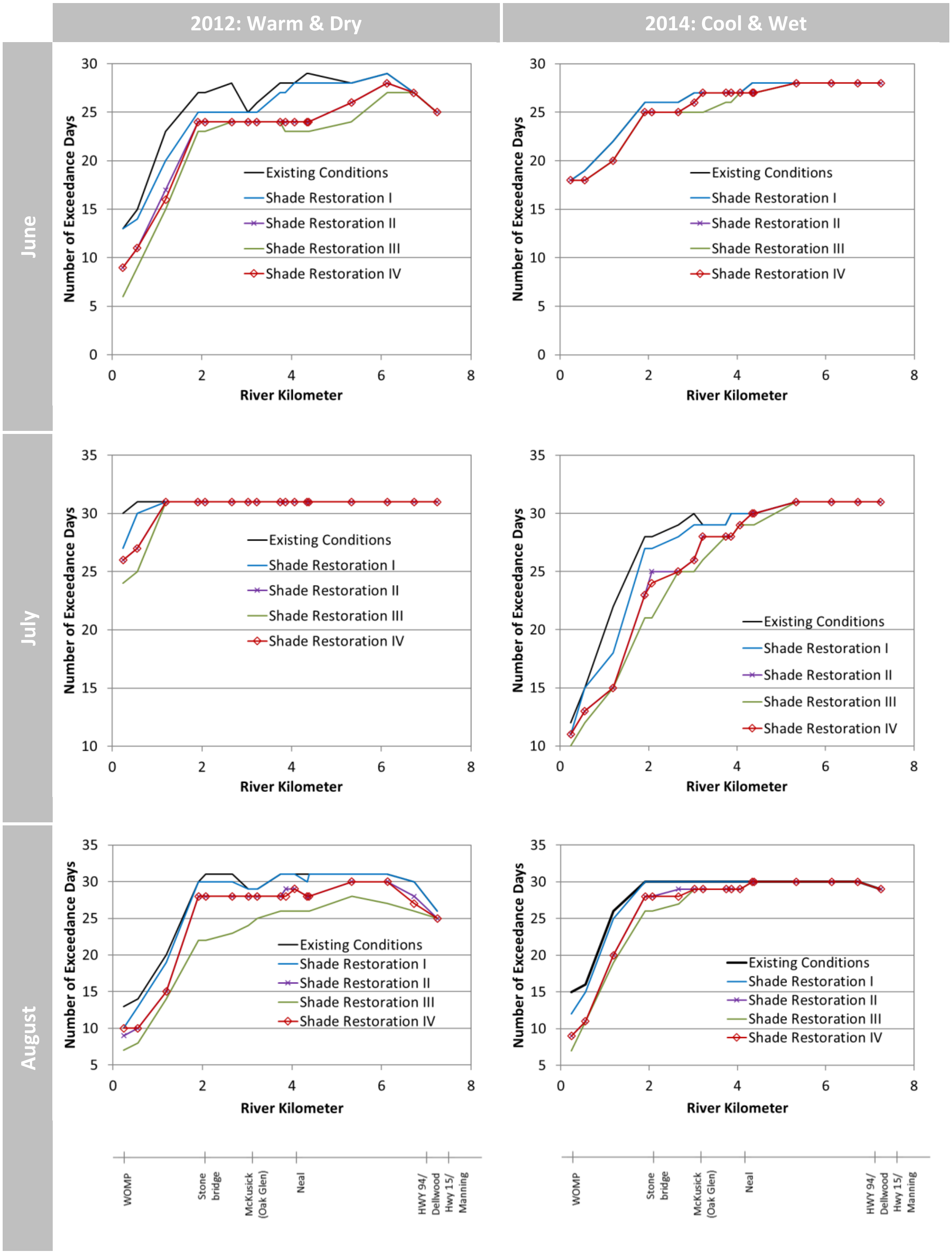


Figure 71. Total Days with at Least 1 Hour Exceeding Threat Temperature

6.3. Discussion

The model results indicate that targeted shade improvements will reduce the monthly mean stream temperatures downstream of County Road 15/Manning Avenue to be below the threat temperature for brown trout (18.3°C) in June for all but the upper most segments in cool/wet climate condition, July during cool/wet climate condition, and August under both climate conditions. The monthly mean stream temperatures in July with a warm/dry climate are expected to exceed threat temperature but remain below the critical temperature at which mortality is expected. The comparison of model results indicates that increased shade will provide a greater stream temperature reduction on a daily and monthly average basis in dry and warm years such as 2012 than wet and cool years such as 2014. This is illustrated on a monthly basis in Figure 61 where there is a greater reduction in stream temperature in the middle reach of the creek in 2012 than in 2014. In addition, a greater reduction in 2012 stream temperatures from shade improvements is illustrated on a daily basis in Figure 62 in comparison to existing conditions. However, when looking at the frequency of temperature exceedances of the threat temperature, such as the number of hours exceeding or the number of days exceeding, shade restoration is shown in Figure 63 and Figure 64 to reduce the frequency of exceedances in July of 2014 more than in 2012 in comparison to existing conditions. This result indicates that other mitigation strategies, such as baseflow augmentation, reduced demands for groundwater pumping, pond disconnection, and beaver management, are needed to more significantly reduce the frequency of exceedances in July of warm and dry years.

The location of the temperature benefits illustrated on the x axis of the graphs also helps illustrate that the higher temperatures and more frequent exceedances are occurring in the middle reach of Brown's Creek (i.e. upstream of Stone Bridge). Generally, the shade restoration scenarios offer greatest stream temperature reduction benefits in the middle reach although there are also benefits in the lower gorge as well. An exception to this result is that the number of days with at least 1 hour exceeding the threat temperature remained constant in the middle reach in the simulation of July 2012, as shown in Figure 64. There is a minor reduction in the number of hours exceeding the threat temperature in the middle reach with the shading scenarios as shown in Figure 63 for the same time period.

The cumulative benefit of shade restoration throughout the study area may be a tipping point for supporting brown trout and coldwater biota at critical periods. In particular, the impact of the shade restoration scenarios on mean stream temperature in July of 2012 shown in Figure 68 indicate that shade restoration could lower the temperature below the threat threshold at the bottom of the gorge, which may provide the refuge for brown trout needed in warm and dry summers. In addition, the results indicate that monthly mean stream temperatures would be lowered to a point below the threat threshold during cool and wet periods throughout the middle reach of Brown's Creek, possibly extending the length of stream accessed by trout under those climate conditions without causing stress. Another cumulative benefit of shade improvements was assessed in the Brown's Creek Thermal Study, which found that restoring shade along the creek would make other stream temperature control strategies, such as baseflow augmentation, more effective. Despite the lag time in canopy establishment (See Section 5.3), shade restoration is an important climate change adaptation investment in that enhanced stream buffers will be in place to compensate for rising air temperatures.

The Brown's Creek Thermal Study estimated the stream temperature reduction benefits of shade restoration to be on the order of 0.5 to 1.1°C for monthly mean temperature. However, the updated scenarios in this study indicate that targeted shade restoration (Scenario IV) will provide benefits on the order of 0.16 to 0.52°C. This difference in benefits is primarily due to the limitations of LiDAR data analysis in estimating the existing shade. As detailed in Section 5, the riparian shade analysis in this study used more detailed field-based data (hemispherical photography) which found existing shade to be greater than what was estimated using LiDAR data, which was the best available data at the time of the Brown's Creek Thermal Study. By underestimating existing shade, the LiDAR data analysis indicated that there were more unshaded areas along Brown's Creek than identified in this study while also indicating that increasing shade would offer a greater benefit in comparison to existing conditions than found in this study if the same benchmark is used to classify a segment as being "unshaded". The difference in the extent and potential benefits of shade restoration is illustrated when looking at Scenarios I and II. The Brown's Creek Thermal Study assessed shade restoration scenarios similar to Scenarios I and II in this study, which raise shade to a minimum of 50% and 75% across the entire model extents. In this Riparian Shading Study, a third level of restoration was added in Scenario III up to a minimum of 85%. In the Brown's Creek Thermal Study, Scenario II resulted in a 20% increase in shade across the modeled reach whereas the similar scenario in this study resulted in an 8% increase in shade. The new Scenario III in this study offers a 12% increase in shade across the model reach while the targeted Scenario IV offers an 8% increase. By acquiring hemispherical photography equipment and analysis software, the District has a better understanding of how much shade is currently provided along the creek and the potential benefit of increasing shade. Since the benefits are lower than previously estimated, these results also indicate the need to look at other mitigation methods to lower stream temperature.

In terms of reducing heat load to the stream, the shade restoration efforts overall would provide an 8% increase in shade over the growing season, which can also be looked at as an 8% reduction in heat load to Brown's Creek. The District's Impaired Biota TMDL study identified the need for a 6% reduction in heat load to the creek to lower stream temperatures below the threat temperature for brown trout (18.3°C). The TMDL allocation was developed with monitoring data at the WOMP station that included a few years of record before the Long Lake Diversion Structure was constructed. The TMDL implementation plan identified the need for further monitoring post-diversion to update the heat load duration curve analysis and refine our understanding of when temperature exceedances occur. Overall, the BCWD's modeling analyses since the TMDL Implementation Plan have indicated that baseflow exceedances are more common than stormflow exceedances (Herb & Correll, 2016). In addition, the creation of the TMDL allocations based at the WOMP station may underestimate the heat load reduction necessary for temperature control upstream of the Brown's Creek Gorge, where temperature is more sensitive primarily due to lower topographic shade. As such, it is expected that more than a 6% reduction in heat load is necessary to meet the threat temperature threshold in the Middle Reach of Brown's Creek. Additional mitigation efforts beyond increasing riparian shade will need to focus on other contributions to high baseflow stream temperatures such as enhancing groundwater contributions and removing beaver dams. Further assessments of the potential cooling benefits offered by beaver management are needed to better understand the extent of potential benefits and the tradeoffs involved, such as flooding, heating in a reservoir, enhanced recharge throughout the floodplain, and overall ecosystem health.

The results of the stream temperature model scenarios are also interesting to consider in relation to the District's ongoing biotic monitoring (See Section 3.8) in the Oak Glen Golf Course in particular. The simulated stream temperatures exceed the threat and critical threshold temperatures under existing and shade restoration scenarios in the golf course. However, finding evidence of natural reproduction of brown trout after the restoration but before the tree canopy has fully established shade suggests that restoration of the in-stream habitat structure (i.e. refugia) and overhanging herbaceous vegetation can significantly improve the conditions supporting trout on a short time frame. The 2012 restoration is also located between very well shaded areas of the creek and the fish survey results may indicate that the restoration provided sufficient short-term improvements to encourage fish passage between the well-shaded segments. Considering these assertions reinforces the benefits of restoring in-stream habitat and quickly enhancing herbaceous vegetation beyond what is indicated by the stream temperature model. As such, the thermal improvement projects identified in the TMDL Implementation Plan and the District's WMP beyond the four shade restoration projects prioritized in this study are still expected to offer significant benefits to aquatic life in Brown's Creek. For example, Segment 8 is identified for morphological improvements in the WMP and is situated between well-shaded segments, which is similar to the Oak Glen Golf Course. Although Segment 8 was not identified as a high priority for shade restoration in this study, it was estimated to have existing shade between 65 to 75% which could be improved by herbaceous and woody vegetation enhancements as part of the morphological restoration.

The Brown's Creek Thermal Study also assessed the potential cooling capabilities of other mitigation strategies, such as baseflow augmentation and pond retrofits. The results indicated that increasing riparian shade could enhance the benefits of these mitigation methods. In addition to providing shading recommendations at specific locations in the study area, this Riparian Shading Study also provides best practices in targeting shade enhancements which could be applied to enhancing shading along surface drainage tributaries to Brown's Creek and around ponds. More recently, annual monitoring by the Washington Conservation District has found that warm water from McKusick Wetland may be a significant heat load to Brown's Creek. Further investigation of this and other reservoirs may aid in addressing stream temperature issues in the creek.

Another take-away from the data analysis and application in the stream temperature model update is that field data is needed to validate and refine shade estimated using LiDAR. In the Brown's Creek Thermal Study, shade was estimated using LiDAR and then was uniformly scaled to calibrate the model to observed stream temperatures. The field-validation process in this Riparian Shading Study developed a log-normal formula to correct shade estimated using LiDAR, which is a non-uniform process. This process removed shade as a calibration parameter in this study and, as a result, other parameters were tested to calibrate the model. The calibration required an increase in groundwater temperature relative to what was modeled in the Brown's Creek Thermal Study. The need for increasing groundwater temperatures to calibrate the existing conditions scenario indicates that:

- temperature of groundwater discharge to the stream was warmer on average than what was indicated by the field measurements in 2012 and 2014,
- groundwater contributions to the stream continues to play a critical role in determining stream temperatures, and

- there may be other sources of heat loads during dry and warm years that were not simulated in the model, such as beaver dams.

The Brown's Creek Thermal Study also identified the need for further analysis of the impact of beaver dams along Brown's Creek. The questions around beaver dam impacts still stand after the Riparian Shading Study per the above discussion. The model uses an average stream width for the modeled extents of the creek and therefore does not include local channel features such as wide bends and beaver ponds. While local stream widening over short distances is not expected to significantly change stream temperature, beaver ponds can have a significant affect both on flow and temperature downstream of the pond, and would make a worthwhile addition to the model in the future. Such future studies would need to focus on specific dam locations and install monitoring equipment to assess relevant variables (e.g. groundwater level, groundwater temperature, stream level, stream temperature, etc.). A beaver dam analysis would not be able to rely on the District's stream temperature model scenarios of 2012 and 2014 since such beaver dam monitoring was not in place during those years. Overall, further assessments of the potential cooling benefits offered by beaver management are needed to better understand the extent of potential benefits and the tradeoffs involved, such as flooding, heating in a reservoir, enhanced recharge throughout the floodplain, and overall ecosystem health. Beaver activity has broad impacts and benefits to urban areas and riparian ecosystems beyond stream temperature that need to be considered as well.

Stepping back from stream temperature analyses, it is also important to recognize the other benefits offered by enhancing the plant communities in riparian buffers along Brown's Creek. As discussed in Appendix B, riparian buffers provide many benefits such as capturing pollutants in urban and rural runoff before they reach the creek. Riparian buffers also provide habitat for terrestrial wildlife, such as pollinators, and are a critical corridor in which terrestrial invasive species need to be controlled to sustain healthy biodiversity. Riparian buffers also provide climate change mitigation benefits unique to urbanizing areas by mitigating heat island effect and sequestering carbon and filtering air pollutants. The District's continued investment in protecting and restoring riparian buffers will yield stream temperature benefits in addition to many others along the riparian corridor.

7. RECOMMENDATIONS

Shade Restoration Projects

The recommendations of this study related to riparian shade include implementing the four targeted shade restoration projects, incorporating shade restoration best practices into the District's other activities, and monitoring progress towards shade targets.

Improvements to these and other segments for thermal benefits were included in the TMDL Implementation Plan and BCWD WMP (Brown's Creek Management Plan) with preliminary cost estimates. The concept plans for the targeted shade restoration projects in Segments 10B, 11, 12, and 13 are provided in Figure 56 to Figure 59. These plans and the detailed cost estimates were used to develop a recommended Thermal Improvement Implementation Plan for stream and shade restoration projects. The implementation plan schedule and costs are detailed in Table 16.

Implementing the targeted shade restoration projects as early as possible is recommended due to the lag time in establishing full shade benefits for these high-priority locations. As such, the four shade restoration projects are recommended for implementation before other thermal improvement activities. No projects are recommended for implementation in 2017 and 2018 to provide sufficient time for gathering funding for the first high-priority shade implementation project in 2019 following this study. The other three shade restoration projects are recommended for implementation in 2020, 2021, and 2022. Segments 12 and 13 are recommended to be implemented last of the four targeted shade restoration projects because it is expected that additional time is needed to attain funding and gain landowner support than the other two projects. The remaining thermal improvements planned in the WMP and TMDL Implementation Plan are included in the recommended schedule between 2023 to 2026.

Thermal improvement projects are a high priority in the 10 year period of the District's WMP and the TMDL Implementation Plan. The WMP included estimated implementation costs for improvements to morphology, vegetation composition, and buffer width as assessed in the TMDL Implementation Plan in 2012. The implementation costs for the high priority shade restoration projects in Segments 10B, 11, 12, and 13 were updated to include the engineering design, administration, two years of maintenance, and contingency.

Remaining funds from the Riparian Shading Study are recommended for use in engaging stakeholders of the high priority shade restoration projects and beginning the design of the first improvement project in Segment 11. Additional funding opportunities are expected to become available in 2018 to further assist in accelerating the implementation of these projects.

Table 16. Thermal Improvement Implementation Plan (Updated from the BCWD WMP's Brown's Creek Management Plan)

Thermal Improvement Implementation Activities **	Segment ID*	Estimated Cost	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026
1,306 feet on City of Stillwater /Millbrook Development	11	$91,922			√							
450 feet on Brown's Creek Cove/Millbrook Development	9	$10,000								√		
325 ft upstream of county Road 5 ***	3	$3,000								√		
3,200 feet adjacent to Millbrook Develop./Holland Property	10B	$162,720				√						
1,800 feet on Oak Glen LLC and State of MNDNR	6	$15,000									√	
653 feet on Schubert properties	4	$15,000									√	
653 feet on City of Stillwater Property (Brown's Creek Park)	8	$94,000							√			
131 ft upstream of Wolf Marine ***	1	$3,000										√
392 ft upstream of Wolf Marine ***	2	$5,750										√
Approximately 1,000 feet on Grogan property	14	$13,000										√
950 feet upstream of Hwy 96	12	$175,274						√				
1,045 ft on Costa Lorraine M Properties	13	$498,235					√					
Total costs for activities to improve reaches of the creek categorized as having degraded stream channel geomorphology by addressing: lack of buffer, stream width, over-hanging banks, and profile and alignment		**$1,086,901**	**--**	**--**	**$91,922**	**$162,720**	**$498,235**	**$175,274**	**$94,000**	**$13,000**	**$30,000**	**$21,750**

** This refers to the proposed thermal improvement projects found in the TMDL Implementation Plan.*

*** Implementation activities identified in Brown's Creek TMDL Implementation Plan (2012), Brown's Creek Thermal Study (2016) and the BCWD WMP (2017). Changes in cost estimates reflect inclusion of design, 2-year maintenance, permitting, and additional investigation costs.*

**** Plantings done in last 5 years have not been evaluated for mortality/success in establishing. Additional tree and herbaceous enhancements may still be required for shade benefits.*

√ Recommended Schedule for Implementation

Shade Restoration Activities and Programs

Beyond the specific projects, it is also recommended that shade restoration be incorporated into other District activities and programs as follows:

1. **Invasive Plant Management**:
   Include herbaceous plantings to enhance understory cover, increase herbaceous canopy height, and minimize exposed banks following the removal of invasive woody and grassy species within 5 m of the stream bank.

2. **Guidance on Best Practices for Increased Shade:**
   The District should develop guidance on best practices for increasing shade while limiting the potential detrimental erosion impacts of dense tree canopy cover.

3. **Management Plans for Plant Communities:**
   Develop management plans for plant communities adjacent to Brown's Creek to enhance and protect the biodiversity and values of these unique communities. Management goals should focus on improved native vegetation communities, increased riparian shading through strategic vegetation design, and increased habitat diversity. The sedge meadow south of the Highway 96 crossing of Brown's Creek (adjacent to Segment 11 in this study) and the Maple Basswood Forest along the lower gorge reach of Brown's Creek are examples of plant communities for which Management Plans would be prepared. Management plans for the Brown's Creek riparian corridor should include:

   a. Mapping of desired plant communities and outcomes,
   b. Identification of seeding mixes and planting choices for specific areas,
   c. Discussion of treatment and management options for invasive species and pests,
   d. Outline of timeline and timing of management activities,
   e. Breakdown of management activity costs,
   f. Suggestions for evaluation methodology,
   g. Identification of potential funding sources, and
   h. Valuable management references.

   Much of the Brown's Creek riparian corridor and immediate watershed is comprised of private land owners. In order to facilitate behavioral changes and improve vegetation conditions, community assessment and engagement will be essential in the long term success of these management plans. Possible community assessment tools include a landowner survey and interviews with individual landowners to help identify what motivates behaviors and what they value about the creek. Further steps could involve hands on activities designed to educate corridor landowners about why riparian vegetation management is important, how riparian vegetation can be designed in a variety of ways to merge with their personal aesthetics, and what funding sources are available to them. In addition, actions could include the creation of a native shoreline team consisting of landowners, in which members are empowered with information and tools to help neighbors facilitate native vegetation establishment and management. Forums, workshops, and other forms of public engagement could also be initiated.

Shade Monitoring and Maintenance

Continued use of the hemispherical photography equipment, modeling tools, and approaches applied in this study is recommended as part of the District's annual monitoring program to achieve the following components to a long term successful shade restoration effort:

- Assess shade before restoration using hemispherical photographs where projects go beyond the representative reaches of this study.
- Assess shade after restoration using hemispherical photographs collected at the same locations as the pre-restoration monitoring. Continued monitoring of shade at the same transects in Reach 7 as in this study will provide the data needed to assess the lag time between plantings to reaching target shade levels.

A detailed plan for monitoring shade in Brown's Creek watershed to meet the above objectives is outlined in Appendix E. The cost estimates for the shade restoration projects include two years of monitoring and maintenance of the herbaceous and tree plantings. Beyond that and monitoring for mortality of tree plantings, this study and the monitoring recommendations in Appendix E do not include any further guidance on evaluating the success of enhancing the plant communities adjacent to the stream segments. It is assumed that such guidance and recommendations would be included in Management Plans specific to each plant community.

In addition to monitoring shade at project locations, there is also the opportunity to identify and restore shade at small sites. During other field work activities, staff should identify riparian areas that have stunted grassy vegetation, emergent vegetation, exposed banks, or new sediment accumulation. The district should allocate $2,600 in annual funding for maintenance of these small sites, including erosion control blanket, planting plugs, and seeding during appropriate times of year (e.g. late spring or summer when there are stable flows) to enhance grassy vegetation and shade. This annual cost is estimated assuming small sites will total 5,000 square feet of improvements.

Disturbances such as grazing or burning will be needed to maintain riparian vegetation composition and prevent succession to over-forested state.

Reducing Stream Temperatures and Restoring Aquatic Life

The stream temperature modeling scenarios indicate that the targeted shade restoration will reduce monthly mean stream temperatures by 0.16 to 0.52°C but will have minimal impact on reducing the number of hours and days exceeding the threat temperature in July during dry and warm years. This result indicates that additional mitigation strategies are still necessary to support coldwater biota in the middle and gorge reaches of Brown's Creek. Other stream temperature control strategies include baseflow augmentation, stormflow management, and mitigating beaver dam impacts. Baseflow is sustained in Brown's Creek by groundwater contributions which could be enhanced by reducing groundwater withdrawals and increasing infiltration in the groundwatershed. Depending on the practice, the latter could also help reduce warm stormflows to the creek. Infiltration might also be enhanced by disconnecting anthropogenic drainage pathways, such as the ditched wetland north of Segment 13 or retrofitting the ponds in Oak Glen Golf Course which are directly connected to Brown's Creek. The Brown's Creek Thermal Study found that such retrofits would become more effective once shade is restored along the creek. Beaver ponds can have a significant affect both on flow and temperature downstream of the pond, and would make a worthwhile addition to the model in the future. The need to further assess these strategies and continue implementation is also underscored by the fact that the creek's temperature will need to be protected from the impacts of climate change both directly on water temperature and indirectly through modifications to the water balance. Further assessment of the potential cooling benefits offered by beaver management is needed along with the potential tradeoffs involved, such as flooding, heating in a reservoir, enhanced recharge throughout the floodplain, and the ecosystem health benefits of beaver activity.

The monitoring needs identified in the Brown's Creek Thermal Study will provide the data needed to address the above opportunities for investigation and stream temperature reduction:

> "A broad array of monitoring data were used in this the project to calibrate and verify the stream temperature model. Monitoring efforts should be continued in the future, to further characterize baseflow sources and to enable trend analysis in stream flow and temperature.
>
> 1) In-stream flow and temperature monitoring should be continued at existing sites (WOMP, Stonebridge, Highway 15/Manning) to build a long-term record and enable trend analysis of flow rates and water temperatures.
>
> 2) Additional temperature monitoring at sites of interest, e.g. wetland and stormwater inputs and beaver ponds. Wherever possible, temperature monitoring should be combined with flow monitoring, to enable better estimates of thermal impact.
>
> 3) Groundwater and baseflow continues to be a data need for Brown's Creek. The existing gaging sites can provide long term records for trend analysis of baseflow, but the seasonal and spatial variability of baseflow inputs is still not well characterized. Pairing piezometer measurements with a means to measure the corresponding flow source rates would be an effective method to characterize baseflow sources.
>
> 4) The BCWD climate station provided valuable information on local precipitation, air temperature, and solar radiation in the watershed. Continued operation of this station in the future will be helpful both for any additional modeling work, and for trend analysis of flow and temperature." (p. 30)

Stream temperature and flow monitoring conducted by the Washington Conservation District (WCD) in addition to aquatic biota monitoring conducted by the District and MPCA provide the data needed to assess the combined effectiveness of stream temperature mitigation implementation activities on restoring aquatic life in Brown's Creek. In the WCD's annual monitoring report, it is recommended that the stream temperature and flow data be analyzed to identify under what flow conditions the threshold temperatures are exceeded each year. This could be conducted by annually updating the heat load duration curves previously developed for the TMDL study (Figure 72) to assess trends in the timing and frequency of exceeding the threshold temperatures for fish stress and mortality at the three long term WCD monitoring locations: the Manning, Stonebridge, and WOMP stations. Section 3.E of the District's Impaired Biota TMDL study details the method used for developing the heat load duration curve.

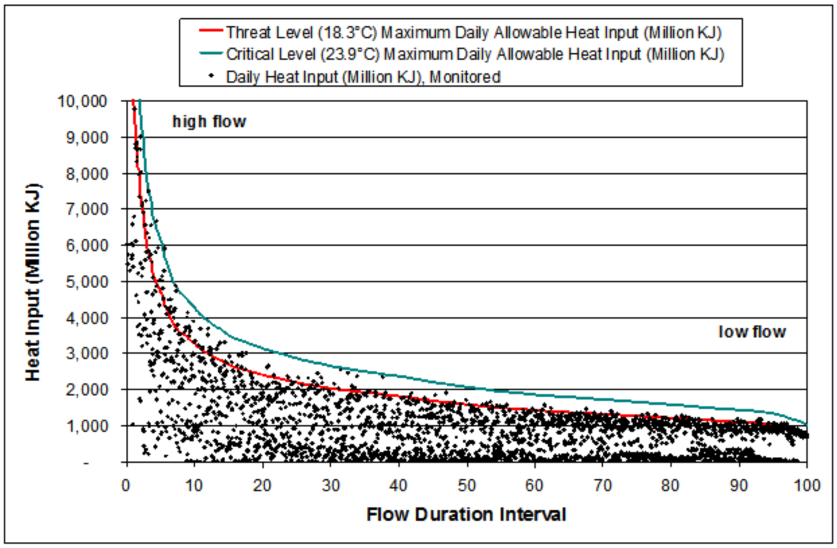


Figure 72. Heat Load Duration Curve 2000-2007 WOMP Station (Emmons & Olivier Resources, 2010)

As the District continues to collaborate with stakeholders on projects and programs to assist in establishing a self-sustaining brown trout population, it is also recommended that a coordinated approach be implemented to marking stocked and surveyed fish. This will assist all stakeholders in evaluating the success of implementation activities and the need for ongoing stocking moving forward.

Broader Implications

The water quality benefits of riparian vegetation recently led to state-wide legislation requiring riparian buffers across Minnesota. Minnesota's buffer law requires buffer restoration along 90,000 miles of public waters and ditches within the next two years. State agencies and local soil and water conservation districts are developing and distributing guidance to farmers to aid in successful compliance, although the enforcement of the new legislation is understandably contentious in agricultural areas. Shade provided by herbaceous vegetation and the resulting benefits to reducing the temperature of small streams and tributaries is yet another reason to protect and enhance riparian buffers across the state. State buffer guidance should consider the results and recommendations of this study to betted reflect these benefits.

In addition, the District should reach out to other watershed management organizations of coldwater systems to share the results of this study and share the equipment and software acquired for this study. Doing so will help answer similar questions in other watersheds and will assist in assessing how transferrable the findings of the studies are in different settings.

In conducting this applied research study and continuing to monitor shade following the implementation of projects, the District is also in a position to advance the dialogue by publishing and presenting their findings in journals and at regional conferences, especially those focused on the management of coldwater fisheries and other surface water-groundwater dependent natural resources.

8. LITERATURE CITED

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APPENDIX A. LITERATURE REVIEW ON ESTIMATING RIPARIAN SHADE

The objective of this section is to review the literature on shade provided by grassy and woody riparian vegetation to small streams of the North-Central United States. The best-suited instruments, measures, and methods for further study on this topic are identified in addition to areas for further research.

A.1. Introduction

Fish and macroinvertebrates found in coldwater streams support regionally significant recreational uses and economic benefits. In Minnesota alone, coldwater angling provides an estimated annual economic value of $148.7 million in direct sales, $90.35 million in income, and 3,300 jobs (Gartner, Love, & Erkkila, 2002). However, rising water temperatures in coldwater streams currently threaten the health and survival of coldwater biota. Almost 60% of the coldwater streams assessed for water quality impairments across the U.S. are currently impaired, which means they are too polluted to naturally support coldwater fisheries. The seventh most common cause of stream impairments across the country is water temperature (U.S. Environmental Protection Agency, 2017). Beyond the current threats and impairments, 62% of suitable habitat for coldwater fisheries is ultimately projected to decline across the country by 2100 at the current rate of climate change. Lost coldwater fisheries will be replaced by less valuable warm water and rough fisheries at an estimated cost of $380 million to $1.5 billion in recreational fishing damages (Jones et al., 2013). Restoring and sustaining naturally reproducing coldwater fisheries is of economic significance regionally and nationally.

High water temperatures cause physiological stress, reduced growth, reduced reproductive success, and increased mortality of coldwater biota. Stream temperature is influenced by the heat fluxes depicted in Figure 73, such as incoming solar radiation, outgoing longwave radiation, evaporative and conductive heat transfers, streambed conduction, and the temperature of flows entering the stream.

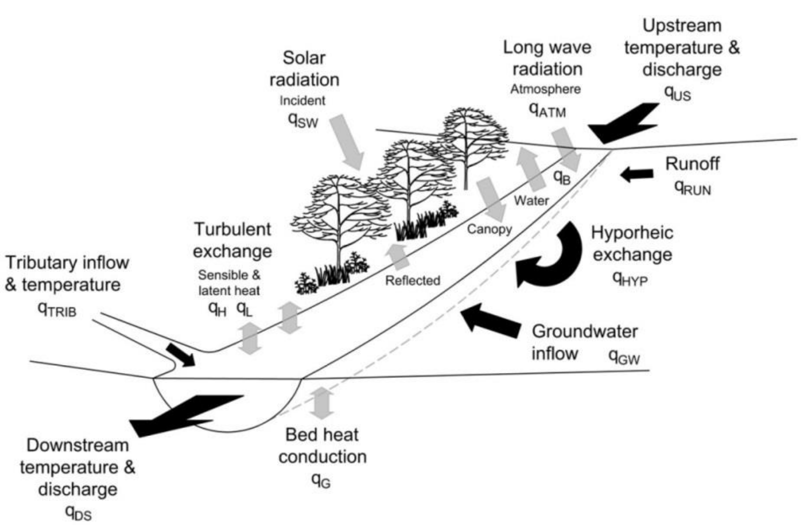

Figure 73. Major Heat Flux Processes in a Stream (Interpretation of Moore et al., 2005)
Note: Does not illustrate the friction generated by rapidly moving water over steep slopes (Moore, Spittlehouse, & Story, 2005)

The first law of thermodynamics (conservation of energy) states that energy cannot be created nor destroyed, only converted from one form to another (Equation 8-1). Applying the first law to stream temperature defines an equation for net heat flux (Equation 8-2).

Change in heat storage = net heat flux = heat energy in – heat energy out **Equation 8-1**

$$q_{net} = q_{sw} + q_{atm} + q_b + q_l + q_h + q_g + q_{us} + q_{ds} + q_{trib} + q_{run} + q_{hyp} + q_{gw}$$ **Equation 8-2**

where q_{sw} is short-wave (solar) radiation, q_{atm} is downwelling long-wave (atmospheric) radiation, q_b is upwelling long-wave (water surface) radiation, q_l is latent heat flux, q_h is sensible heat flux, q_g is conduction between the water and the bed, q_{us} is the volume and temperature of incoming flows upstream of the system boundary, q_{ds} is the volume and temperature of flows leaving the system, q_{trib} and q_{run} are the respective volume and temperature of flows entering the stream from tributaries and surface runoff, q_{hyp} is the hyporheic exchange, and q_{gw} is the volume and temperature of groundwater flowing into the stream (Deas & Lowney, 2000). The water temperature rises when the net heat flux (q_{net}) is positive.

Specific heat sources and human activities influencing heat fluxes into and out of coldwater streams are illustrated in Figure 74. The branches of the flowchart illustrate the causal pathways from heat sources and human activities that affect water temperature and, ultimately, impair biotic health. Many of the causal changes occur as land is developed, harvested, or farmed. This is consistent with the observed decline in ecosystem health and biodiversity of coldwater streams due to the effects of urbanization and intensive agriculture (Wang, Lyons, & Kanehl, 2003; Wang, Lyons, Kanehl, & Gatti, 1997). Altering land cover in a watershed influences both the water and energy balance of the system and, as a result, can increase stream temperatures directly and indirectly. For example, warm discharge from industrial sites directly increases stream temperature whereas bank erosion indirectly increases stream temperature by increasing the surface area exposed to solar radiation. Impervious surfaces introduced to the landscape through urbanization reduce infiltration, reduce groundwater discharge to streams, increase runoff, and increase temperature of runoff. Intensive agriculture includes active farming or intensive grazing of stream corridors which typically results in removal of the vegetative canopy shading the stream.

Climate change is also altering the overarching meteorological conditions that affect stream temperature. Climate change impacts include modified air temperature, humidity, cloud cover, precipitation quantity and intensity, vegetation composition and cover, growing season, and groundwater temperatures. At a much smaller scale, microclimates can also develop above a stream where meteorological parameters such as wind velocity are different from those above the riparian vegetation canopy (Hewlett & Fortson, 1982; Weatherley & Ormerod, 1990).

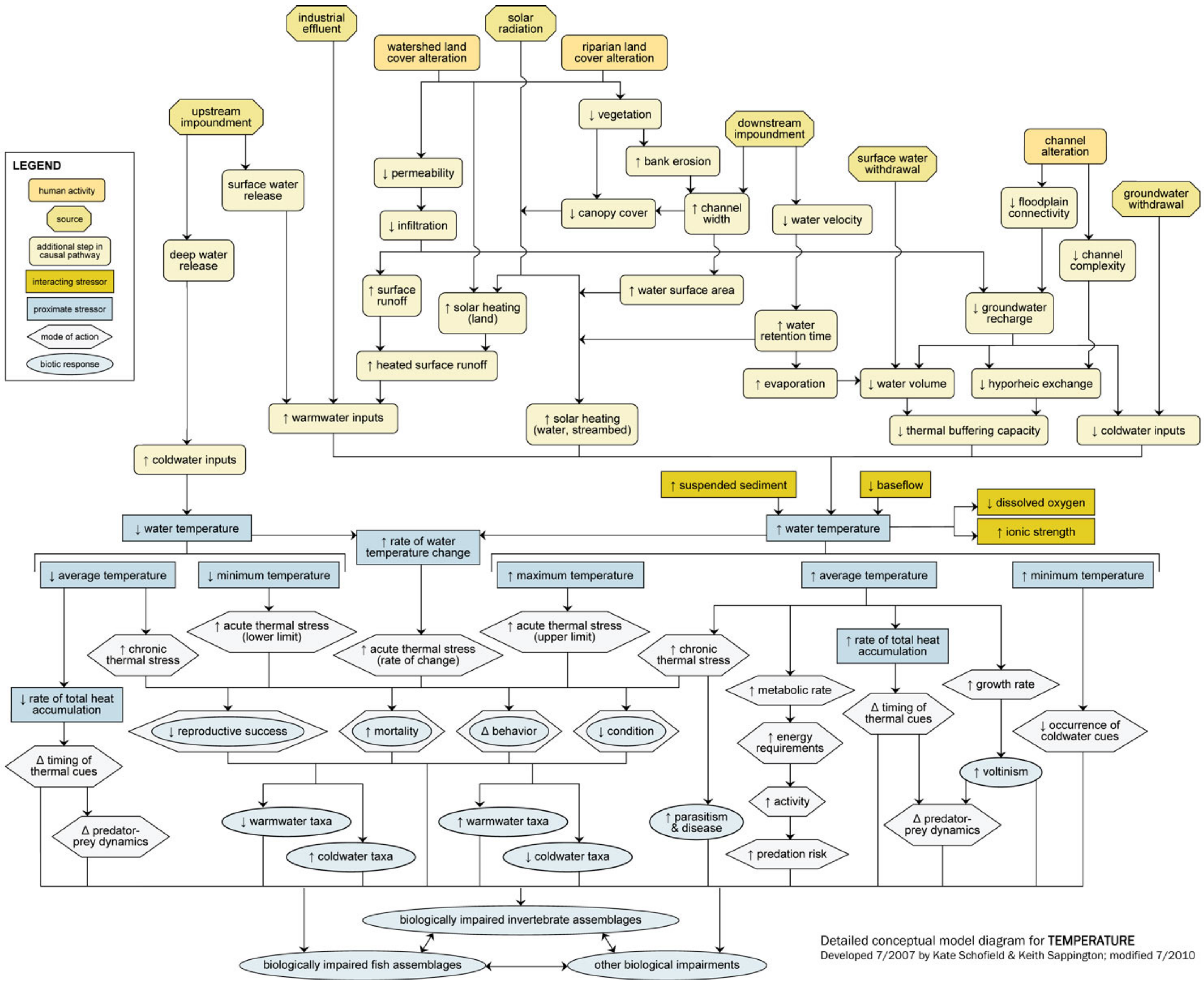

Figure 74. Detailed Diagram of Causal Pathways to Changing Water Temperature and Impaired Biota (Sappington & Norton, 2010)

Strategies to limit thermal pollution of streams can be categorized as rainfall event controls and baseflow controls. Event controls lower the temperature of stormwater runoff from warm, impervious surfaces before discharging to the stream. Baseflow controls lower the temperature of the stream during baseflow conditions which occur between rainfall events and are a critical period of temperature stress for aquatic organisms (Herb & Correll, 2016). Stream baseflow temperature can only be controlled by channel morphology, groundwater contributions, and riparian vegetation. Channel morphology, such as overhanging banks, can shade the outer edges of the stream. Deep channels and pools provide refugia for fish and macroinvertebrates on warm summer days. Groundwater inputs (Mellina et al., 2002) and hyporheic exchange (Constantz, 1998, 2010) provide cool inputs into the stream, the greatest of which occur in small headwater streams (Bren, 1998; Burkart, James, & Tomer, 2004). Riparian vegetation limits the amount of radiation reaching the stream surface by intercepting incoming solar and atmospheric radiation by either absorbing or reflecting the incoming radiation. This mechanism is more simply referred to hereafter as shade. Riparian vegetation also influences the microclimate immediately above the stream, such as air temperature, humidity, and wind speed, which can also affect heat fluxes such as evaporation, conduction, and long wave emission rates (Davies-Colley & Payne, 1998; Rutherford, Davies-Colley, Quinn, Stroud, & Cooper, 1997). Since solar radiation is a dominant contributor to warming streams, shade is one of the most important mechanisms for reducing thermal pollution (Dent et al., 2000).

The purpose of this review is to identify the best-suited methods for comparing shade provided by grassy and woody riparian vegetation. We hypothesize that (1) shade is dependent upon the plant morphology of riparian buffers but can be amplified or dampened by other site characteristics and (2) grassy vegetation provides less shade than woody vegetation. This review focused on small streams in North-Central America but studies from other regions were referenced where applicable. The methods identified in this review will be applied in the BCWD Riparian Shading Study.

The focus of this review on riparian shade is not intended to diminish the importance of other stream temperature controls, such as groundwater inflows, or the significance of other benefits provided by riparian buffers. Instead, the focus is intended to justify the needs and methods for future quantified analysis of shade variation based on vegetation type. Such studies will define the limits of riparian shade management such that other stream temperature control strategies will be pursued where shade alone is insufficient to meet target stream temperatures.

The review begins with background on studies of riparian shade impacts on stream temperature and biotic health, in addition to outlining common terminology found in the literature. The review is then organized into sections reviewing the methods for measuring and modeling shade, followed by the future outlook for areas of further research. The best-suited methods for assessing both grassy and woody riparian shading are identified in addition to ancillary diagnostic data needed to explain variation in measured shade.

A.2. Background

Multiple sources testify to the benefits of forested buffers on stream temperature while also warning that deforestation causes stream temperature increases of 2 to 5°C (Herunter, Macdonald, & MacIsaac, 2003; Minshall, Robinson, & Lawrence, 1997). A diverging area in the literature is that there are compelling indications that grassy vegetation improves the health of coldwater streams in comparison to woody vegetation, although the mechanisms remain unclear (Hunt, 1979; Marshall, Fayram, Panuska, Baumann, & Hennessy, 2008).

The shade provided by grassy buffers is typically estimated or described in qualitative terms in the literature. For example, multiple studies qualitatively noted that grassy buffers provided less shade than forested buffers (Hunt, 1979; John Lyons, Thimble, & Paine, 2000; B. W. Sweeney, 1993). No research in the Upper Midwest has rigorously measured shade in streams with grassy vegetation, although some have estimated shade using models. Grassy riparian shade was estimated as an input to multiple models developed to simulate stream temperature but field measurements were not collected to calibrate and validate the estimated parameterization (Blann, Frost Nerbonne, & Vondracek, 2002; Boegh, Olsen, Conallin, & Holmes, 2009; DeWalle, 2010). Beyond the geographic area of this review, one study in Oregon measured canopy cover along a stream with riparian grasses, sedges, forbs, and sparse willow trees. These meadow sites were found to have cover between 9 and 35% (Kelley & Krueger, 2005).

Other site factors influence how much shade is provided by the same vegetative canopy. For example, Kelley and Krueger (2005) also found that streams with east-west orientation had greater shade than north-south oriented streams. The difference was likely due to the declination of the sun and the position of the vegetation. Stream azimuth is one of multiple site characteristics beyond vegetation type that may dictate stream shade. Throughout the review, studies are identified that that assessed the impacts of spatially and temporally variable physical characteristics, however these findings are typically limited to sites with woody vegetation. Overall, the quantifiable difference in shade due to plant morphology may be amplified or dampened by other characteristics but the extent of this influence on shade in grassy streams is unclear based on current literature.

A.2.1. Terminology: Canopy Cover, Canopy Closure, and Shade

Understanding the differences between canopy cover, canopy closure, and shade are essential when considering the literature regarding shade provided by different types of riparian vegetation.

Canopy cover and closure were included in this review because they are sometimes used as a surrogate or predictor of shade. There is inconsistency in use of the term *canopy cover* in the literature of forest management and ecological research. This review utilizes the forestry definition of *canopy cover* as the percent of forest area occupied by the vertical projection of tree crowns (Bonnor, 1967). An example of assessing canopy cover above a stream is illustrated in Figure 75(a). In comparison, ecological research uses the same term *canopy cover* to refer to the relative amount of sky hemisphere obscured above a given point, but this is more accurately referred to as *canopy closure* (Jennings, Brown, & Sheil, 1999). Canopy closure is the projection of a hemisphere onto a plane (Daubenmire, 1959) and is expressed as a percentage of non-visible sky within a certain zenith angle (Korhonen, Korhonen, Rautiainen, & Stenberg, 2006). An example of assessing canopy closure above a stream is illustrated in Figure 75(b). In the example shown, the full zenith angle of 180° is being assessed. Although the example is shown from a cross-sectional perspective, canopy closure may be assessed in all directions to look at the full hemisphere. In the illustrated examples, canopy closure is approximately 67% whereas canopy cover is approximately 70%. The difference between measurements varies based on the streamside vegetation and the zenith angle used in the canopy closure measurement. In addition, closure may or may not include topography in addition to vegetative canopy closure. Another parameter referenced in the literature is *openness*, which is simply one minus canopy closure. The terms canopy cover and closure are used distinctly hereafter to clearly describe the methods and findings of past studies.

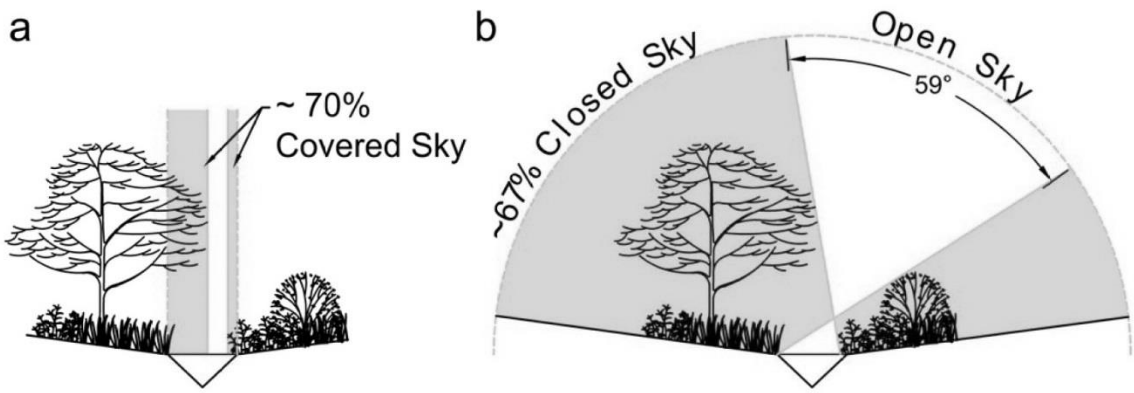

Figure 75. Canopy Cover (a) and Canopy Closure (b) Measured Across a Stream

Of these two somewhat analogous parameters, canopy closure is more common in ecologically oriented research because it is a measure of canopy architecture that can better assist in estimating the amount of solar radiation intercepted by the canopy than canopy cover. In comparison, canopy cover only indicates how much radiation would reach the ground when the sun is directly above a point on the ground. Both canopy cover and closure vary throughout the growing season due to changes in plant height and leaf area. Neither parameter has diurnal variation since they are independent from the position of the sun and the intensity of solar radiation.

In comparison, *stream shade* is the percentage of solar energy that is obscured or reflected by vegetation or topography above a stream (Dent et al., 2000). Unlike canopy cover and closure, stream shade varies throughout each day and season due to the position of the sun and intensity of solar radiation. The orientation of a stream modifies the effectiveness of streamside vegetation in blocking incoming solar radiation. For example, two trees on the east and west banks of a north-south channel (Figure 76(a)) will provide limited shade due to the angle of the sun. In comparison, the same vegetation on the south bank of an east-west channel would provide full shade while the north bank vegetation would provide minimal shade benefit (Figure 76(b)). Grassy vegetation in both instances would provide less shade unless the ratio of vegetation height to channel width was high enough for grasses to provide similar shade levels.

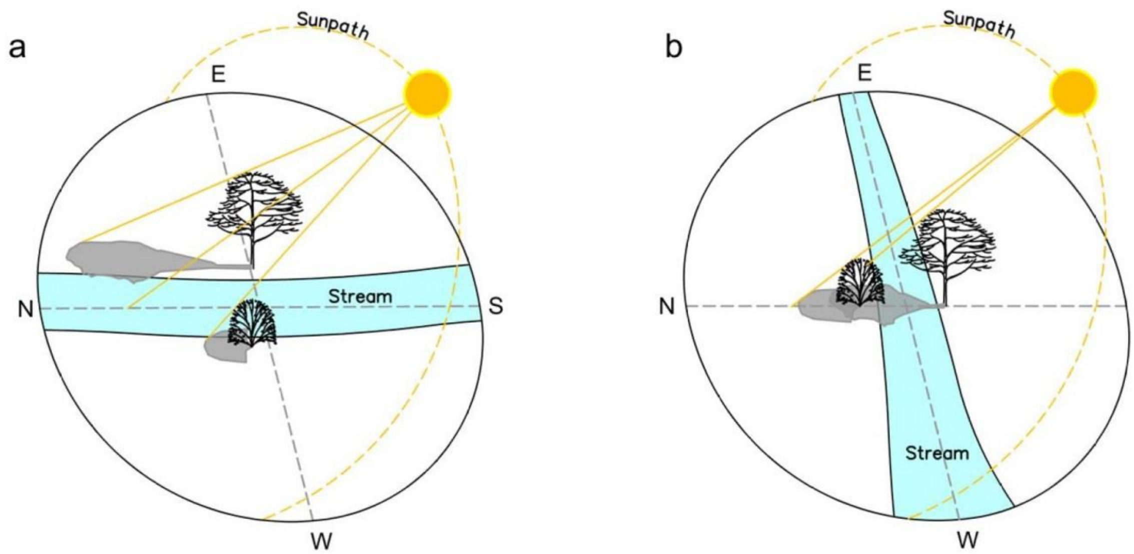

Figure 76. Midday Shading of Streams with North-South (a) and East-West (b) Orientations in Northern Hemisphere

A.3. Direct and Indirect Measurements

Indirect and direct measurements of shade are common in the literature, in addition to references to the two other parameters previously described (canopy cover and closure). The instruments and methods for directly and indirectly measuring canopy cover, canopy closure, and shade by air/space and ground are reviewed in this section. Their applicability for comparing shade provided by grassy and woody riparian vegetation is also assessed. This review did not include canopy growth models, such as the crown diameter regression (Bechtold, Mielke, & Zarnoch, 2002) or the somewhat related variables of leaf area index and biomass.

A.3.1. Air and Space-Borne Methods

Remote sensing was first linked to the fields of stream ecology and fluvial geomorphology in 2002 when technology improvements enabled identification of riverine systems at a hectametric or kilometric scale (Fausch, Torgersen, Baxter, & Li, 2002; Mertes, 2002). Since then, the resolution of data collected through this method has continued improving at a rapid pace. This section provides a brief introduction to remote sensing from satellite and aircraft and outlines the applicability and limitations of such methods in assessing canopy cover, canopy closure, and shade.

Remote sensing equipment includes both the platform (e.g. satellite, aircraft, or drone) and the sensor which collects the data. Data in the USA is typically collected from conventional or unmanned aircraft, not satellites, due to government regulations limiting satellite imagery resolution to 50 cm (Carbonneau & Piégay, 2012). The sensors are used to collect optical imagery, light detection and ranging (LiDAR) data which shows elevation, and other data, such as infrared.

The following four properties describe the resolution of a remote sensing data acquisition system:

- **Spatial resolution**: the ground footprint of a single image pixel or number of data points collected on a unit area basis, which defines the size of the smallest object which can be resolved on the ground;
- **Spectral resolution**: the range of radiation wavelengths and the width of individual band, which defines the ability to identify certain material, such as chlorophyll;
- **Temporal resolution**: the elapsed time between repeated imagery, which defines how well changes can be detected; and
- **Radiometric resolution** (also referred to as bit depth): the amount of information devoted to and stored with each pixel, which defines how fine differences in image brightness can be refined (Carbonneau & Piégay, 2012).

Remote sensing imagery is used for the study and management of riparian vegetation to map vegetation types, vegetation species, and historical changes, and to measure vegetation characteristics. For example, remotely sensed data can be used to assess morphological features, maximum stand age, and height of vegetation. Canopy density, canopy closure and shade can also be assessed using LiDAR data in combination with Geographic Information System (GIS) analysis methods. For example, a Light/Laser Penetration Index (LPI) can be determined by analysis of LiDAR data (Barilotti, Sepic, Abramo, Crosilla, & Growing, 2007) and in turn can be used to estimate openness (one minus canopy closure) although LPI results in high closure estimates in settings with low and dense vegetation in comparison to other methods of estimating closure (Bode, Limm, Power, & Finlay, 2014).

Several GIS analysis tools are available to simulate solar radiation above a canopy and the shadow cast by vegetation on a ground or river surface. These tools have been developed to assist in light-sensitive variables, such as plant growth, while they are also used for evaluating potential locations for solar energy generation. First, a digital surface model (DSM) raster of the canopy is derived from LiDAR (Greenberg, Hestir, Riano, Scheer, & Ustin, 2012; Hollaus, Wagner, Eberhöfer, & Karel, 2006) or photogrammetry (Lisein, Pierrot-Deseilligny, Bonnet, & Lejeune, 2013). Second, GIS-based solar radiation models are run to simulate the solar radiation reaching points or areas of interest, such as segments along the surface of a stream. Examples of these tools include the ArcMap solar radiation analysis tool and the GRASS GIS r.sun solar model. Each tool has various settings to modify aspects of the analysis such as the duration of the simulation or the frequency at which to calculate total solar radiation. The ArcMap tool conducts this analysis by determining if the stream is shaded for all sun angles over the course of a day and integrates the total solar radiation reaching each point over the analysis time period defined by the user. Both the ArcMap and GRASS models have limitations in that they cannot simulate solar radiation that penetrates through the canopy either by small gaps or by reflection off the vegetation. This limitation results in close to 100% shade estimates for cases where vegetation completely overhangs across the stream surface. This limitation was successfully accounted for using LPI in a study of a 17 m wide creek with both woody and grassy riparian vegetation through development and application of the Subcanopy Solar Radiation (SSR) model (Bode et al., 2014). While such tools can be applied at a regional or watershed scale using remotely sensed datasets, multiple studies recommended extensive empirical data to assess broad spatial variations (Julian, Stanley, & Doyle, 2008). LiDAR and other GIS datasets can also be useful in estimating the physical parameters of topography and riparian vegetation adjacent to the stream in order to upscale or extrapolate estimated shade at specific points using ground-based methods (Section A.3.3).

The spatial resolution of LiDAR data and the timing of data collection are other limitations to using GIS-based solar radiation models for shade estimates. Spatial resolution is an important consideration, especially for small reaches and vegetation structure where field measurements may be more appropriate (Coroi, Skeffington, Giller, Gormally, & O'Donovan, 2007). An object must be eight times larger than the pixel size to be detected by half of the pixels (i.e. 50% accuracy) or 16 times larger for 80% accuracy. When trying to capture vegetation, this means the resolution of imagery needs to be less than 1 m for large trees or less than 10 cm for shrubs, and even smaller for grasses (Carbonneau & Piégay, 2012). Users may begin to face computational power limitations when beginning to use high resolution LiDAR datasets. Publically available LiDAR in Minnesota is often collected after leaf-fall and so shade estimated using such LiDAR is typically underestimated (Herb & Correll, 2016). The cost of collecting LiDAR in the summer and with the detail necessary for assessing shade from grassy vegetation was estimated in 2017 to be approximately $13,500 for the study area of the BCWD Riparian Shading Study. Field and remote measurements of riparian characteristics (e.g. percent canopy cover, organic litter, canopy continuity, tree clearing, bank stability, and flood damage) were compared and found field measurements to be more cost effective at small scale between 1 to 200 km while remote image analysis was superior at large scale from 200 to 2000 km (Johansen, Phinn, Dixon, Douglas, & Lowry, 2007).

Overall, the benefits of remote sensing and GIS science advancements to riparian management include the capability of repeated, synoptic data collection and the measurement of numerous biophysical parameters. However, the objective and scale of the application must be considered to determine if field measurements are more cost-effective than remote sensing methods. Remote sensing technology could be used for other helpful information, such as mapping the location of specific types of vegetation; however, such analysis is not pursued further in this study. The applicability of remotely sensed data for assessing stream shade is expected to continue to change as the technology for collecting, processing, and analyzing the data continues to quickly improve and become more cost-effective.

A.3.2. Ground-Based Methods

There are indirect and direct ground-based methods for measuring shade. The only way to directly measure shade is to measure solar radiation above and below the canopy for the same monitoring period. Multiple instruments are available for indirectly estimating canopy cover, canopy closure, and shade from the ground, including the densiometer, the clinometer, the solar pathfinder, and hemispherical photography (Table 17). This section reviews indirect and direct methods organized by each type of equipment. Visual estimation was not included because of its low accuracy.

Clinometer

A clinometer is commonly used by foresters to estimate the height of trees or the grade of a slope. As illustrated in Figure 77, a clinometer can also be used to measure the angle from the horizon (dashed line) to the open sky above topographic formations or riparian vegetation. From these measurements, users can calculate the percentage of a 180° arc that is blocked by vegetation or topography. Some users collect four measurements - facing upstream, downstream, the right bank, and the left bank – and then average these measurements to estimate percent canopy surrounding the point in the stream. For the purpose of this review, measurements using a clinometer are described as 'canopy closure', however some sources refer to it as providing estimates of shade (Dent et al., 2000). The clinometer measurements can also be used to estimate canopy cover directly above the stream.

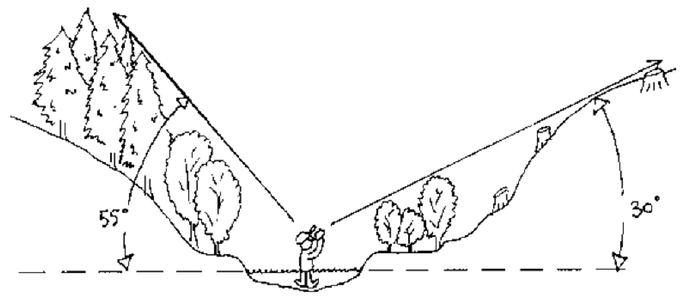

Figure 77. Clinometer Used to Estimate Topographic (30°) and Vegetative Cover (55°) Angles (Dent et al., 2000)

Overall, the clinometer is a relatively quick and inexpensive approach to estimating canopy closure and cover, although it does not account for gaps within canopies. In a comparative study of shade and cover/closure methods, canopy cover was found to be underestimated by the clinometer at sites with patchy riparian forest due to limitations of measurements in four directions at each point and overestimated at sites with closed canopy because it did not account for openings within the canopy (Kelley & Krueger, 2005).

Densiometer

As shown in Figure 78, the densiometer is a small convex spherical mirror that reflects the canopy above the ground or a stream when the densiometer is held level. Canopy cover is estimated by counting the number of grid intersections engraved onto the mirror that are covered by vegetation. Due to the limited view angle, observations using the densiometer are most clearly described as 'canopy cover', however a wider view angle could be used to better estimate canopy closure. Canopy cover estimated using a densiometer was found to have a significant relationship with cover estimated using hemispherical photographs of the same sites, although densiometer measurements were consistently lower than those using hemispherical photographs likely due to the limited view angle of the densiometer (Kelley & Krueger, 2005; Ringold, Van Sickle, Rasar, & Schacher, 2003).

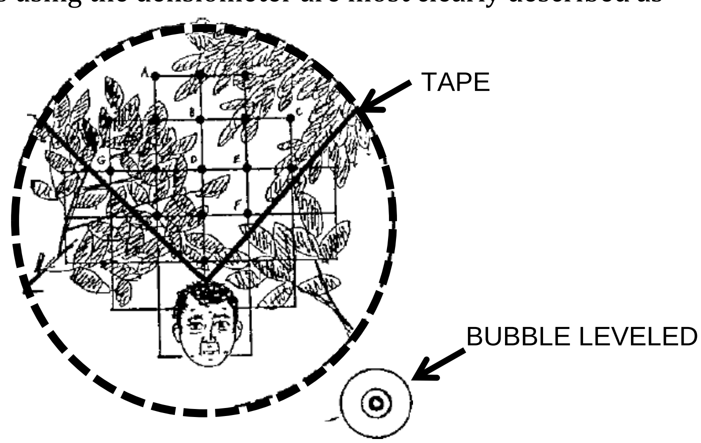

Figure 78. Modified Densiometer (Dent et al., 2000)

Table 17. Ground-Based Methods for Indirectly Measuring Cover, Closure and Shade

Method	Canopy Cover	Canopy Closure	Stream Shade	Type of Veg. Cover Estimated	Sample Size [1]	Accuracy	Difficulty	Speed of measurement	Durability	Data Processing	Special Operating Conditions	Equipment Cost
Visual estimate [3]	☒	☐	☐	F	Large	Low	Simple	Quick	High	Low	None.	$0
Clinometer [1, 2]	☒	☒	☐	F	Medium	Unknown	Simple	Quick	High	Low	Internal moisture can obscure reading & foul moving parts if dropped in stream. [2]	$200
Densiometer [1, 2, 3]	☒	☒	☐	F	Large	Quite accurate	Simple	Quick	High	Low	Difficult to keep hand-held device level. [2]	$100
Solar pathfinder [2]	☐	☐	☒	F, M	Unknown	Unknown	Simple	Quite Quick	Medium	High	Prone to user error. Operating equipment in center of rapidly stream can be challenging. [2]	$300
Hemispherical photography [1.2, 3]	☒	☒	☒	F, M, G	Small	High	Simple	Quite Slow	Delicate	High	Different lighting conditions can cause problems. [2] Cloudy conditions provide best contrast.	$5000 to $9500

Notes: F = Forest, M = Mixed, G = Grass

[1] (Kelley & Krueger, 2005)

[2] (Dent et al., 2000)

[3] (Paletto & Tosi, 2009), including GRS and spherical densiometers

Protocols for indirect methods are available from other sources such as the Oregon Water Quality Monitoring Technical Guidebook (Dent et al., 2000).

Canopy cover or closure measurements using the densiometer or clinometer are sometimes used as a surrogate or index of shade using relationships between the two measurements; however, the variability (R^2 = 0.62 to 0.72) may be unacceptable in some studies and is likely due to vegetation and channel characteristics (Dent et al., 2000). One study used all three methods: a clinometer, densiometer, and hemispherical photographs at the same locations to estimate canopy cover, in addition to shade estimated using the hemispherical photographs. The study compared the canopy cover to shade at the same locations. The results indicated that shade is more likely to be proportional to cover at sites with east-west orientated streams because the sun is directly over the stream when energy inputs are low at the beginning and end of the day. Shade is less likely to be proportional to cover at sites with north-south orientation because the least shade will be provided when the sun is directly overhead in the middle of the day (when energy inputs are highest). In the northern hemisphere, this means that vegetation on the south bank of east-west oriented reaches provides more shade than the north bank, and north-south oriented reaches are more constantly exposed to radiation through the southern facing opening of the riparian canopy. Research requiring an understanding of shade, and not cover or closure, should employ methods suited to directly or indirectly measuring shade (Kelley & Krueger, 2005). As such, indirect estimates of shade based on cover or closure measured using a clinometer or densiometer are inappropriate for assessing grassy and forested shade.

Solar Pathfinder

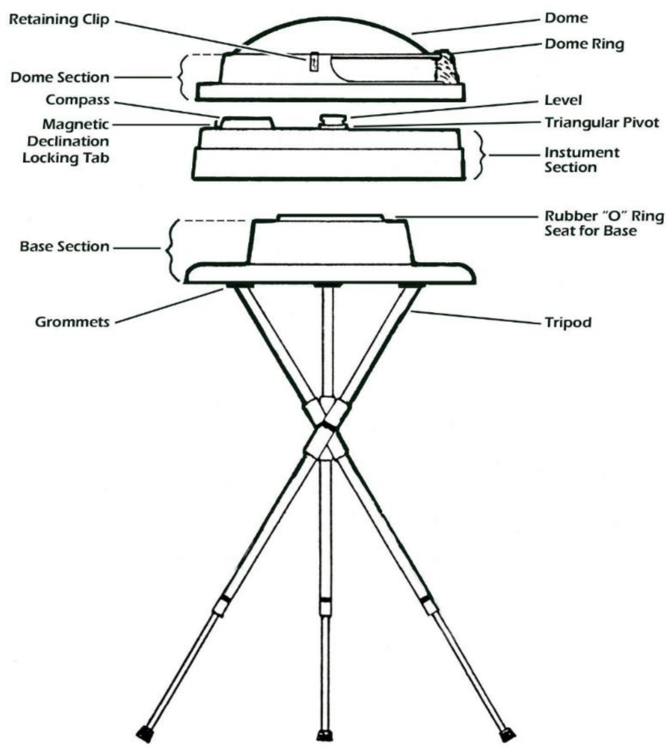

Figure 79. Solar Pathfinder (SolarPathinder, 2016)

Shade can be interpreted from a single, instantaneous field photograph collected using the Solar Pathfinder. The Solar Pathfinder is an apparatus that was developed for application in urban settings to evaluate tree shade in potential sites for solar panels. To use the pathfinder, the apparatus is set up on a rooftop or other point of interest using the tripod illustrated in Figure 79. A solar pathway chart is located on the hemisphere at the top of the apparatus. Users are meant to take a photograph of the solar pathway chart at the top of the apparatus to record the reading (i.e. shadow cast by surrounding vegetation or buildings) at each site. This method is less precise than hemispherical photographs (Dent et al., 2000).

Hemispherical Photography

Overall, hemispherical photography provides the most reliable estimates of shade for the full range of canopy structure and the imagery collects the maximum amount of information, although it is more expensive and fragile than the other instruments (Davies-Colley & Payne, 1998). Hemispherical photographs can be used to estimate canopy cover using a 30° viewing angle in addition to canopy closure using a viewing angle greater than 60° (Paletto & Tosi, 2009). The quality of hemispherical images relies on the resolution of the image captured by the camera (i.e. the number of pixels) and calibration of the fisheye lens to the camera. In addition, the software used to assess canopy structure from the photographs may affect the results, which is discussed later in this section. One study also reviewed the sample size required to attain reliable measurements. In the open meadow site, the hemispherical photo method was the only practical method since it required the smallest sample size. This was because the hemispherical photograph method provided the most repeatable and accurate measurements of all instruments (Kelley & Krueger, 2005).

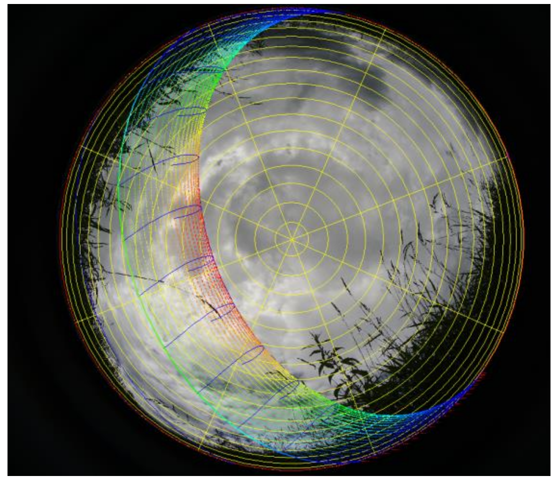

Figure 80. Hemispherical Photo with Sun Path

Hemispherical photographs are processed using software such as WinSCANOPY, HemiView, and Gap Light Analyzer (GLA) to simulate solar radiation above and below the canopy, and estimate shade provided by topography and riparian vegetation (Jarčuška, Kucbel, & Jaloviar, 2010; Regent Instruments Inc., 2015; Rich, Wood, Vieglais, Burek, & Webb, 1999). GLA is a freeware option and use of it requires additional software, such as Sidelook, to pre-process hemispherical photographs to differentiate between canopy and sky. The other options, such as WinSCANOPY and HemiView, are sold in packages with the necessary equipment to collect hemispherical photographs and include technical support for use of the software. From a review of the available information on the three options, WinSCANOPY was found to be best-suited for use in assessing both grassy and forested vegetation because of the higher resolution camera, the provision of a calibrated fisheye lens, and advanced features in the software beyond HemiView, such as multiple methods of assessing the same parameters. Jarčuška, Kucbel, and Jaloviar (2010) found that use of GLA and Sidelook provided different results than WinSCANOPY, indicating that consistent hardware and software are required for repeatable results. As such, results from past studies using hemispherical photograph analysis may not be comparable to future analyses if different hemispherical photography hardware, software, and settings of each are used. Even when using the same equipment and software there are modifications which may significantly impact the results, such as the exposure settings when collecting the photograph, the procedure for classifying sky and canopy regions in the photograph, and the analysis settings in the software. The analysis is particularly sensitive to overexposed photographs (Glatthorn & Beckschäfer, 2014). The temporal variability in riparian shade estimated using GLA has been reduced by confining analyses to summer and baseflow conditions (Julian et al., 2008). Hemispherical photographs have also been used to assess the sensitivity of shade to the orientation of a stream by rotating the images to different azimuths in GLA (Julian et al., 2008). Recent advancements in the application of machine learning will likely assist in streamlining the classification of sky and canopy regions of imagery (Bour, El Merabet, Ruichek, Messoussi, & Benmiloud, 2017), which would be particularly helpful in processing a large number of photographs. One of the remaining limitations to estimating shade by analyzing hemispherical photographs is that radiation reflected off of leaves through the canopy to the stream surface is not represented in the analysis (Regent Instruments Inc., 2015).

Hemispherical photography is preferred over the solar pathfinder due to the difference in precision. Although the hemispherical photograph method is more expensive because of initial equipment and software costs, it does afford a proportionately higher degree of accuracy and repeatability. This reduces the need for replicating measurements to enhance precision. In addition, the hemispherical photograph method is applicable for comparing the influence of grasses, shrubs, and trees on light penetration (Dent et al., 2000). Overall, hemispherical photography was the best suited technique for assessing the structure of plant canopies and estimation of solar radiation (Paletto & Tosi, 2009), the latter of which is reviewed further in the next section.

Pyranometer or Other Light Sensor

The only way to directly measure shade is to measure solar radiation using individual sensors or arrays of sensors above and below the canopy for the same monitoring period. Total or global solar radiation can be measured using a solar radiometer, such as the pyranometer and pyrheliometer. Other sensors quantify radiation as heat or as photosynthetically active radiation (PAR). Alternative sensors, such as light meters, were not reviewed in detail due to their limited spectral range. With any sensor, radiation varies spatially and temporally due to the position of the sun, atmospheric conditions, topography, and vegetation structure. Measurements below the canopy also have a high level of variability at the microsite scale. The uncertainties can be accounted for by increasing the number of sensors in an array or aggregating results over time (Link, Marks, & Hardy, 2004). While arrays of solar and thermal radiometers have been successfully deployed to measure radiation reaching the ground below a tree canopy (Link et al., 2004), no studies were found which deployed an array on a stream surface.

Using sensors to directly measure shade at the stream surface over a long period of time may pose practical and financial challenges. For example, potential damage to the sensors would need to be mitigated by the method of installation and/or uninstallation / reinstallation to avoid damage during storms. Depending on the scale of the study, installing multiple sensor arrays at points of interest along the stream may be cost-prohibitive. In addition, the sensitivity of the sensor to spatially variable cloud cover or other atmospheric conditions would necessitate collection of the "above canopy" measurements close and simultaneous to the "below canopy" measurements. Due to these limitations, direct measurements of solar radiation may be better suited to parameterizing and validating the results of solar radiation models, in addition to assessing how shade changes seasonally and spatially due to establishment of tree foliage (Archibold & Ripley, 2004).

With any of the ground-based methods of assessing shade, there is also the remaining question of how scalable the results are beyond the monitoring locations or beyond the study area/watershed. Results of indirect and direct measurements of solar radiation and shade at a given point along a river with a mix of forested and unforested riparian buffers have been upscaled or extrapolated to the entire watershed using a raster of the river with information regarding adjacent vegetation, river width, channel orientation, and canopy cover calculated using land cover rasters and empirical relationships between physical characteristics and shade (Julian et al., 2008).

A.3.3. Ancillary Data

Riparian vegetation and channel characteristics are important to monitor in stream shade analyses because they can assist in diagnosing the reasons for variability in stream shade and, in doing so, can assist in predicting shade in un-monitored areas. As noted throughout the review, site characteristics such as stream azimuth can amplify or dampen the shade provided by vegetation. Other ancillary data should be collected in order to consider these factors when analyzing the results of directly or indirectly measured shade. This additional data is also important in that it will help researchers compare the results in different study areas. A review of methods for measuring each parameter is beyond the scope of this review but is specified by the OWEB Watershed Assessment Manual (Dent et al., 2000). The following vegetation and channel characteristics may account for variability in stream shade:

- *Buffer width*: Distance from stream's edge to the outer edge of riparian vegetation.
- *Buffer height*: Estimate average height of riparian stand each side of the stream.
- *Dominant overstory species*: Document the dominant tree species of tree in the stand.
- *Dominant shrub species*: Document the most common and shade-influencing shrub.
- *Species composition*: Document the percentage of conifer, hardwood, mixed tree, shrub, and grassland.
- *Diameter distributions and basal area*: Measure diameter of trees within a given survey plot at 4.5 feet above the ground. Use the diameters to calculate basal area.
- *Stand health*: when measuring diameter, document tree health (dead, diseased, or dying).
- *Activities within the riparian area:* Document factors influencing plant species such as beavers, grazing, mechanical disturbance, fire, restoration, or recreational activities.
- *Classification of valley type, valley width and constraint ratio*: Such as Rosgen Classification.
- *Bankfull width*: Width of the channel at the average annual high water mark.
- *Gradient*: Slope of the channel.
- *Sinuosity*: Ratio of the valley slope to the channel slope.
- *Wetted width*: Using a tape measure the width of the wetted surface, subtracting mid-channel point bars and islands that are above the bankfull depth.
- *Thalweg depth*: Measure the deepest part of the channel with surveyor's rod or tape.
- *Substrate*: Estimate the percent of channel bed composed of each size class of material
- *Stream azimuth*: Measured with a compass by orienting yourself downstream and with the direction of the valley (not a meander).
- *Topographic shade angle*: Using a clinometer measure the angle to the highest topographic source of shade (ridge top, terrace) orienting yourself in four directions (upstream, left, right and downstream).

It is assumed that other factors at a study location scale, such as climate and watershed characteristics, would also be included in the background of the study.

A.4. Modeling (Theoretical Relationships)

In the midst of the development and advancement of stream temperature models since the 1980s, multiple algorithms have also been developed to estimate shade based on physical characteristics. This section provides some background on these algorithms but the reader is directed to original source material for detailed methodologies.

There is some overlap between this and previous sections in the simulation of solar radiation. Some of the indirect methods of measuring shade include simulation of solar radiation, such as in the GIS tools used to assess LiDAR-derived canopy surfaces and the software used to process hemispherical photographs. The algorithms described below both simulate the position of the sun, the intensity of solar radiation, and the shadow cast by topography and riparian vegetation.

One of the first algorithms to assess shade across a stream surface (Quigley, 1981) was applied and modified for the Stream Network Temperature (SNTEMP) model. The SNTEMP model represented shade across the stream surface as a function of characteristics defined on both the left and right banks of the stream, including topographic shade (which determines the local time of sunrise and sunset), height of vegetation, crown measurement, vegetation offset, and vegetation density (Theurer et al., 1984).

Another program named SHADE was later developed to dynamically calculate riparian shade at a watershed scale using (at that point) novel remotely sensed data and GIS technologies (Chen, Carsel, McCutcheon, & Nutter, 1998). The model was built to be used in stream temperature models in the Hydrologic Simulation Program-FORTRAN (HSPF). The SHADE algorithm was also adapted with some modifications into the stream temperature model CE-QUAL-W2 (Annear, Berger, & Wells, 2001).

Both of the above efforts to model shade across the stream surface used the density of the canopy to represent the transmission of direct solar radiation through vegetation to the stream surface. Another method was later developed to estimate the radiation extinction coefficient using a path-length form of Beer's law instead of the vegetation density input (DeWalle, 2010). DeWalle (2010) applied this updated model in assessing the impact of changing buffer characteristics on shade in multiple scenarios. The results indicated that vegetation on the south bank of east-west streams provided 70% of total daily shade (i.e. south bank vegetation provides more shade than vegetation on the north bank). In addition, the results indicated that for small streams up to 6 m wide, only the first 12 m of buffer width is needed to provide shade for stream temperature control as long as the vegetation is tall (~30 m) and has a dense leaf area index (~6). Vegetation beyond a 12 m buffer width provides minimal benefits in terms of stream shade (DeWalle, 2010). The results suggested that shade could be optimized by maintaining a buffer height to stream width ratio of at least 5, although the model was limited in in that it ignored the effects of overhanging vegetation. DeWalle (2010) also provided the following generalized equation for estimating an optimum buffer width for an east-west stream:

$$buffer\ width\ for\ E-W\ stream = \frac{buffer\ height}{\tan(max.\ solar\ altitude)} - \frac{stream\ width}{2}$$

The works of DeWalle (2010), Chen et al. (1998), and Davies-Colley and Rutherford (2005) were later modified to create SHADE2 (Li, Jackson, & Kraseski, 2012). Li et al. (2012) also conducted a sensitivity analysis to assess the effects of varying vegetation buffer characteristics on stream shade. Both sensitivity analyses by Li et al. (2012) and DeWalle (2010) are helpful in developing guidelines for improved buffer design. In addition, the complexity of shade response to multiple physical characteristics of the stream and vegetation helps illustrate why understanding these dynamics from field observations seems so challenging.

All of the above models calculate instantaneous shade at defined time intervals throughout a single day, which is then integrated to calculate total daily shade. The shade input used in many stream temperature models is average shade over multiple days. However, no studies were found that assessed the extent to which shade varies throughout the growing season either through model analysis or field measurements. Representing heterogeneous vegetation at a single location (i.e. a mixture of grassy and woody vegetation) seems to be a limitation of most models. SHADE appears to be the only model that can assess heterogeneous vegetation characteristics along the length of the stream, whereas all other models require average or idealized (i.e. straight channel) characteristics. Actual shade along a meandering stream was found to be bounded by modeled shade for an idealized straight channel and a circular pool (Davies-Colley & Rutherford, 2005). None of the model algorithms have represented the effect of riparian vegetation on diffuse solar and long-wave radiation. The effect of riparian vegetation on diffuse radiation has previously been identified as small and negligible (DeWalle, 2008). An overall gap in the literature for modeling stream shade is a lack of analysis in very small streams (~1 to 3 m wide) and grassy buffer vegetation. In addition, none of the models consider vegetation growth as a factor causing temporal variability in shade.

A.5. Outlook for Further Areas of Research

Much of the literature provides detailed analysis of the benefits of forested buffers in terms of stream temperature and other stream management objectives. In contrast, two of the reviewed studies found coldwater fish habitat improved in sites with grassy riparian vegetation in comparison to sites with woody vegetation. However, the reasons behind this correlation are unclear. Grassy canopy is clearly less extensive than woody canopy coverage but the extent to which other site characteristics amplify or dampen the effectiveness of each canopy in shading a stream shade is unclear, especially for grassy riparian buffers.

The literature does not present a clear understanding of how much shade is provided by grassy vegetation – especially for small streams – whereas multiple studies have reported on canopy cover, closure, and shade in woody areas. Since shade is a key mechanism by which riparian vegetation controls stream temperature, this gap severely limits a quantified approach to planning and implementing riparian management for the purpose of protecting coldwater streams and fisheries. Further research into the relationship between canopy cover, canopy closure, and shade should instead focus on standardizing best practices in directly measuring shade or interpreting shade from hemispherical photographs. In addition, clear terminology for instantaneous, total daily and average seasonal shade should be applied in future studies to assist transfer of findings to other research and application. Using consistent approaches in the field will also assist in understanding the influence of physical stream and vegetation characteristics on shade. Another helpful area for future research is assessing the temporal variability of shade in terms of the position of the sun and growth of vegetation. This would assist other researchers in collecting field observations within a timeframe that can reasonably be used as representing typical vegetation conditions during peak thermal stress.

Heterogeneous stream channel and vegetation characteristics result in significant variability in stream shade observed in the field, making it challenging for designers and decision makers to have clear take-aways for best practices in optimizing buffers for stream temperature control. Stream shade models are especially useful in understanding the effect of each characteristic on stream shade. However, multiple improvements to stream shade models could improve their usefulness even further, such as the following capabilities:

- Variable canopy structure at multiple setbacks from a single point in the stream
- Vegetation growth over the period of analysis
- Provide the typical range of vegetation parameters for common riparian species
- Aggregate results for an entire stream segment
- Output instantaneous, daily, monthly, and seasonal shade results
- Graphical and accessible user interface for designers and decision makers
- Effect of riparian vegetation on diffuse solar and long wave radiation

Understanding the amount of shade provided by grassy and woody riparian vegetation in the Upper Midwest would better inform stream temperature model parameters, stream restoration design, and riparian management decisions. Quantitative comparison of the two will also assess if shade is a mechanism correlating grassy buffers with IBI improvements. Comparing the two vegetation types does not imply that one may be better in all cases. Instead, the comparison informs an understanding of where forested and grassy buffers are best suited to meet watershed management objectives, such as stream temperature control.

Future studies assessing the physical characteristics of monitoring sites in addition to estimating shade will address the current gap of understanding how much shade is provided by grassy vegetation in comparison to woody buffers and will expand our understanding of what other factors affect stream shade. Understanding stream shade in this way is critical to managing and protecting coldwater ecosystems. Such studies will enable the development of energy budgets for coldwater stream TMDLs and will inform a targeted approach to riparian management to restore stream shade where it is needed most. Even further, understanding the limits of restoring stream shade necessary for identifying when and where other stream temperature mitigation measures, such as augmenting groundwater contributions to a stream, are needed to support viable coldwater fisheries.

A.6. Conclusions

Hemispherical photography is the best-suited method for comparing shade provided along small streams by grassy vegetation to woody vegetation in future studies. Direct measurements of shade using arrays of pyranometers or other light sensors are useful in validating indirect measurements of shade from hemispherical photography. Canopy cover and closure are not acceptable surrogate measurements for shade because they do not vary based on the position of the sun in the sky. Canopy cover only assesses how much of the sky is blocked by canopy directly above a point, whereas canopy closure assesses how much of the sky is blocked in the hemisphere above the same point.

In addition to shade, ancillary data are needed to assess which stream and vegetation characteristics impact shade the most. The following site characteristics should be monitored to diagnose why shade varies between monitoring points and assess which variables can be used to predict shade:

Channel Characteristics:

- Classification of valley type, valley width and constraint ratio
- Bankfull width
- Gradient
- Sinuosity
- Wetted width
- Thalweg depth
- Substrate
- Stream azimuth
- Topographic shade angle

Riparian Vegetation:

- Buffer width
- Buffer height
- Dominant overstory species
- Dominant shrub species
- Species composition
- Diameter distributions and basal area
- Stand health
- Canopy cover
- Activities within the riparian area

APPENDIX B. TRADE-OFFS OF GRASSY AND WOODY RIPARIAN VEGETATION

The nationwide encouragement of forested buffers was originally intended as a best management practice to mitigate the effects of logging near stream systems, such as impacts on hydrology, water quality, and biodiversity ("Federal Water Pollution Control Act," 1972; Lantz, 1971). Application of this practice of restoring a state (i.e. forested land cover) rather than a function (e.g. biotic health in streams) in prairie streams of the North-Central America has unclear justification. The body of literature was reviewed to seek out the most recent information regarding the comparative benefits of grassy and woody riparian buffers with respect to their environmental functions such as sediment control, phosphorus control, increasing dissolved oxygen, supporting aquatic fauna, and maintaining groundwater inputs to the creek. All of these functions are relevant to the watershed management objectives and priorities of the BCWD. This review was used to develop well-informed riparian management decisions primarily focused on stream temperature management, but with a full view of the potential trade-offs with other watershed management objectives.

The purpose of this review was to summarize the relevant literature on the comparative benefits of grassy and woody riparian vegetation types found in the study area. Four distinct types of existing riparian vegetation are found in the study area and are referred to hereafter as woody, shrubby, grassy, and manicured (Figure 81). The literature generally refers to shrubby vegetation as a subtype of woody vegetation. Throughout the study area, there is variation in age, buffer width, and combinations of these vegetation types although manicured conditions are rare. There was only one location with manicured conditions in the study area where riprap and ornamental plants are maintained along the stream's edge and buffered upland by mowed turf grass. The literature review did not cover the benefits or impacts of such conditions because they are generally understood to be contrary to the watershed management objectives of the BCWD.

Woody and grassy vegetation have a range of possible definitions in the literature. Few studies provide detailed information on specific vegetation characteristics. For example, forestry management studies typically compare forested to unforested or deforested conditions when assessing the impacts of clear cut harvesting. Such studies do not discern if the deforested conditions are bare-earth or herbaceous cover. This review uses the following definitions of Lyons, Thimble, and Paine (2000):

> "Woody vegetation includes both shrubs and trees, but they must occur at a density that provides at least 75 percent canopy closure at a height of more than 2 m for the riparian zone to be considered wooded. Based on this definition, wooded riparian zones will shade most of the stream bank and channel during summer months. Grassy vegetation encompasses grass, forb, and herbaceous species that do not exceed 2 m in height. Grassy vegetation must cover more than 75 percent of the ground in dense growths with no more than a few widely scattered trees or shrubs present for the riparian zone to be considered grassy." (p. 920)

Grassy riparian zones consist of unmanaged (i.e., prairie, meadow) vegetation while manicured riparian zones consist of managed landscapes (i.e., lawn, pasture, riprap).

Figure 81. Existing Riparian Vegetation Types in Study Area: (1) Woody, (2) Shrubby, (3) Grassy, (4) Manicured

The comparative benefits of grassy and woody riparian vegetation are summarized in Table 18. The left column in Table 18 outlines the environmental, social, and financial benefits of riparian vegetation. The benefits are described as objectives to more clearly indicate the type of change that would address the stressors in Brown's Creek and priorities in the BCWD. In addition, some of the benefits can be influenced by multiple mechanisms introduced by riparian vegetation (e.g. filtering surface runoff while also improving water quality by nutrient uptake) and these mechanisms are defined as well. This list of benefits is not intended to be a comprehensive list of all benefits of riparian vegetation to stream ecosystems but instead outlines the factors most relevant to the BCWD. Each vegetation type is classified as providing no, some, or full benefits to small coldwater streams as indicated by the symbols in the right columns.

Some benefits of riparian buffers were not reviewed due to time constraints, lack of literature, or lack of relevancy to the study area. For topics not covered herein, readers are directed to Lyons et al. (2000) which provides a comprehensive review of the comparative environmental benefits of grassy and woody riparian vegetation along small streams in North-Central America, including bank stability, channel morphology, erosion, terrestrial runoff, subsurface inputs, hydrology, organic matter, primary production, macroinvertebrates, cover, water temperature, and fish.

Table 18. Comparative Benefits of Woody and Grassy Riparian Vegetation for Small Coldwater Streams

Benefit	Woody	Grassy
Support aquatic fauna (fish and macroinvertebrates)	◔	◕
Reduce suspended sediment in the stream by:		
(1) Stabilizing stream bank (channel morphology)	◔	◕
(2) Stabilizing upland areas	◑	◑
(3) Filtering sediment from runoff before it reaches stream	●	●
Improve microclimate conditions as a means to reduce stream temperature	◔	●
Raise or maintain groundwater levels in order to increase or sustain groundwater contributions to the stream.	○	○
Improve carbon cycling and dissolved oxygen levels.	◑	◑
Reduce phosphorus in the stream by:		
(1) Controlling TSS (see above)	◔	◕
(2) Filtering dissolved phosphorus from runoff	◑	●
(3) Nutrient uptake in hyporheic zone	◔	●
Adapt to climate change	n/a	n/a
Maintain vegetated buffer (i.e. maintenance requirements)	◑	◑
Landowner willingness	n/a	n/a

○ no benefits are provided under any condition

◔ ◑ ◕ partial benefits are provided (to varying extents of 25, 50, and 75%), sometimes under different conditions

● full benefits are provided under all conditions

n/a – unclear differentiation of benefits in literature

Beyond the environmental benefits of buffers are social and financial benefits, although few were included in this review. The social benefits of riparian buffers include the following, although it is unclear if grassy or woody vegetation provide greater benefits:

- Aesthetic benefits, which are typically evaluated with surveys of people using or living adjacent to the stream.
- Recreational benefits, such as supporting fishing, swimming, canoeing, walking, picnicking, and bird watching in or near the riparian buffer. Such benefits can partially be assessed by the number of people using the recreational opportunities, or benefitting from the riparian buffer.
- Quality of life is an overarching, cumulative improvement from the many benefits of riparian buffers impacting community and land owners, such as aesthetics, property values, and tax revenues.
- Noise mitigation.
- Crime and safety on trails adjacent to riparian buffer.
- Educational opportunities (e.g. Home Owner Association volunteers).

The following financial costs and benefits of riparian buffers are more appropriate to assess when reviewing specific restoration opportunities while others (e.g. DNR fish stocking) are beyond the scope of this study:

- Capital cost.
- Operations and maintenance costs.
- Monitoring of performance.
- Longevity of infrastructure.
- Land acquisition, landowner compensation, and landowner negotiations, which could include considering conflicts with adjacent land use, such as golf courses.
- DNR fish stocking.
- Avoiding regulatory fines, such as TMDL related fines through the St. Croix phosphorus TMDL.
- Avoided dredging cost in Wolf Marina, although the source of sediments has not been assessed and confirmed.
- Property value.
- Funding sources.
- Income from hunting and harvesting.

B.1. Aquatic Fauna

Aquatic fauna in coldwater stream systems are supported by the physical structures of their habitat and by water quality, both of which are influenced by riparian vegetation.

Coldwater fish require several key habitat features to feed, hide, and spawn. First, salmonids need clean gravel large enough so that it is not moved by high flows and small enough for spawning females to excavate their nests. Second, fish require a variety of feeding and hiding areas, including deep pools and riffles for adults in addition to shallow and slow flowing areas for juveniles. Third, they need cover to protect themselves from predation near the feeding and spawning areas, such as roots, overhanging banks, overhanging vegetation, debris accumulation, and pore spaces within the streambed. Fourth, juveniles require low velocity refugia in side channels and off-channel features in the floodplain during high flows in the main channel (Cramer, 2012).

As outlined in the next section regarding the impact of riparian vegetation on channel morphology, it seems that grassy vegetation may be better suited to providing the physical habitat ideal for coldwater fish although some woody debris would provide good diversity in the habitat structure. Large woody debris provides excellent cover for fish (J Lyons, Thimble, & Paine, 2000), however the excessive erosion, sedimentation, and flattening of the channel cross section typically observed in forested channels would neglect the substrate, diverse depths, and overhanging banks that are ideal for salmonid habitat. Shrubs are not a good alternative for fish habitat since they do not provide much woody debris, do not have much root mass, and provide minimal cover (J Lyons, Thimble, et al., 2000). In comparison, the overhanging and undercut banks found in grassy reaches are very supportive of salmonids. The potential for emergent vegetation to become established in shallow areas of streams in order to provide cover and stabilizing functions was not assessed in this literature review.

In addition to habitat structure, fish are also supported by water quality. Certain temperatures, pH, oxygen, and turbidity levels are necessary to support the biological integrity of a stream system, including macroinvertebrates and in turn higher trophic levels (i.e. economically important fish). As such, understanding the processes changing these parameters is essential to protecting fish habitat. The processes include water cycling, sediment transport, nutrient cycling, and environmental thermodynamics. There are multiple ways in which these processes interact. For example, the amount of water entering a stream from groundwater and tributaries via the water cycle influences the stream temperature via environmental thermodynamics. In turn, stream temperature affects the physical, chemical, and biological components of aquatic systems (Table 19) with impacts beyond the biotic health of fish. For example, water temperature affects rates of nutrient cycling and the solubility of oxygen, both of which are tied to other water quality issues such as algal blooms. Ultimately, stream temperatures must be maintained within a specified range to support the health of macroinvertebrates and fish. For example, brown trout (*Salmo trutta*) begin to experience increased physiological stress, reduced growth, and egg mortality when water temperature exceeds 18.3°C. Direct mortality is expected at the critical stream temperature of 23.9°C (Mccullough, 1999).

Table 19. Attributes of Aquatic Ecosystems Affected by Temperature (Sappington & Norton, 2010)

Category	Attributes
Physical	Water density, thermal stratification, solubility of oxygen & other chemicals
Chemical	Rates of nutrient cycling, contaminant transformation rates
Biological	Organism survival, growth, reproduction, development, behavior, habitat preference, competition

Overall, multiple sources testify to the benefits of forested buffers on stream temperature and warn that deforestation causes stream temperature increases of 2 to 5°C (Herunter et al., 2003; Minshall et al., 1997). Measured canopy cover in streams with forested buffers varies from 50 to 88% (Kelley & Krueger, 2005). There is agreement in literature that forested buffers provide more shade than grassy buffers, although the latter has typically been assessed by qualitative analysis. Sweeney and Newbold (2014) identified a range of forested buffer widths needed to protect stream temperatures in different settings. Their findings illustrated that multiple factors influence the relationship of stream temperature and vegetation beyond plant morphology, such as channel width, length of exposed channel, topography, azimuth, latitude, and longitude. Forested buffers also provide other benefits, such as sediment control, to varying extents based on buffer width (Bernard W. Sweeney & Newbold, 2014). There is divergence in the literature regarding the relation of these other benefits to stream temperature and biotic health.

There are compelling indications that grassy vegetation improves the health of coldwater streams in comparison to woody vegetation, although the mechanisms remain unclear. Experiments conducted by the Wisconsin Department of Natural Resources found increased trout biomass in reaches where woody streambank vegetation had been removed in strip cuts. Stream temperature and solar radiation reaching the stream also increased at these sites but these impacts seemed to be overcome by other factors in order to improve biotic health. For example, trout habitat was correlated with mean summer stream flow which increased at these sites (Hunt, 1979). More recently, another study found that grassy vegetation and management practices improved the fish community structure (i.e.

IBI[7] scores) in coldwater streams in rural southwestern Wisconsin in comparison to sites with forested buffers. The improved IBI scores were found in areas with intensive implementation of conservation practices since the 1970s, such as planting riparian grass cover, as well as in areas where the wooded canopy was degraded (Marshall et al., 2008). Possible causality or mechanisms behind the correlation of grassy buffers with improved IBI were not assessed in the same study, but other studies have identified the benefits of grassy buffers in comparison to forested buffers.

In addition to coldwater fish, riparian vegetation also effects aquatic macroinvertebrates. For example, the contribution of woody debris into the stream supports shredders such as stoneflies and caddisflies. In comparison, grassy vegetation support more collectors and grazers than in woody reaches. Overall, grassy vegetation supports more invertebrates per unit area than woody vegetation (J Lyons, Thimble, et al., 2000), although justification for this difference remains unclear.

B.2. Erosion, Sediment, and Channel Morphology

Suspended sediment is one of the stressors influencing the biotic impairments in Brown's Creek. Sediment in the stream is relevant to sustaining the health of coldwater streams because coldwater fish cannot reproduce where fine sediment has settled onto the streambed, sediment suspended in the water column impairs gill function, and suspended sediment can also raise water temperatures. Erosion and sedimentation of a stream also changes the channel's shape and pathway, which can degrade or enhance aquatic habitat for coldwater biota. This section summarizes the relation of riparian vegetation on sediment based on its ability to (1) change the shape of the channel, (2) stabilize upland riparian buffers, and (3) filter sediment from runoff before it reaches the stream.

B.2.1. Channel Morphology

The literature consistently identifies the effects of grassy and woody vegetation on the channel shape. Numerous studies found that channels are significantly wider when they have forested buffers in comparison to narrow channels with grassy buffers (Davies-Colley, 1997; Hession, Pizzuto, Johnson, & Horwitz, 2003; Jackson, Leigh, Scarbrough, & Chamblee, 2015; McBride, Hession, & Rizzo, 2008; B. W. Sweeney, 1992; B W Sweeney et al., 2004; Trimble, 1997; Zimmerman, Goodlett, & Comer, 1967). Channel widening may be due to weak bank armoring when understory vegetation is suppressed by tree canopy (Blann et al., 2002; Davies-Colley, 1997; Stott, 1997), woody debris destabilizes/scours the channel (J Lyons, Thimble, et al., 2000), and there are highly turbulent flows over forested buffers (McBride, Hession, Rizzo, & Thompson, 2007). Urbanized watersheds tend to have wider channels than undeveloped watersheds, however channel widening due to forested buffers is independent of urbanization (Hession et al., 2003). A narrow forested buffer (~1 to 3 m wide) was also found to widen the channel, although to a lesser extent than very wide forested buffers (Jackson et al., 2015).

[7] Indices of biotic integrity (IBI) are frameworks for evaluating the health of biota in cold and warm water stream systems. IBI frameworks and protocols are defined by the U.S. EPA and state agencies, with specific metrics for cold and warmwater systems as well as for fish and macroinvertebrates (Chirhart, 2014). Poor IBI scores indicate that natural systems are polluted or degraded to the point where fish and macroinvertebrates are no longer supported. As such, results of IBI analyses are indicators of overall stream health. However, once a stream is identified as being impaired, additional study and assessment is needed to identify the biological, physical, or chemical reasons for degradation.

In addition to changing the width to depth ratio, riparian vegetation has been found to change the profile of the stream. Down cutting (i.e. downward erosion through the streambed) has been observed in rivers where wooded buffers have replaced historically prairie or savanna landscapes in the bluffland tributaries to the Mississippi River (Nerbonne & Vondracek, 2001; Sovell, Vondracek, Frost, & Mumford, 2000; Trimble, 1993, 1997). Woody streams tend to have fewer pools, more sediment, and more variation in dimensions and water velocity than grassy streams (J Lyons, Thimble, et al., 2000). One study diverged from this trend in analyzing the diversity of habitat in wadeable streams in Tennessee using the Shannon-Wiener method and found that grassy streams had less diverse habitat than forested streams, including higher proportions of run and glide habitat (Jackson et al., 2015). Streams with forested buffers have also been found to have steeper longitudinal slope than streams with grassy buffers (Jackson et al., 2015) while another study found no difference in channel slope based on riparian vegetation (Hession et al., 2003).

In comparison to woody vegetation, successional buffers (grasses and forbs) allow for dense vegetative cover, less bank erosion, stable banks, and narrower, deeper channels than woodland buffers (Beschta & Platts, 1986; Murgatroyd & Ternan, 1983; Nerbonne & Vondracek, 2001; Peterson, 1993; Sovell et al., 2000; Zimmerman et al., 1967). For example, intensive rotational grazing and grassy buffers led to less fine substrate in the stream channel as compared to continuous grazing of woody buffers in southwestern Wisconsin trout streams (J Lyons, Weigel, Paine, & Undersander, 2000). Another study of a stream in Wisconsin estimated that grassy reaches could trap and store approximately 2,100 to 8,800 m^3 of sediment per stream kilometer more than forested reaches (Trimble, 1997). Stream narrowing may be related to grassy vegetation having very dense fine root mass in top 30 cm of the streambank which helps to accumulate sediments in the inside bend over time (Jackson et al., 2015).

One diverging area of research is whether the impacts of forested buffers on channel erosion and geometry are a benefit or detriment to stream temperature and biotic health. Sweeney et al. (2004) refer to wider channels as being beneficial to the ecosystem because the larger streambed offers a larger ecosystem per unit length, which is supported by earlier research on improved macroinvertebrate health in forested stream settings (B. W. Sweeney, 1993). However, channel widening both increases the surface area subject to solar radiation and results in a shallow stream which minimizes the chance for cool refugia for biota. The deep and narrow shape identified in grassy stream systems reduces the stream surface exposed to radiation and provides cool refugia for biota at the bottom of the channel due to vertical stratification of stream temperature. The natural succession of the channel form and riparian vegetation in Wisconsin streams is illustrated in Figure 82 and Figure 83. The recommended management strategy for supporting trout and other wildlife is to implement controls that maintain stages D, E, and F (White & Brynildson, 1967).

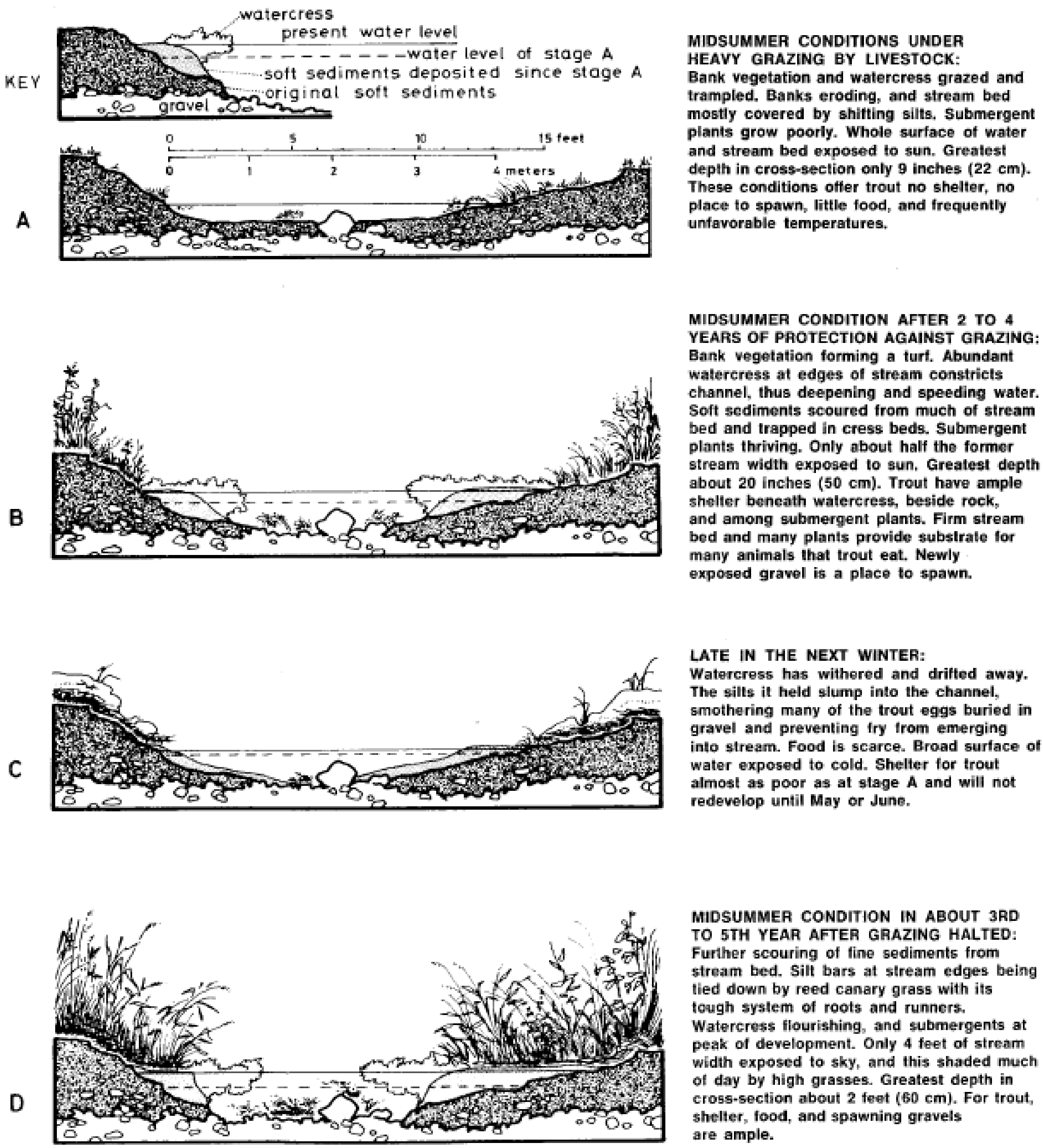

Figure 82. Early Stages in the Natural Development of a Fertile Lowland Wisconsin Trout Stream from Overgrazed (a) to Very Productive (D) (White & Brynildson, 1967)

Continued on next page

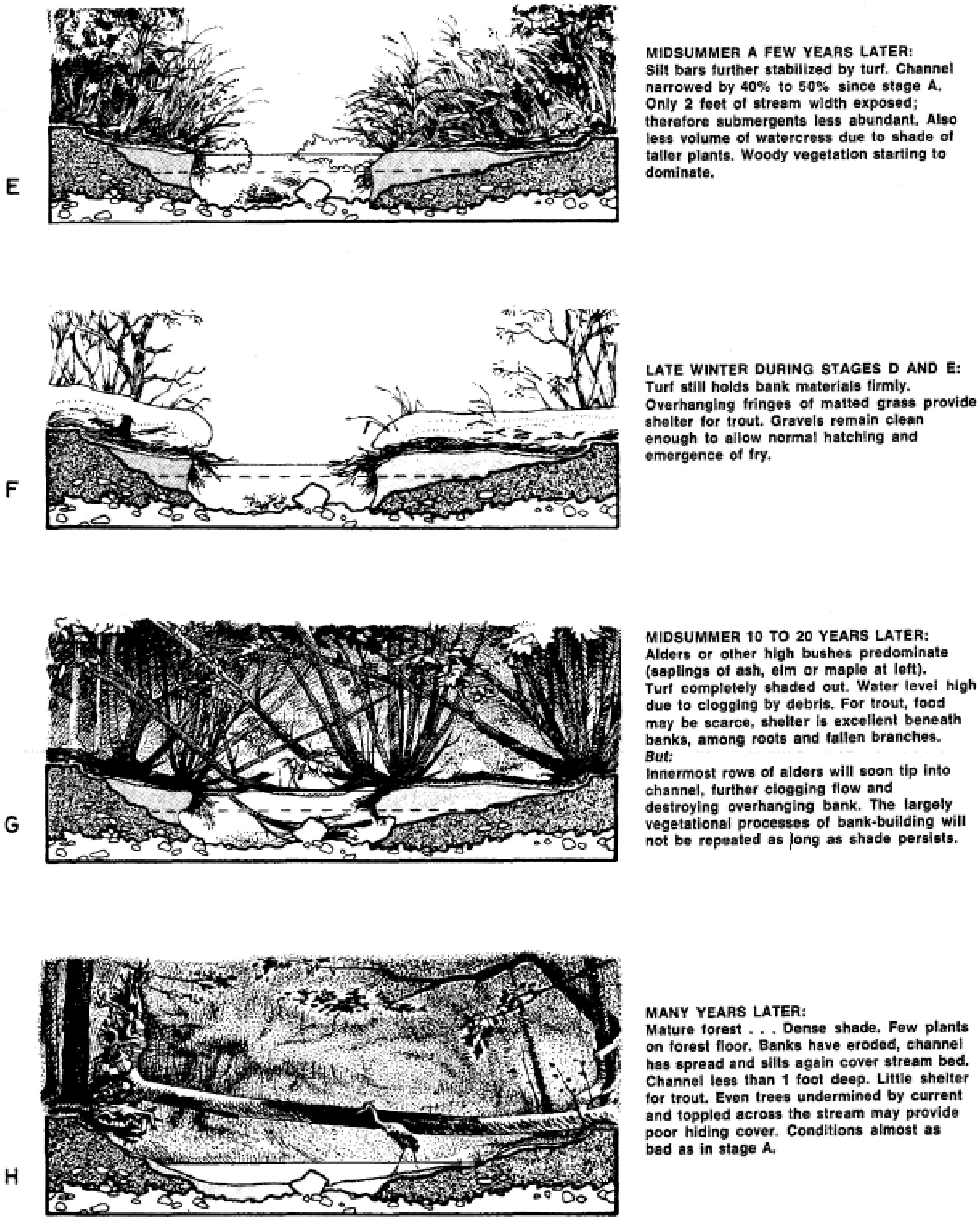

Figure 83. Late Stages in the Natural Development of a Fertile Lowland Wisconsin Trout Stream from Very Productive (E-F) to Overforested (G&H) (White & Brynildson, 1967)

Blann et al. (2002) developed stream temperature models of small coldwater streams (6 to 8 m wide) in southeastern Minnesota and found that mean and maximum stream temperatures were more sensitive to the width to depth ratio than percent shading. The daily mean temperatures increased by 0.3 to 0.48°C when the width to depth ratio increased from 15 to 30. In contrast, daily mean temperatures fluctuated by 0.18 to 0.28°C when the width to depth ratio was held constant. Narrow streams with grassy and woody buffers had nearly identical efficacy of mediating temperatures. For example, a narrow segment with a grassy buffer (36% shade) mediated temperature as well as a similar segment with a woody buffer (68% shade). These findings indicated that shading became more important to control stream temperature as the width to depth ratio increased (i.e. shading was needed more when the stream widened). In addition, grassy riparian vegetation on stream segments with a width less than 2.5 m were able to provide 50% shade, which was similar to the shade provided by woody vegetation (Blann et al., 2002). These findings clarify that the amount of shade provided by grassy and forested vegetation may be sufficient for channels that have stabilized in the width to depth ratio typical of that riparian vegetation. Further research on the correlation of riparian vegetation and health of aquatic fauna are reviewed in Section B.1.

The width to depth ratio of a channel is relevant to coldwater biotic health due to its implications for stratification of water temperatures through the water column, the impact of suspended sediment on fish gill function, the fate of sediment along the stream changing suitable substrate for fish habitat.

Other factors, such as changes to flow regime and sediment load in a watercourse, also have a significant impact on channel morphology but are not within the scope of this review.

B.2.2. Erosion Control in Riparian Buffer Zones

Upland of the immediate channel banks, woody vegetation is better than grassy vegetation at stabilizing high banks (i.e. greater than 1 m above the water surface) and very steep slopes (i.e. greater than 1:1 or 100% slopes). Bank stability can be further enhanced by mechanical stabilization methods, such as installation of large rip-rap at the toe of the slope. Grassy vegetation may be more appropriate woody vegetation to stabilize areas with low banks and flat slopes (J Lyons, Thimble, et al., 2000).

B.2.3. Filtering Sediment from Runoff

Filtering sediment from runoff before it reaches a stream is critical to prevent impacts on water quality in the receiving water body. Filtering out sediment is also necessary to protect groundwater dependent natural resources, such as Brown’s Creek, and adjacent groundwater dependent wetlands because fine sediments captured by riparian vegetation can clog soils in the riparian buffer and reduce the amount of groundwater recharge occurring in the buffer zone (Boulton, Findlay, Marmonier, Stanley, & Valett, 1998b).

The effectiveness of riparian buffers in treating pollutants in runoff varies based on buffer width (Bernard W. Sweeney & Newbold, 2014). The recommended buffer width to achieve a specific function, such as sediment removal, was previously reviewed for the BCWD in the Statement of Need and Reasonableness (SONAR) as a basis for the District’s rules for development activity. The SONAR identifies the recommended buffer widths in Table 20 for sediment control based on the slope of the ground and sensitivity of the receiving water body.

Table 20. Minimum Buffer Width Based on Topography and Sensitivity of Resource (Emmons & Olivier Resources, 2001, 2007a)

Special Feature	Recommended Minimum Width (feet)
Shallow slopes (<5%) or low quality wetland	50
Steep slopes (5-15%) and/or sensitive wetland	100
Slopes over 15%	Consider buffer width additions

Areas with woody vegetation have slightly better infiltration capabilities than grassy areas, although in the end the sediment trapping capabilities for runoff are roughly similar. Site specific conditions dictate the efficiency of woody and grassy filter strips (John Lyons et al., 2000).

B.3. Microclimate

Microclimate is a combination of multiple parameters, such as the wind speed, relative humidity, and air temperature, immediately above the stream surface. Shifts in microclimate due to variation in riparian vegetation can significantly change the energy budget of a stream and ultimately influence stream temperature. For example, latent heat in grassy reaches was found to be 60 to 87% less than forested reaches (Garner, Malcolm, Sadler, Millar, & Hannah, 2015). A detailed energy-balance study of a grassy and forested reaches of a pristine, sub-arctic stream found that over two years of detailed climate monitoring, both latent heat and sensible heat were sinks (losses) for stream temperature during the summer in both forested and grassy reaches, however the average magnitude of both sinks was greater in the grassy reach. Latent heat (evaporation) was an energy loss in both reaches and was greater in grassy than forested conditions likely due to lower humidity and higher wind speed above the water surface where it was bounded by grassy vegetation. Sensible heat was also an energy loss in the summer for both reaches and was greater for grassy than forested likely due to higher wind speed causing more turbulence in the air above the water surface (Hannah, Malcom, Soulsby, & Youngson, 2008). Overall, the literature indicates that the microclimate above grassy streams has a greater potential to cool the temperature of the stream in the summer than it does in woody streams. However, the applicability of these findings to Brown's Creek is unclear since the studies were conducted in a sub-arctic climate.

B.4. Groundwater and Baseflow

Significance

Brown's Creek is a groundwater dependent natural resource and the creek's baseflow is sustained by groundwater discharging into the stream. We are interested in understanding how changing riparian vegetation could change groundwater levels near the stream and ultimately change baseflow. Maintaining or increasing baseflow is one method of cooling stream temperatures and is considered beneficial to trout habitat.

Other factors impacting groundwater and baseflow include land development and groundwater pumping. Groundwater recharge in urbanizing areas is largely impacted by the construction of impervious surfaces, which disconnect surface water-groundwater interactions. The BCWD has implemented retrofit projects and rules for development activity to reverse and prevent such disconnection. Pumping reduces the amount of groundwater available in the water balance to recharge the creek and can ultimately reduce baseflows as well. The Brown's Creek Thermal Study (2016) assessed the potential stream temperature improvements from lowering groundwater demands.

Review

The literature assessing the impact of vegetation on groundwater levels and baseflow are framed as the impacts of establishing woody vegetation (afforestation), removing woody vegetation (deforestation or harvest), allowing woody vegetation to re-establish after harvest (regeneration) and conversion of one dominant woody species to another.

Afforestation results in multiple changes to the water budget that reduce groundwater recharge and ultimately lead to lowering of the local water table. As trees establish, the changes to the water budget include increased interception, increased evapotranspiration, and increased water-holding capacity in the unsaturated zone of the soil profile. A review of studies in Ireland and Northern Europe found that afforestation increases the fraction of rainfall that is intercepted by the canopy and then evaporates before it reaches the ground. Coniferous forests tend to intercept and evaporate more rainfall than deciduous forests due to the higher roughness coefficient of coniferous foliage. In addition, trees have a greater demand for groundwater than grasses which results in greater transpiration. Highly organic forest litter has a high capacity for holding water. A higher potential infiltration rate through soils in forested areas than in grassy areas is counteracted by the greater demand for water by the trees and by capillary action. Capillary action moves groundwater higher into the unsaturated zone of the soil profile to address the soil moisture deficit in soils below forests. The soil moisture deficit below forests is typically greater than below grasses. All of these modifications to the water budget decrease the amount of rainfall that recharges groundwater in forested areas which generally results in reduced surface runoff, erosion, streamflow, and groundwater recharge near the stream during flood events (Allen & Chapman, 2001). Another review of studies in small streams of North-Central America identified the same trend that wooded floodplains have lower local water tables than grassy floodplains due to the higher water demand of woody vegetation. As such, forested riparian buffers are more likely to reduce baseflow than grassy buffers of a stream (J Lyons, Thimble, et al., 2000).

Paired watershed studies monitor at least two watersheds – a control and a treatment watershed – over two periods (calibration and treatment) to assess the impacts of the treatment(s) on the water balance and biogeochemical processes. The calibration period accounts for differences between the watersheds, although they should be selected for similar size, geology, climate, and other factors. Seasonal climate variations over the entire study are accounted for by monitoring the control watershed. In forestry studies, experimental forests typical undergo various stages of forestry (i.e. harvest/deforestation, afforestation, regrowth, and forest conversion) with various treatments (i.e. grazing or herbicide application to prevent regrowth) and are compared to an undisturbed control watershed. These studies often refer to volume of water discharged to the downstream water body as *water yield*. A synthesis of these experimental forest studies supports the previously discussed trends in that forest harvesting (i.e. deforestation) decreases interception, decreases evapotranspiration, increases groundwater recharge, and raises the groundwater table. The resulting impact on groundwater discharge to the receiving surface water body depends on the distance of the harvest to the waterbody and the geology. In general, if the groundwater discharges to the surface water body faster than groundwater recharges, then the harvest will not impact water yield or streamflow. Overall, forest harvesting typically increases groundwater fluxes to surface water bodies, including an increase in dry-season baseflow. These trends are subject to local variation in climate, vegetation, soils, and geology. In addition, harvesting is only expected to have a demonstrable effect on water yield if more than 20% of a watershed is harvested. In addition, soil compaction during harvesting can reduce infiltration to the point where baseflows do not increase after harvesting. While the general hydrologic response to harvesting is clear, specific predictions of impacts at a site cannot be made precisely unless the site has been intensively studied (Levia, Carlyle-Moses, & Tanaka, 2011).

Groundwater levels and streamflows respond within days to forest harvest (deforestation) while they take years to respond to afforestation. The latter is likely due to the time needed to reach equilibrium in the water cycle with the new water use by the trees (Brown, Zhang, McMahon, Western, & Vertessy, 2005). The immediate impact of clearcutting a forest on the flow regime in the receiving watercourse was tested in the Hubbard Brook Experimental Forest. The results indicated that more days throughout the year had a baseflow at the clear-felled site than the forested site, where the watercourse appears to become intermittent during the growing season. This experiment and another strip-cutting experiment were monitored for over twenty years, at which point a the number of days with baseflow receded as the trees regenerated (Hornbeck, Martin, & Eagar, 1997).

The above cited reviews acknowledged that their findings generalize the impacts of forestry on groundwater recharge and discharge in relation to streamflow. The ability to develop a clear, direct linkage from literature for broad application is limited by the lack of long term field experiments extending from pre-forestry, harvest, regrowth, and repeated harvest. Allen and Chapman (2001) noted that site specific trends can only be assessed with a detailed understanding of the interrelationships between variables such as “land cover, rainfall, infiltration, evapotranspiration, the spatial distribution of water-table and piezometric altitudes, and the anisotropic nature of the surface water/groundwater circulation system” (p.394). Two-dimensional modeling is recommended to understand the hyporheic zone at specific locations in a watershed (Boulton, Findlay, Marmonier, Stanley, & Valett, 1998a). Modeling of small stream systems in southeastern Minnesota suggested that woody buffers increased lateral groundwater flow and decreased stream temperatures in comparison to grazed and grassy buffers (Blann et al., 2002).

Take-Aways

Although the broad-scale trend that forest harvest increases groundwater levels and baseflow is consistent in the literature, it remains unclear how applicable this trend would be to riparian vegetation management in Brown’s Creek due to its unique characteristics and the small scale of riparian management activities relative to the size of the watershed. The literature suggests that changing less than 20% of the vegetation in a watershed will not have a significant impact on groundwater levels and baseflow. As the District considers riparian management alternatives, the impacts on the local groundwater table should not be a concern if only small changes are made to the vegetation composition. It is recommended that any sites with large-scale changes be monitored before and after the activities take place to assess impacts on groundwater levels and baseflow.

Additional modeling, such as a 2D groundwater-surface water model, may provide further insight into how vegetation could impact baseflow in Brown's Creek.

B.5. Organic Carbon and Primary Production

Carbon contributions to streams from plant debris are necessary to support aquatic microorganisms and macroinvertebrates and the sources of the material largely dictate the type of assemblages. Woody riparian buffers contribute more woody debris to streams than grassy riparian buffers (Jackson et al., 2015) and typically support shredders and detrivores. However, as noted in Section B.1, grassy buffers support more invertebrates (typically collectors and grazers) per unit area than woody vegetation (J Lyons, Thimble, et al., 2000).

The light transmitted through the riparian canopy to the water surface is the primary energy source for aquatic ecosystems. Woody riparian buffers can become too dense and provide so much shade that it becomes the limiting factor for photosynthesis and primary production in the stream ecosystem (J Lyons, Thimble, et al., 2000). Too much primary production can occur in systems with high nutrient loads and can have detrimental impacts on stream ecosystems, such as eutrophication and depletion of dissolved oxygen.

B.6. Phosphorus

Phosphorus control is relevant to the BCWD because Brown's Creek is a tributary to the Lake St. Croix which has a TMDL for phosphorus. Soils and duff layer qualities are important in determining efficacy of forested buffers in treating surface runoff. In general, forested buffers are very good at infiltrating, slowing down and modifying runoff. Woodlands are better at assimilating nitrogen except when nitrogen-fixing shrubs are present. Grassy buffers are also effective at infiltrating runoff and trapping sediment at a rate similar to woodlands. Grassy buffers are generally more effective at assimilating phosphorus than woodland buffers (J Lyons, Thimble, et al., 2000).

B.7. Climate Change Adaptation

While climate change mitigation benefits will help reduce greenhouse gas emissions, climate change adaptation is also necessary to estimate and plan for climate change impacts that can no longer be avoided. In a coldwater stream such as Brown's Creek, climate change is expected to change precipitations patterns which may impact flow regime in the creek, air temperatures, stream temperature, and the health of vegetative communities. Adaptation strategies can be further categorized as those that *resist* the impacts of climate change, those that *facilitate* changes, and those that encourage *resilience* to change.

The USGS and Wisconsin DNR have conducted multiple studies on the projected impacts of climate change on streams and lakes across the upper Midwestern United States. Most recently, they found that streams have a more variable warming rate than lakes which indicates that environmental factors such as hydrology and land-use may be more influential in enabling or mitigating the impacts of climate change on stream systems than lakes (Read, 2016). Models of 50 fish species were developed for 393 sites across Wisconsin, 69 of which included brown trout, in order to assess the impacts of climate change on each species. The total length of stream supporting brown trout was projected to decrease under the limited, moderate, and major warming scenarios by 7.9, 33.1, and 88.2%, respectively (J. Lyons, Stewart, & Mitro, 2010). Multiple simplifications limit the detail of such models and interrelationships in assessing the stream ecosystems. For example, the impact of rising air temperatures on stream temperatures is expected to vary based on factors such as groundwater, streamflow, and riparian vegetation characteristics (Wehrly, Brenden, & Wang, 2009). Adaptation strategies outlined in the Coldwater Fish and Fisheries Working Group Report prepared by the Wisconsin Initiative on Climate Change Impacts include a combination of watershed management, riparian management, water management, and stream restoration strategies. They also recommend using stream temperature models to evaluate if the loss of coldwater fisheries is inevitable. As it relates to this review, their recommendations regarding riparian management are to consider the trade-offs and locally conducted research on grassy and woody alternatives so that:

> "Management of appropriate riparian vegetation can be used to promote stream bank and channel stability, to reduce erosion and siltation in streams, to protect streams from damage attributable to high flow events, and to provide shading during summer to maintain the lower temperatures of groundwater input over longer lengths of coldwater streams." (Mitro, Lyons, & Sharma, 2010)

Climate change is also expected to impact terrestrial vegetation and natural habitats. Biodiversity is already threatened by the non-climate stressors of habitat fragmentation, habitat loss, invasive species, and pollution. While climate change effects could be *resisted* by intensively managing those non-climate stressors, *facilitation* and *resilience* strategies should also be considered during scenario planning for ecological assessments conducted as part of projects such as designing a stream restoration with riparian plantings. Regions with current climates analogous to the projected future of Minnesota in 50 years have been estimated as those located approximately 500 km SSW. The most significant ecosystem impacts anticipated for oak savannas include:

- "Increased tree mortality from drought, pests, and disturbances;
- Influx of exotic submersed aquatics in lakes;
- Shorter hydroperiods in wetlands, and
- Expansion of weedy grassland species" (Galatowitsch, Frelich, & Phillips-Mao, 2009).

The key adaptation strategies in this setting are to:

- "Manage forests for reduced water stress;
- Use fire to reduce dominance by weedy grassland species; and
- Monitor changes in community composition to detect species' declines" (Galatowitsch et al., 2009).

Overall, this review of climate change adaptation strategies broadly indicates that the BCWD is implementing appropriate strategies to mitigate the impacts of climate change on Brown's Creek however there are additional strategies the District could implement to assist vegetation in adapting to climate change. Projections indicate that there may be increased tree mortality from drought, pests, and disturbances, meaning that particular attention to assisting tree species in the watershed is needed to maintain canopy cover and shade. Additional studies and more rigorous literature review would help assess the specific range of impacts climate change may have to the water and energy balance of the creek, in addition to the potential subsequent impacts on vegetation.

B.8. Maintenance

When left undisturbed, riparian vegetation will follow a typical pathway of succession from grassy to woody vegetation. As such, disturbances such as grazing or burning would be necessary to maintain a grassy buffer with dominant herbaceous vegetation (J Lyons, Thimble, et al., 2000). In comparison, maintenance of forested buffers in the BCWD is also proving to be a challenge with need for bank stabilization projects and management of invasive species such as buckthorn, honeysuckle, and oriental bittersweet. An important consideration for any seeding or planting to enhance vegetative communities is considering the growth and survival rates of both grassy and woody vegetation in order to mitigate such losses where possible through increased number of plantings or procedures to follow in the early years of establishing the new plant communities.

B.9. Landowner Willingness

Improvements to riparian vegetation along some segments of Brown's Creek will depend on the willingness of landowners to partner with the BCWD on implementation activities. One study from the Chesapeake Bay area surveyed both urban and agricultural landowners (both residential) in urbanizing watersheds. The study participants were 80% male, 73% college educated, and of an average age of 62. The study findings include the following:

- Owners of large rural properties rank themselves more knowledgeable on buffers compared to owners of small rural properties.
- Urban residents had less exposure to buffer information compared to rural residents.
- Urban residents also rank their stream reaches as having higher water quality compared to rankings by rural residents.
- Urban residents are 94% less likely than rural residents to be willing to implement buffers.
- Outcome expectations associated with riparian buffer implementation were also a positive predictor ($p = 0.032$), meaning that as respondents more strongly believed that a buffer next to their stream would make various improvements, they were more willing to implement a buffer.
- A greater proportion of neighborhood friendships increased implementation willingness ($p = 0.044$). Land use type, parcel size, and stream length were not associated with increased buffer implementation willingness
- Gaining support of urban residents for buffer implementation may require modifying buffer implementation – i.e. more types, sizes, shapes to fit the urban aesthetic and also focus more on increased appearances and decreased maintenance efforts.
- This will likely require education and outreach on what urban buffers are, what types of programs they may qualify for, and information focused on expectations and tangible outcomes (e.g. better drinking water, nature for kids to play) with a particular emphasis on local examples.

- Peer pressure also appears to be a real thing where neighborhoods are tight knit. Residents follow the lead of their neighbors with respect to both existing norms and the potential for change. Residents are more likely to implement buffer if a close friend does it.
- Landowner expectation seems to be the one identified mechanism to change attitudes toward buffers.
- Transitioning landscapes may not have definitive norms for lawn behavior and as such there may be areas more easily swayed to implement buffers. (Armstrong & Stedman, 2012)

These findings indicate that landowner outreach, education, and neighborhood-wide action strategies may assist in gaining the support of landowners in implanting buffer improvements. Specifically understanding the aesthetic preferences of landowners in the study area with respect to riparian buffers would require surveys and outreach.

B.10. Conclusions and Management Implications

Riparian vegetation is relevant to multiple components of stream ecosystems. Overall, the most relevant trade-offs related to establishing forested buffers on Brown's Creek are the potential detrimental impacts on channel morphology and trout habitat, in addition to several benefits of having some woody vegetation near the stream. The practical implications for these trade-offs is that both grassy and woody riparian vegetation provide benefits to coldwater stream systems and riparian management strategies should use a balanced, mosaic approach with a variety of vegetation types. This means that multiple benefits could arise from thinning out over-forested buffers while others could result from targeted tree plantings in open meadows. For this Riparian Shading Study, a widespread tree-planting approach to increase shade would likely result in several detrimental impacts such as increased erosion of the streambanks. The Riparian Shading Study should assess and propose measures to increase shade while mitigating the potential detrimental impacts of changes to the riparian buffers. In addition, the following take-aways are particularly relevant to this study:

- Minor changes to riparian vegetation are not expected to impact local groundwater table levels.
- Additional strategies may be needed to assist vegetation in adapting to climate change, particularly trees.
- Additional analysis of climate change impacts on the water and energy balances of Brown's Creek would assist in making decisions related to climate change adaptation.
- Additional maintenance activity, such as grazing or burning, may be needed to maintain a mix of grassy and woody riparian vegetation and prevent over-forestation.

Riparian buffers provide many other benefits that were not covered in this review. Riparian buffers provide habitat for terrestrial wildlife, such as pollinators, and are a critical corridor in which terrestrial invasive species need to be controlled to sustain healthy biodiversity. Riparian buffers also provide climate change mitigation benefits unique to urbanizing areas by mitigating heat island effect and sequestering carbon and filtering air pollutants. One area that warrants further literature review and study are the trade-offs for each vegetation type related to beaver habitat and activity in an urbanizing watershed. These potential trade-offs are particularly relevant since beaver activity can directly raise stream temperature in reservoirs behind dams and/or could decrease downstream as a result of enhanced groundwater recharge below the reservoirs. Beaver activity also has broader impacts and benefits to urban areas and riparian ecosystems beyond stream temperature that need to be considered together.

Table 21. Transect Locations and Channel Characteristics

Date	Reach	Transect	Station (1) (m)	Latitude	Longitude	Purpose	Wetted Width (m)	Thalweg Depth (m)	Width to Depth Ratio (-)	General Azimuth (2) (°)	Rosgen Classification	Bankfull Width (m)	Gradient (-)	Sinuosity (-)	Substrate
7/3/2017	3	1	6524	45.077780	-92.860500	Transect	2.477	0.459	5.4	38	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/3/2017	3	2	6516	45.077720	-92.860500	Transect	2.089	0.454	4.6	72	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/3/2017	3	3	6502	45.077710	-92.860300	Transect	3.537	0.756	4.7	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/3/2017	3	4	6487	45.077650	-92.860400	Transect	2.858	0.912	3.1	-25	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/3/2017	3	5	6477	45.077570	-92.860400	Transect	2.604	0.622	4.2	40	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/3/2017	3	6	6465	45.077470	-92.860400	Transect	2.248	0.640	3.5	-16	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/4/2017	3	7	6457	45.077450	-92.860500	Transect	2.832	0.457	6.2	31	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/4/2017	3	8	6436	45.077380	-92.860400	Transect	2.261	0.531	4.3	-55	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/4/2017	3	9	6426	45.077420	-92.860300	Transect	2.769	0.500	5.5	-69	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/4/2017	3	10	6413	45.077350	-92.860200	Transect	2.457	0.592	4.2	-57	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/4/2017	3	11	6402	45.077270	-92.860300	Transect	2.381	0.576	4.1	49	E4/5	2.438	0.0048	1.29	Gravel/Sand
7/13/2017	7	1	2872	45.072850	-92.833400	Transect	2.864	0.470	6.1	38	C4c	4.877	0.004	1.10	Very Fine Gravel
7/13/2017	7	2	2859	45.072950	-92.833400	Transect	2.692	0.713	3.8	-22	C4c	4.877	0.004	1.10	Very Fine Gravel
7/13/2017	7	3	2848	45.073060	-92.833400	Transect	2.870	0.585	4.9	-27	C4c	4.877	0.004	1.10	Very Fine Gravel
7/13/2017	7	4	2835	45.073150	-92.833500	Transect	3.658	0.317	11.5	-39	C4c	4.877	0.004	1.10	Very Fine Gravel
7/13/2017	7	5	2824	45.073230	-92.833600	Transect	2.311	0.442	5.2	-62	C4c	4.877	0.004	1.10	Very Fine Gravel
7/13/2017	7	6	2807	45.073300	-92.833600	Transect	3.366	0.460	7.3	45	C4c	4.877	0.004	1.10	Very Fine Gravel
7/14/2017	7	7	2760	45.073710	-92.833600	Transect	3.531	0.366	9.6	12	C4c	4.877	0.004	1.10	Very Fine Gravel
7/14/2017	7	8	2747	45.073820	-92.833600	Transect	3.086	0.540	5.7	-20	C4c	4.877	0.004	1.10	Very Fine Gravel
7/14/2017	7	9	2736	45.073860	-92.833700	Transect	3.696	0.302	12.2	-72	C4c	4.877	0.004	1.10	Very Fine Gravel
7/14/2017	7	10	2726	45.073960	-92.833700	Transect	3.150	0.299	10.5	-10	C4c	4.877	0.004	1.10	Very Fine Gravel
7/14/2017	7	11	2674	45.074390	-92.833800	Transect	2.934	0.366	8.0	-8	C4c	4.877	0.004	1.10	Very Fine Gravel
7/16/2017	6	1	3263	45.071150	-92.836500	Transect	2.591	0.302	8.6	44	E4	4.267	0.011	1.10	Coarse Gravel
7/16/2017	6	2	3252	45.071220	-92.836400	Transect	2.946	0.223	13.2	44	E4	4.267	0.011	1.10	Coarse Gravel
7/16/2017	6	3	3242	45.071270	-92.836300	Transect	3.048	0.534	5.7	68	E4	4.267	0.011	1.10	Coarse Gravel
7/16/2017	6	4	3226	45.071340	-92.836100	Transect	2.819	0.134	21.0	44	E4	4.267	0.011	1.10	Coarse Gravel
7/16/2017	6	5	3209	45.071370	-92.835900	Transect	2.591	0.320	8.1	61	E4	4.267	0.011	1.10	Coarse Gravel
7/16/2017	6	6	3200	45.071410	-92.835800	Transect	2.755	0.390	7.1	50	E4	4.267	0.011	1.10	Coarse Gravel
7/17/2017	6	7	3185	45.071510	-92.835700	Transect	3.327	0.384	8.7	15	E4	4.267	0.011	1.10	Coarse Gravel
7/17/2017	6	8	3178	45.071580	-92.835700	Transect	3.277	0.366	9.0	26	E4	4.267	0.011	1.10	Coarse Gravel
7/17/2017	6	9	3151	45.071510	-92.835400	Transect	3.150	0.226	14.0	-56	E4	4.267	0.011	1.10	Coarse Gravel
7/17/2017	6	10	3142	45.071470	-92.835300	Transect	4.216	0.253	16.7	68	E4	4.267	0.011	1.10	Coarse Gravel
7/17/2017	6	11	3126	45.071500	-92.835100	Transect	3.493	0.351	10.0	-60	E4	4.267	0.011	1.10	Coarse Gravel
7/24/2017	5	11	4972	45.073680	-92.850100	Transect	3.658	0.332	11.0	73	C4	3.566	0.003	1.27	Gravel
7/24/2017	5	10	4991	45.073640	-92.850300	Transect	3.759	0.436	8.6	-61	C4	3.566	0.003	1.27	Gravel
7/24/2017	5	9	5000	45.073690	-92.850400	Transect	2.413	0.494	4.9	79	C4	3.566	0.003	1.27	Gravel
7/24/2017	5	8	5007	45.073720	-92.850500	Transect	2.845	0.348	8.2	-29	C4	3.566	0.003	1.27	Gravel
7/24/2017	5	7	5032	45.073830	-92.850700	Transect	2.996	0.287	10.5	87	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	6	5040	45.073800	-92.850800	Transect	2.413	0.271	8.9	73	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	5	5050	45.073820	-92.850900	Transect	2.388	0.256	9.3	-68	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	4	5066	45.073810	-92.851100	Transect	2.667	0.335	8.0	59	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	3	5075	45.073760	-92.851200	Transect	2.972	0.256	11.6	-81	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	2	5092	45.073770	-92.851400	Transect	2.743	0.302	9.1	-71	C4	3.566	0.003	1.27	Gravel
8/2/2017	5	1	5103	45.073840	-92.851500	Transect	2.540	0.220	11.6	-42	C4	3.566	0.003	1.27	Gravel
8/6/2017	4	11	5771	45.074990	-92.856438	Transect	3.277	0.220	14.9	77	C4	3.566	0.003	1.27	Gravel
8/6/2017	4	10	5778	45.075008	-92.856517	Transect	2.464	0.195	12.6	-49	C4	3.566	0.003	1.27	Gravel
8/6/2017	4	9	5790	45.075040	-92.856614	Transect	2.540	0.256	9.9	-59	C4	3.566	0.003	1.27	Gravel
8/6/2017	4	8	5800	45.075051	-92.856729	Transect	4.750	0.150	31.8	68	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	7	5811	45.074993	-92.856846	Transect	3.327	0.354	9.4	-90	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	6	5822	45.075054	-92.856961	Transect	4.191	0.226	18.6	-87	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	5	5836	45.075089	-92.857125	Transect	3.099	0.354	8.8	-84	C4	3.566	0.003	1.27	Gravel

Date	Reach	Transect	Station (1) (m)	Latitude	Longitude	Purpose	Wetted Width (m)	Thalweg Depth (m)	Width to Depth Ratio (-)	General Azimuth (2) (°)	Rosgen Classification	Bankfull Width (m)	Gradient (-)	Sinuosity (-)	Substrate
8/8/2017	4	4	5845	45.075022	-92.857223	Transect	5.207	0.271	19.2	67	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	3	5856	45.074998	-92.857361	Transect	4.293	0.131	32.7	-74	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	2	5871	45.075065	-92.857540	Transect	3.785	0.256	14.8	-65	C4	3.566	0.003	1.27	Gravel
8/8/2017	4	1	5886	45.075144	-92.857680	Transect	3.785	0.198	19.1	-30	C4	3.566	0.003	1.27	Gravel
8/13/2017	1	1	7246	45.082376	-92.862881	Transect	2.845	0.531	5.4	-39	E5	2.286	0.0001	1.01	Sand
8/13/2017	1	2	7233	45.082340	-92.862726	Transect	2.464	0.363	6.8	-64	E5	2.286	0.0001	1.01	Sand
8/13/2017	1	3	7221	45.082285	-92.862588	Transect	2.667	0.271	9.8	-65	E5	2.286	0.0001	1.01	Sand
8/13/2017	1	4	7209	45.082225	-92.862459	Transect	2.591	0.366	7.1	-55	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	5	7197	45.082178	-92.862322	Transect	2.235	0.579	3.9	-53	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	6	7184	45.082114	-92.862191	Transect	3.073	0.521	5.9	-55	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	7	7172	45.082053	-92.862067	Transect	2.184	0.610	3.6	-43	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	8	7160	45.081977	-92.861960	Transect	3.048	0.476	6.4	-43	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	9	7148	45.081925	-92.861822	Transect	2.388	0.439	5.4	-51	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	10	7135	45.081862	-92.861691	Transect	2.362	0.637	3.7	-59	E5	2.286	0.0001	1.01	Sand
8/19/2017	1	11	7122	45.081808	-92.861554	Transect	2.540	0.518	4.9	-67	E5	2.286	0.0001	1.01	Sand
8/29/2017	2	11	6807	45.079736	-92.860022	Transect	2.515	0.195	12.9	-5	C3	4.267	0.004	1.02	Cobble
8/29/2017	2	10	6817	45.079817	-92.860055	Transect	2.515	0.174	14.5	-16	C3	4.267	0.004	1.02	Cobble
8/29/2017	2	9	6831	45.079949	-92.860068	Transect	3.251	0.159	20.5	-13	C3	4.267	0.004	1.02	Cobble
8/29/2017	2	8	6843	45.080042	-92.860084	Transect	2.464	0.241	10.2	-13	C3	4.267	0.004	1.02	Cobble
8/29/2017	2	7	6853	45.080133	-92.860065	Transect	2.591	0.335	7.7	31	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	6	6869	45.080261	-92.859964	Transect	2.286	0.302	7.6	27	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	5	6882	45.080371	-92.859906	Transect	2.286	0.302	7.6	45	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	4	6891	45.080441	-92.859848	Transect	2.489	0.342	7.3	26	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	3	6905	45.080565	-92.859834	Transect	2.743	0.229	12.0	-7	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	2	6915	45.080657	-92.859834	Transect	2.388	0.287	8.3	11	C3	4.267	0.004	1.02	Cobble
8/30/2017	2	1	6933	45.080810	-92.859870	Transect	4.470	0.250	17.9	-7	C3	4.267	0.004	1.02	Cobble
9/10/2017	3	0	6684	45.078759	-92.860235	Test	2.159	0.211	10.3	0	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/10/2017	3	6	6465	45.077473	-92.860448	Stage	1.981	0.546	3.6	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/10/2017	3	6	6465	45.077473	-92.860448	Stage	1.981	0.546	3.6	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/10/2017	3	6	6465	45.077473	-92.860448	Stage	1.981	0.546	3.6	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/10/2017	3	6	6465	45.077473	-92.860448	Stage	1.981	0.546	3.6	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/10/2017	3	6	6465	45.077473	-92.860448	Stage	1.981	0.546	3.6	-19	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/11/2017	3	9	6426	45.077420	-92.860300	Stage	2.845	0.652	4.4	-67	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/11/2017	3	9	6426	45.077420	-92.860300	Stage	2.845	0.652	4.4	-67	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/11/2017	3	9	6426	45.077420	-92.860300	Stage	2.845	0.652	4.4	-67	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/11/2017	3	9	6426	45.077420	-92.860300	Stage	2.845	0.652	4.4	-67	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/11/2017	3	9	6426	45.077420	-92.860300	Stage	2.845	0.652	4.4	-67	E4/5	2.438	0.0048	1.29	Gravel/Sand
9/12/2017	2	0	6953	45.080987	-92.859853	Stage	3.048	0.211	14.5	1	C3	4.267	0.004	1.02	Cobble
9/12/2017	2	0	6953	45.080987	-92.859853	Stage	3.048	0.211	14.5	1	C3	4.267	0.004	1.02	Cobble
9/12/2017	2	0	6953	45.080987	-92.859853	Stage	3.048	0.211	14.5	1	C3	4.267	0.004	1.02	Cobble
9/12/2017	2	0	6953	45.080987	-92.859853	Stage	3.048	0.211	14.5	1	C3	4.267	0.004	1.02	Cobble
9/12/2017	2	0	6953	45.080987	-92.859853	Stage	3.048	0.211	14.5	1	C3	4.267	0.004	1.02	Cobble
9/13/2017	4	5	5836	45.075091	-92.857132	Stage	2.946	0.339	8.7	-89	C4	3.566	0.003	1.27	Gravel
9/13/2017	4	5	5836	45.075091	-92.857132	Stage	2.946	0.339	8.7	-89	C4	3.566	0.003	1.27	Gravel
9/13/2017	4	5	5836	45.075091	-92.857132	Stage	2.946	0.339	8.7	-89	C4	3.566	0.003	1.27	Gravel
9/13/2017	4	5	5836	45.075091	-92.857132	Stage	2.946	0.339	8.7	-89	C4	3.566	0.003	1.27	Gravel
9/13/2017	4	5	5836	45.075091	-92.857132	Stage	2.946	0.339	8.7	-89	C4	3.566	0.003	1.27	Gravel
9/14/2017	6	0	3281	45.071036	-92.836660	Test	2.667	0.500	5.3	37	E4	4.267	0.011	1.10	Coarse Gravel

(1) Creek distance from the St. Croix based on stationing used in the Brown's Creek Thermal Study.

(2) General azimuth measured relative to due south.

Table 22. Vegetation Characteristics at Transects

Date	Reach	Transect	Vegetation Type (1)		Wetted Edge (2) (m)		Height of Herb. Veg. (m) Max.		Height of Herb. Veg. (m) Mode		Max. Height of Woody Vegetation (3) (m)		Reach Buffer Width (4) (m)		Dominant Overstory Species		Dominant Understory Species		Additional Species	
			L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
7/3/2017	3	1	M	M	-0.241	-0.241	1.775	1.714	NA	NA	8.704	13.570	44.501	189.352	BW	BW	ELD	RC	JW,SN	JW,SN
7/3/2017	3	2	M	G	-0.457	-0.121	1.989	1.867	NA	NA	8.704	12.754	44.501	189.352	BW	NONE	RC	RC	ELD	SN,JW
7/3/2017	3	3	G	G	0.000	-0.051	1.928	1.958	NA	NA	1.424	1.272	44.501	189.352	NONE	NONE	RC	RC	SN,JW	SN
7/3/2017	3	4	G	M	-0.152	-0.089	1.653	2.171	NA	NA	1.216	1.366	44.501	189.352	NONE	MXB	RC	RC	SN	SN,JW
7/3/2017	3	5	G	G	-0.381	-0.165	1.958	1.501	NA	NA	1.111	1.148	44.501	189.352	NONE	NONE	SN	RC	SN,JW	SN
7/3/2017	3	6	G	G	-0.229	-0.442	1.989	1.592	NA	NA	1.189	1.041	44.501	189.352	NONE	NONE	RC	RC	SN,JW	NONE
7/4/2017	3	7	M	G	0.000	-0.165	3.086	1.958	NA	NA	1.161	1.840	44.501	189.352	NONE	NONE	SA	RC	SN	JW,SN
7/4/2017	3	8	G	G	-0.432	0.191	1.958	1.684	NA	NA	1.161	1.753	44.501	189.352	NONE	NONE	RC	RC	JW,SN,HT	SN,JW
7/4/2017	3	9	G	G	-0.279	0.000	1.867	2.019	NA	NA	1.261	1.146	44.501	189.352	NONE	NONE	RC	RC	SN,MF	SN,JW,WP
7/4/2017	3	10	M	G	-0.051	-0.216	2.080	1.684	NA	NA	4.131	1.146	44.501	189.352	MXB	NONE	SA	NONE	RC,SN,JW,BJ	RC,SN,JW,BT
7/4/2017	3	11	M	G	-0.432	-0.146	1.470	1.806	NA	NA	1.329	1.382	44.501	189.352	MXB	MXC	RC	RC	HT,JW,FM,WSW	JW
7/13/2017	7	1	M	M	-0.229	-0.857	2.050	NA	NA	NA	3.926	4.044	9.164	8.172	RM,SWO	SWO	GDW,SN,RC	LS,GDW	JW	JW,RC,WP,BE,GC
7/13/2017	7	2	M	M	0.000	0.000	NA	2.202	NA	NA	6.194	3.151	9.164	8.172	RM	SWO	GDW	GDW	PG,BC,BFT,BS, CA,FB,BFT,GO,HP	BN,RC,WP,SN
7/13/2017	7	3	M	M	-0.229	-0.203	1.562	1.989	1.257	1.257	4.209	2.721	9.164	8.172	RM,BB,T	SWO,CH,RP	JW	LS	SWMIL,RC,SW,WP,HT	RC,JW,SGO,BN,SN,GC,HT
7/13/2017	7	4	M	G	0.000	0.000	1.897	1.409	1.348	1.196	2.566	2.421	9.164	8.172	CH,GDW	NONE	RC	JW	JW,SN,CD,MH,LS,RM,C,WP,FB	LS,JW,SN,RC,NC,FB,BGB, CD,WG,DF,GLGO,MB
7/13/2017	7	5	G	G	-0.127	-0.038	1.867	1.958	1.257	1.257	2.145	2.391	9.164	8.172	NONE	NONE	RC	NA	JW,HT,S,BN,SGO,WH,WHBB, BT,BS,GLGO,PS,ALT	RC,FM,JW,MB,FB,GO
7/13/2017	7	6	G	G	0.000	-0.038	1.989	1.928	1.257	1.257	2.277	2.336	9.164	8.172	NONE	NONE	SOR	NBF	RC,SN,JW,GC,BN,CMIL, SWTL,SWW,FB	JW,RC,SWMIL,HT,WP,LS,CGO, FB,BGB,MB,ALT,PS,GLGO
7/14/2017	7	7	M	M	-0.127	-0.025	1.836	1.928	1.227	1.318	2.388	2.346	9.164	8.172	SWO,RM	SWO,RM	RC	RC	JW,SN,NBF,FB,GLGO, PS,BLA,WG,BGB	JW,GI,SWMIL,YR,CD, WG,WC,BGB
7/14/2017	7	8	M	M	0.000	-0.457	2.050	1.867	1.348	1.196	2.171	2.766	9.164	8.172	SWO	SWO	JW	NBF	NBF,RC,GO,GM,WHBB, SOR,BGB,WG,GWD	WB,S,JW,RDW,BGB, SGO,PS,CT
7/14/2017	7	9	M	G	0.000	0.140	1.592	1.775	1.196	1.018	2.427	2.469	9.164	8.172	SWO	NONE	LS	NA	JW,NBF,RC,GLGO,FB,BT,GO,PS	JW,RC,SWMIL,SOR,GC,SM,BGB, BS,WHBB,MB,GO,WG,GLGO
7/14/2017	7	10	G	G	-0.152	-0.051	2.019	1.638	1.196	1.288	2.180	2.856	9.164	8.172	NONE	NONE	SOR	NA	JW,RC,LS,MB,GO,SPR	JW,RC,SWMIL,PB,AWH,WHBB, GO,WH,WG,BE,PS,BGB
7/14/2017	7	11	M	M	0.152	-0.940	2.080	2.080	1.562	1.440	10.856	5.005	9.164	8.172	HL	KC	RC	RC	CR,JW,BTD,ALT,BLA	SN,CR
7/16/2017	6	1	F	F	-0.076	0.457	NA	NA	NA	NA	4.448	4.758	16.891	6.902	SW,MM,AM	BE,SW,RDW	RC	RC	JW,CA,NEA,DW	JW,B,SN
7/16/2017	6	2	F	F	0.000	0.000	NA	NA	NA	NA	4.448	5.433	16.891	6.902	SW	WBC,SW	NA	RC	B,JW,RC,FB,GC,GLGO,YR, GO,S,DW,GM,MM	SN,B,T,DW
7/16/2017	6	3	F	F	0.000	0.292	NA	NA	NA	NA	5.614	6.293	16.891	6.902	SW,BE	SW,SA,BE	RC	JW,BN	JW,SN,B,DW,GB,R	RC,SN,AG
7/16/2017	6	4	F	F	0.406	0.318	NA	NA	NA	NA	6.788	5.957	16.891	6.902	BE,GB,DW	BE	GI	GI	DW,JW,RC,BC	JW,GA
7/16/2017	6	5	F	F	0.686	0.229	NA	NA	NA	NA	6.452	6.276	16.891	6.902	BE	SA,BE	JW	JW	SW,RC,GI	GI,SNR,GO,SF
7/16/2017	6	6	F	F	0.229	0.203	NA	NA	NA	NA	8.953	6.276	16.891	6.902	BE,DW	BE	DW	SW	JW,RC,MM	JW,SW,WN,MM
7/17/2017	6	7	F	F	0.254	0.254	NA	NA	NA	NA	7.287	5.766	16.891	6.902	BE,SA,DW	SA,AM,DW	JW	B	RC,GI,B,GO	BE,GA,DF,GI,S,GO,SF,SW
7/17/2017	6	8	F	F	0.000	0.356	NA	NA	NA	NA	5.818	5.026	16.891	6.902	SA,RDW	SA,RDW	RC	SA	JW,SN,SW,WP,S,GO,SM	RC,JW,GI
7/17/2017	6	9	F	F	0.000	0.127	NA	NA	NA	NA	5.072	7.013	16.891	6.902	RDW,BE	SIM	RR	NA	JW,B,RC,VP,R	SW,JW,DW,BN, GI,CGO,B,MM
7/17/2017	6	10	F	F	-0.356	0.732	NA	NA	NA	NA	3.513	4.815	16.891	6.902	RM,BE,AM,SM	BE	BE,DW	BE,R	JW,RC,GI,SN,B,RDW,YR,GO,R	BN,GI,DW,RR
7/17/2017	6	11	F	F	0.737	0.000	NA	NA	NA	NA	4.368	3.852	16.891	6.902	DW	DW	RDW	JW	SW,BE,JW,RC,SN,WP,FB	RC,SW,BE,RM,GO,RDW,SN
7/24/2017	5	11	M	F	0.102	0.495	1.623	NA	1.623	NA	5.565	4.513	60.564	62.346	SA	SA	FB	SF	RC,SN,JW,WP,BC,GO	JW,R,GO
7/24/2017	5	10	M	F	0.000	0.000	1.245	NA	1.245	NA	4.428	5.372	60.564	62.346	BE	SA,DW	RC	JW	JW,WP,SN	RC,SN,LF
7/24/2017	5	9	M	M	0.127	-0.305	1.653	1.653	1.196	1.288	5.919	2.302	60.564	62.346	AM,SA	SA,DW,BE	RC	SN,JW	JW,WP,SN	RC,SF,LF,WP,AM, ALT,MB,YR,FB,W
7/24/2017	5	8	F	F	-0.254	0.305	NA	NA	NA	NA	7.003	3.937	60.564	62.346	SA,BE	AM,BE	RC	JW	JW,SN,SF	SN,G
7/24/2017	5	7	M	F	0.000	0.229	1.524	NA	1.524	NA	6.211	4.123	60.564	62.346	SA,BE	SA,AM	JW	JW,BC	LS,RC,CA,FM,ALT, WN,GSW,GC,LF	RC,SN,WN,ARR,PG,MH,DW
8/2/2017	5	6	M	M	0.787	0.254	0.175	1.775	0.256	1.440	4.311	4.833	60.564	62.346	SA,GB,BE	SA	SWTL	RC	SPR,LS,BLA,WP,NBF,PF,L	SW,WP,LS,SPR,JW,PS,FB

Date	Reach	Transect	Vegetation Type [1]		Wetted Edge [2] (m)		Height of Herb. Veg. (m)				Max. Height of Woody Vegetation [3] (m)		Reach Buffer Width [4] (m)		Dominant Overstory Species		Dominant Understory Species		Additional Species	
							Max.		Mode											
			L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
8/2/2017	5	5	G	G	0.000	0.965	1.989	2.171	1.379	1.318	3.773	5.128	60.564	62.346	SA,GB,BE	SA,MXB	RC	RC	JW,SW,BGB,FB,SOR,BON	JW,LS,FB,SOR
8/2/2017	5	4	G	G	0.406	-0.152	1.958	1.806	1.562	1.501	4.827	6.713	60.564	62.346	SA,BE	SA,MXB	RC	RC	JW,FM,FB,WP,BC,SWMIL,CT,BON	CT,SN,JW,BLA
8/2/2017	5	3	M	F	-0.051	0.330	1.440	1.440	0.561	NA	4.641	9.064	60.564	62.346	SA,MXB	SA,MXB	RC	JW	PS,FB,WG,SOR,SW,BON	DW,RC
8/2/2017	5	2	G	M	-0.102	0.457	2.476	1.867	1.288	1.440	4.641	8.004	60.564	62.346	BE,MXB	SA,DW,MXB	RC	JW	JW,BLA,BON,SN	RC,YR,GO,CT
8/2/2017	5	1	G	M	-0.102	0.406	2.019	2.110	1.440	1.440	4.435	6.383	60.564	62.346	BE,MXB	SA,DW,BE,MXB	RC	RC	LS,PS,SN,AG,BON, BLA,WP,JW,CT,FB	JW,WP,CT,FB,SN,WG,AG
8/6/2017	4	11	F	F	0.889	0.000	1.592	NA	1.440	NA	5.150	5.786	59.165	51.416	SA	CB	JW	CB	SN,BT,BW,RC,SSFN	SA,JW,SSFN
8/6/2017	4	10	F	F	0.102	1.295	1.501	0.896	1.227	0.195	5.150	5.745	59.165	51.416	SA	SA	JW	SWTL	BE,SN,SSFN,GC,RC,R,HT	GO,RC,SN,JW,HT,SSFN
8/6/2017	4	9	M	F	-0.610	0.610	1.928	0.988	1.745	0.622	2.129	4.800	59.165	51.416	BE	SA	RC	JW	LF,WP,SN,HP,GO,CGO	SSFN,RC,BTD,SWD
8/6/2017	4	8	M	M	0.203	0.000	1.501	1.531	1.018	1.318	8.235	5.620	59.165	51.416	SA,BE,GB	SA	RC	JW	JW,BTD,SWTL,GO,FB,PS,SSFN,CT, BLA,NSW,GSW,JP,WCUC,NWP	BN,SSFN,SN,SF,BE,ENS
8/8/2017	4	7	M	F	-0.610	0.914	1.867	1.168	1.348	1.168	8.235	16.333	59.165	51.416	SA,MXB	SA,CB	RC	JW	JW,CT,JP,SN,WCUC	SSFN,WPI,RP,SWTL
8/8/2017	4	6	M	F	-0.076	0.356	2.019	1.318	1.227	1.318	6.188	11.833	59.165	51.416	GDW	SA,BE	GDW	JW	SW,RC,FM,CT,WCUC,SW, JW,SSFN,JP,SN,MM,CE	S,GO,RC,SSFN,GC
8/8/2017	4	5	F	F	0.000	0.432	0.774	1.018	0.470	0.409	8.983	15.663	59.165	51.416	CB,SA	SA,CB,BE	NA	JW	SSFN,BTD,JW,CA, CB,RR,SF,CJ,SNR	BTD,GC,SSFN,SF,LF
8/8/2017	4	4	F	F	0.000	0.000	0.835	0.835	0.348	0.165	7.390	17.586	59.165	51.416	SA,CB,HS	CB,SA	CB	LF	JW,LF,RR,CB	JW,SSFN
8/8/2017	4	3	F	F	0.000	1.219	0.927	NA	0.500	NA	6.459	19.686	59.165	51.416	CB,SA	SA,HS,CB,MXB	PG	LF	RR,CB,SSFN,JW,LF,S	JW,SSFN,MM
8/8/2017	4	2	F	F	0.406	0.711	1.018	NA	0.592	NA	12.667	16.135	59.165	51.416	SA	CB,SA,BE	BTD	LF	HP,HS,RC,SSFN,JW, BN,CB,LF,GC,C	SSFN,BC,HS
8/8/2017	4	1	M	F	0.000	0.254	1.836	1.501	1.196	1.501	13.231	14.613	59.165	51.416	SA,BE	BE,GB	SSFN	JW	JW,RR,LF,WP,JP,RC,LPFO	SSFN,CT,RC,SW,HS
8/13/2017	1	1	G	G	-0.279	-0.356	1.745	1.379	1.196	0.988	5.681	6.680	134.498	121.968	CE	NONE	RC	RC	JP,SN,WP,JW,LS,BN	JW,SN,SSFN,SN, WP,WCUC,WSW
8/13/2017	1	2	G	G	-0.457	-0.203	1.806	2.019	1.111	1.196	5.287	5.821	134.498	121.968	NONE	DW	RC	BT	ALT,SN	JW,SSFN,SN,RC,GO,BT
8/13/2017	1	3	G	G	-0.102	-0.533	1.928	1.928	1.196	1.288	1.582	1.780	134.498	121.968	NONE	NONE	RC	RC	JW,SN,BT,LS,SSFN	JW,SN,WP,BC,DW,AM,SSFN,BT
8/13/2017	1	4	G	G	-0.254	-0.076	1.318	1.562	0.988	1.257	1.573	1.682	134.498	121.968	NONE	NONE	RC	RC	SSFN,FB,WP,SN,ALT,GO,GWD	JW,SN,SSFN,BT
8/19/2017	1	5	G	G	-0.406	-0.610	1.897	1.928	0.866	1.257	1.631	1.933	134.498	121.968	NONE	PBI	RC	RC	FM,FB,BT,JW,GO,SW	WP,JW,SSFN,BT
8/19/2017	1	6	G	G	-0.330	0.000	1.714	2.171	0.774	1.111	1.590	4.366	134.498	121.968	NONE	PBI,SA	RC	JW	FM,SN,SSFN	RC,SSFN,FM,SN,GO
8/19/2017	1	7	G	M	-0.610	-0.559	1.003	1.562	1.003	1.111	1.564	5.330	134.498	121.968	NONE	SA,GB	RC	RC	JW,BT,SN,SSFN	JW,SSFN,BT
8/19/2017	1	8	M	M	-0.914	0.000	1.592	1.745	1.018	1.196	3.559	5.330	134.498	121.968	SA	SA,GB	FM	FM	RC,JW,ALT,BT	SSFN,FB,WP,GO,BT
8/19/2017	1	9	M	M	-0.203	-0.762	1.653	1.379	0.957	1.111	3.559	3.276	134.498	121.968	SA,GB	SA	RC	RC	FM,JW,SSFN,GO,ALT,NSW	FB,WP,JW
8/19/2017	1	10	G	M	-0.813	-0.610	1.684	1.958	1.018	1.196	1.957	3.483	134.498	121.968	NONE	SA	RC	RC	JW,BT	FB,JW
8/19/2017	1	11	G	G	-0.406	-0.203	1.806	1.989	1.196	1.227	1.638	2.436	134.498	121.968	NONE	SA	RC	RC	FM,JW,WP,BT	FB,JW,SF
8/29/2017	2	11	M	M	-0.203	-0.635	1.714	1.501	1.227	0.957	10.597	15.588	4.084	60.459	WW,WPI, GB,HS	PCW,SA,GB,PO	RC	WSW	FM,WP	RC,LS
8/29/2017	2	10	M	M	-0.279	-0.076	1.867	1.470	1.018	1.470	15.674	19.262	4.084	60.459	WW,WPI, GB,HS	PCW,SA,GB,PO	NA	RC	BN,RC,LS,JW,SN,SSFN,CMIL	CT,BN,JP,WSW
8/29/2017	2	9	F	F	0.254	0.127	0.439	0.348	0.439	0.348	15.946	12.961	4.084	60.459	SA,GB,BE,WW	GB,BE,BCH	SSFN	GB	RR,GB	MM
8/29/2017	2	8	M	F	3.175	0.279	0.744	0.165	0.744	0.165	13.183	20.424	4.084	60.459	SP,SIM,WS, GB,RB,BE	GB,HS	TG	GB	NONE	NONE
8/29/2017	2	7	M	F	1.905	0.000	0.531	0.439	0.531	0.439	13.183	20.424	4.084	60.459	SP,WS,GB, RB,BE	GB,SA,MM	TG	RR	NONE	NONE
8/30/2017	2	6	M	M	0.152	-0.406	1.018	2.202	0.866	1.348	7.260	18.258	4.084	60.459	RP,SP,AB,RB,WW	GB,WW	H	BN	TG,RC,SSFN,JW,BT,PLWH	BE,RC,WP,HP,SSFN, ALT,GB,LF
8/30/2017	2	5	M	M	0.000	0.000	1.928	2.050	0.927	1.379	12.920	1.996	4.084	60.459	RB,T,SIM,WW	WW,WPI	SSFN	NA	RC,JP,WG,WP,TG,AM, BON,BE,SWMIL, SCF	RC,JW,ALT,BES,SSFN,DW, BT,PS,HP,FM,LS,GB
8/30/2017	2	4	M	M	0.076	0.000	0.912	1.867	1.196	1.196	19.515	1.907	4.084	60.459	WW,SM,SIM	WW,WPI	BT	H	CA,SSFN,BN,LS,TG, GI,BL,PLWH,MH	JW,SN,RC,BT,RR, SSFN,AM,PA
8/30/2017	2	3	M	M	0.889	0.000	0.287	1.531	0.287	1.018	14.452	2.446	4.084	60.459	RP,SM,SIM	WW,WPI,PCW,B E	TG	SSFN	NONE	RC,BES,SN,WP, CA,JW,WHBB
8/30/2017	2	2	M	M	1.245	0.102	0.256	2.202	0.256	1.257	18.045	12.393	4.084	60.459	DW,WW,RP, SM,SIM	DW,BE,WPI, SIM,PO,SPI	TG	H	NONE	GB,PA,DW,BL,JW, SSFN,RC,BT,S,JP
8/30/2017	2	1	F	F	0.000	1.111	1.168	1.168	0.470	0.470	17.624	16.528	4.084	60.459	BE,SIM	GB,BE,SIM	SSFN	SSFN	BT,SF,CA,MM,GB	JW,SA

Date	Reach	Transect	Vegetation Type [1]		Wetted Edge [2] (m)		Height of Herb. Veg. (m)				Max. Height of Woody Vegetation [3] (m)		Reach Buffer Width [4] (m)		Dominant Overstory Species		Dominant Understory Species		Additional Species	
							Max.		Mode											
			L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R	L	R
9/10/2017	3	0	G	G	-0.076	0.000	2.476	1.836	1.318	1.531	1.256	1.465	44.501	189.352	NONE	QA,SA,DW	NA	RC	SN,RC,SSFN,BT,JW,CT,BON,WCUC	AM,JW,YR,SN
9/10/2017	3	6	G	G	-0.254	-0.229	2.324	2.324	1.227	1.018	1.161	1.113	44.501	189.352	NONE	SA	RC	RC	SN,JW	SF,JW,HT,WCUC,SN
9/10/2017	3	6	G	G	-0.254	-0.229	2.324	2.324	1.227	1.018	1.161	1.113	44.501	189.352	NONE	SA	RC	RC	SN,JW	SF,JW,HT,WCUC,SN
9/10/2017	3	6	G	G	-0.254	-0.229	2.324	2.324	1.227	1.018	1.161	1.113	44.501	189.352	NONE	SA	RC	RC	SN,JW	SF,JW,HT,WCUC,SN
9/10/2017	3	6	G	G	-0.254	-0.229	2.324	2.324	1.227	1.018	1.161	1.113	44.501	189.352	NONE	SA	RC	RC	SN,JW	SF,JW,HT,WCUC,SN
9/10/2017	3	6	G	G	-0.254	-0.229	2.324	2.324	1.227	1.018	1.161	1.113	44.501	189.352	NONE	SA	RC	RC	SN,JW	SF,JW,HT,WCUC,SN
9/11/2017	3	9	G	G	-0.508	0.000	2.324	2.324	1.257	2.171	1.261	1.146	44.501	189.352	NONE	NONE	RC	JW	SN,WCUC,JW,CT	RC,WP,SN,BT
9/11/2017	3	9	G	G	-0.508	0.000	2.324	2.324	1.257	2.171	1.261	1.146	44.501	189.352	NONE	NONE	RC	JW	SN,WCUC,JW,CT	RC,WP,SN,BT
9/11/2017	3	9	G	G	-0.508	0.000	2.324	2.324	1.257	2.171	1.261	1.146	44.501	189.352	NONE	NONE	RC	JW	SN,WCUC,JW,CT	RC,WP,SN,BT
9/11/2017	3	9	G	G	-0.508	0.000	2.324	2.324	1.257	2.171	1.261	1.146	44.501	189.352	NONE	NONE	RC	JW	SN,WCUC,JW,CT	RC,WP,SN,BT
9/11/2017	3	9	G	G	-0.508	0.000	2.324	2.324	1.257	2.171	1.261	1.146	44.501	189.352	NONE	NONE	RC	JW	SN,WCUC,JW,CT	RC,WP,SN,BT
9/12/2017	2	0	F	F	0.483	1.806	1.245	1.018	1.245	1.018	15.538	7.871	4.084	60.459	GB,SA,BE,RP	SA,GB	GB	JW	CA,JW,SSFN,BT,LS,HP,SF,NBM	SSFN,RC,BT,NBM
9/12/2017	2	0	F	F	0.483	1.806	1.245	1.018	1.245	1.018	15.538	7.871	4.084	60.459	GB,SA,BE,RP	SA,GB	GB	JW	CA,JW,SSFN,BT,LS,HP,SF,NBM	SSFN,RC,BT,NBM
9/12/2017	2	0	F	F	0.483	1.806	1.245	1.018	1.245	1.018	15.538	7.871	4.084	60.459	GB,SA,BE,RP	SA,GB	GB	JW	CA,JW,SSFN,BT,LS,HP,SF,NBM	SSFN,RC,BT,NBM
9/12/2017	2	0	F	F	0.483	1.806	1.245	1.018	1.245	1.018	15.538	7.871	4.084	60.459	GB,SA,BE,RP	SA,GB	GB	JW	CA,JW,SSFN,BT,LS,HP,SF,NBM	SSFN,RC,BT,NBM
9/12/2017	2	0	F	F	0.483	1.806	1.245	1.018	1.245	1.018	15.538	7.871	4.084	60.459	GB,SA,BE,RP	SA,GB	GB	JW	CA,JW,SSFN,BT,LS,HP,SF,NBM	SSFN,RC,BT,NBM
9/13/2017	4	5	F	F	0.000	0.483	0.835	1.018	0.561	0.439	8.983	15.663	59.165	51.416	GB,SA	SA,GB,BE	SSFN	SSFN	BT,CA,LS,GB,RR,GO,RC,SNR,W	JW,SF,LF,BN
9/13/2017	4	5	F	F	0.000	0.483	0.835	1.018	0.561	0.439	8.983	15.663	59.165	51.416	GB,SA	SA,GB,BE	SSFN	SSFN	BT,CA,LS,GB,RR,GO,RC,SNR,W	JW,SF,LF,BN
9/13/2017	4	5	F	F	0.000	0.483	0.835	1.018	0.561	0.439	8.983	15.663	59.165	51.416	GB,SA	SA,GB,BE	SSFN	SSFN	BT,CA,LS,GB,RR,GO,RC,SNR,W	JW,SF,LF,BN
9/13/2017	4	5	F	F	0.000	0.483	0.835	1.018	0.561	0.439	8.983	15.663	59.165	51.416	GB,SA	SA,GB,BE	SSFN	SSFN	BT,CA,LS,GB,RR,GO,RC,SNR,W	JW,SF,LF,BN
9/13/2017	4	5	F	F	0.000	0.483	0.835	1.018	0.561	0.439	8.983	15.663	59.165	51.416	GB,SA	SA,GB,BE	SSFN	SSFN	BT,CA,LS,GB,RR,GO,RC,SNR,W	JW,SF,LF,BN
9/14/2017	6	0	F	F	0.381	0.254	1.470	1.714	1.196	0.866	6.827	6.990	16.891	6.902	BE,DW	BE,SA	JW	JW	RC,GC,SSFN,C,B,GI	RC,SSFN,GI,B

[1] G = grassy, F = forest, M = mixed

[2] Wetted edge is the distance from the water's edge to riparian vegetation. A positive number means there was an exposed (un-vegetated) bank. A negative wetted edge was tracked to indicate there was very dense vegetation and streambank hanging above the water surface.

[3] Maximum height of woody vegetation assessed using 2011 LiDAR data within 10 m of transect.

[4] Average buffer width for representative reaches estimated using aerial imagery. Mowed grass or pavement was not considered a buffer.

Herb. = herbaceous

Position of observation denoted by: L = left, R = right when looking downstream

All heights of vegetation measured relative to the water surface.

NA = data not available or not collected

GB — Invasive or exotic species identified

Table 23. Plant Identification Key

Acronym	Common Name	Scientific Name
AB	American basswood	*Tilia americana*
AG	American germander	*Teucrium canadense*
ALT	Arrow-leaved tearthumb	*Persicaria sagittata*
AM	Amur maple *	*Acer ginnala*
ARR	American red raspberry	*Rubus idaeus*
AWH	American water horehound	*Lycopus americanus*
B	Common burdock *	*Arctium minus*
BB	Buttonbush	*Cephalantus occidentalis*
BC	Blue cohosh	*Caulophyllum thalictroides*
BCH	Black cherry	*Prunus serotina*
BE	Boxelder	*Acer negundo*
BES	Black-eyed Susan	*Rudbeckia hirta*
BFT	Birds-foot trefoil *	*Lotus corniculatus*
BGB	Dark green bulrush	*Scirpus atrovirens*
BJ	Colorado bluejoint grass	*Calamagrostis canadensis*
BL	Blue lobelia	*Lobelia siphilitica*
BLA	Broad-leaf arrowhead	*Sagittaria latifolia*
BN	Bittersweet nightshade **	*Bidens connata*
BON	Common boneset	*Eupatorium perfoliatum*
BS	Bebb's sedge	*Carex bebbii*
BT	Purple-stem beggarticks	*Bidens connata*
BTD	Devil's beggarticks	*Bidens frondosa*
BW	Black willow	*Salix nigra*
C	Clover	*Trifolium* spp.
CA	Canada anemone	*Anemone canadensis*
CB	Common buckthorn *	*Rhamnus cathartica*
CD	Curly dock **	*Rumex crispus*
CE	Cut leaf elderberry	*Sambucus nigra laciniata*
CGO	Canada goldenrod	*Solidago canadensis*
CH	Cock-spur hawthorn	*Crataegus crus-galli*
CJ	Creeping jenny **	*Lysimachia nummularia*
CR	Common reed	*Phragmites* spp.
CMIL	Common milkweed	*Asclepias syriaca*
CT	Canada thistle *	*Cirsium arvense*
DF	Daisy fleabane	*Erigeron strigosus*
DW	Dogwood	*Cornus* spp.
ELD	Elderberry	*Sambucus* spp.
ENS	Enchanter's nightshade	*Circaea lutetiana*
FB	Fowl bluegrass	*Poa palustris*
FM	Fowl manna grass	*Glyceria striata*
G	Grass (unidentified)	*n/a*
GA	Green ash	*Fraxinus pennsylvanica*
GB	Glossy buckthorn *	*Frangula alnus*
GC	Giant chickweed **	*Myosoton aquaticum*

Acronym	Common Name	Scientific Name
GDW	Gray dogwood	*Cornus racemosa*
GI	Ground ivy **	*Glechoma hederacea*
GLGO	Grass-leaved goldenrod	*Euthamia graminifolia*
GM	Garlic mustard *	*Alliaria petiolata*
GO	Goldenrod	*Solidago* spp.
GSW	Great St. John's-wort	*Hypericum pyramidatum*
GWD	Great water dock	*Rumex britannica*
H	Hosta **	*Funkia* spp.
HL	Imperial honey locust	*Gleditsia triacanthos 'Impcole'*
HP	America hog peanut	*Amphicarpaea bracteata*
HS	Honeysuckle *	*Lonicera* spp.
HT	Horsetail	*Equisetum* spp.
JP	Spotted joe-pyeweed	*Eutrochium maculatum*
JW	Jewelweed, Spotted touch-me-not	*Impatiens capensis*
KC	Kentucky coffeetree	*Gymnocladus occidentalis*
L	Loosestrife *	*Lythrum* spp.
LF	Lady fern	*Athyrium Filix-femina*
LPFO	Lesser purple fringed orchid [U]	*Platanthera psycodes*
LS	Lake sedge	*Carex lacustris*
MB	Marsh bellflower	*Campanula aparinoides*
MF	Monkey flower	*Mimulus* spp.
MH	Meadow horsetail	*Equisetum pratense*
MM	Mountain maple	*Acer spicatum*
MXB	Mixed broadleaf trees	*n/a*
MXC	Mixed coniferous trees	*n/a*
NA	Not applicable (no dominant species)	
NBF	Northern blue flag	*Iris versicolor*
NBM	Nodding bur-marigold	*Bidens cernua*
NC	Narrowleaf cattail **	*Typha angustifolia*
NEA	New England aster	*Symphyotrichum novae-angliae*
NONE	no vegetation	
NSW	Nodding smartweed	*Persicaria lapathifolia*
NWP	Northern water plantain	*Alisma triviale*
PA	Panicled aster	*Symphyotrichum lanceolatum*
PB	Pennsylvania buttercup	*Ranunculus pensylvanicus*
PBI	Paper birch	*Betula papyrifera*
PCW	Plains cottonwood	*Populus deltoides*
PF	Purple monkey flower, Allegheny monkey flower	*Mimulus ringens*
PG	Prickly gooseberry	*Ribes cynosbati*
PLWH	Purple-leaved willow-herb	*Epilobium coloratum*
PO	Pin oak	*Quercus palustri*
PS	Porcupine sedge	*Carex hystericina*
QA	Quaking aspen	*Populus tremuloides*
R	Raspberry	*Rubus* spp.

Acronym	Common Name	Scientific Name
RB	River birch	*Betula nigra*
RC	Reed canary grass *	*Phalaris arundinacea*
RDW	Red-osier dogwood	*Cornus sericea*
RM	Red maple	*Acer rubrum*
RP	Red pine	*Pinus resinosa*
RR	Red raspberry	*Rubus idaeus*
S	Sedge	*Carex* spp.
SA	Speckled alder	*Alnus incana*
SCF	Straw-colored flatsedge	*Cyperus strigosus*
SF	Sensitive fern	*Onoclea sensibilis*
SGO	Showy goldenrod	*Solidago speciosa*
SIM	Silver maple	*Acer saccharinum*
SM	Sugar maple	*Acer saccharum*
SN	Stinging nettle	*Urtica dioica*
SNR	White snakeroot	*Ageratina altissima*
SOR	Soft rush	*Juncus effusus*
SP	Spruce	*Picea*
SPI	Scotch pine **	*Pinus sylvestris*
SPR	Spikerush	*Eleocharis spp.*
SSFN	Small-spike false nettle	*Boehmeria cylindrica*
SW	Sandbar willow	*Salix interior*
SWD	Smartweed	*Persicaria* spp.
SWMIL	Marsh/swamp milkweed	*Asclepias incarnata*
SWO	Swamp white oak	*Quercus bicolor*
SWTL	Thyme-leaf speedwell **	*Veronica serpyllifolia*
SWW	Water speedwell	*Veronica catenata*
T	Tamarack	*Larix laricina*
TG	Kentucky bluegrass **	*Poa pratensis*
VP	Veiny pea	*Lathyrus venosus*
W	Watercress *	*Nasturtium officinale*
WB	Wild bergamot	*Monarda fistulosa*
WBC	Wild black currant	*Ribes americanum*
WC	White clover **	*Trifolium repens*
WCUC	Wild cucumber	*Echinocystis lobata*
WG	Woolgrass	*Scirpus cyperinus*
WH	Water hemlock	*Cicuta maculata*
WHBB	Bulblet-bearing water hemlock	*Cicuta bulbifera*
WN	Canadian wood nettle	*Laportea canadensis*
WP	Wild pea, Marsh vetchling	*Lathyrus palustris*
WPI	White pine	*Pinus strobus*
WS	White spruce	*Picea glauca*
WSW	Water smartweed	*Persicaria amphibia*
WW	Weeping willow **	*Salix babylonica*
YR	Yellow rocket	*Barbarea* spp.

* Exotic/Invasive Species
** Non-Native Species
[U] Unique Species

Table 24. Photo Analysis Results at Transects

Date	Reach	Transect	Time of Photo			Lens Height (m)			Gap Fraction				Openness				Growing Season Shade (WinSCANOPY) Variable Lens Height				Growing Season Shade (WinSCANOPY) Constant Lens Height				Growing Season Shade (LiDAR)
			C	L	R	C	L	R	C	L	R	Avg	C	L	R	Avg	C	L	R	Avg	C	L	R	Avg	
7/3/2017	3	1	10:52	10:57	11:04	0.476	0.318	0.337	0.35	0.12	0.21	0.23	0.50	0.12	0.19	0.27	0.88	0.95	0.74	0.85	0.88	0.95	0.74	0.85	0.11
7/3/2017	3	2	12:12	12:17	12:31	0.286	0.432	0.349	0.45	0.28	0.28	0.34	0.33	0.22	0.21	0.26	0.13	0.45	0.76	0.45	0.20	0.45	0.76	0.47	0.11
7/3/2017	3	3	13:15	13:23	13:28	0.298	0.298	0.298	0.73	0.48	0.66	0.62	0.55	0.35	0.50	0.47	0.13	0.36	0.08	0.19	0.20	0.36	0.13	0.23	0.11
7/3/2017	3	4	14:05	14:30	14:21	0.343	0.368	0.343	0.72	0.63	0.59	0.65	0.55	0.49	0.45	0.50	0.10	0.18	0.38	0.22	0.17	0.18	0.63	0.33	0.11
7/3/2017	3	5	15:49	15:54	15:58	0.343	0.311	0.419	0.66	0.42	0.45	0.51	0.49	0.32	0.35	0.38	0.21	0.64	0.42	0.42	0.35	0.64	0.84	0.61	0.11
7/3/2017	3	6	16:39	16:48	16:45	0.292	0.305	0.337	0.67	0.41	0.46	0.51	0.50	0.30	0.35	0.38	0.19	0.51	0.39	0.36	0.28	0.51	0.64	0.48	0.11
7/4/2017	3	7	11:22	11:25	11:33	0.222	0.337	0.241	0.55	0.30	0.40	0.42	0.44	0.28	0.30	0.34	0.62	0.77	0.48	0.63	0.62	0.77	0.65	0.68	0.11
7/4/2017	3	8	12:06	12:08	12:21	0.324	0.248	0.248	0.79	0.58	0.59	0.65	0.61	0.44	0.46	0.50	0.07	0.16	0.45	0.23	0.12	0.16	0.61	0.30	0.06
7/4/2017	3	9	12:52	13:05	13:09	0.267	0.248	0.267	0.73	0.20	0.68	0.54	0.56	0.17	0.52	0.42	0.06	0.69	0.23	0.33	0.09	0.69	0.33	0.37	0.06
7/4/2017	3	10	13:53	14:01	13:57	0.216	0.362	0.298	0.70	0.43	0.52	0.55	0.52	0.34	0.39	0.41	0.16	0.37	0.48	0.34	0.20	0.37	0.74	0.44	0.06
7/4/2017	3	11	14:27	14:32	14:35	0.216	0.222	0.248	0.78	0.42	0.66	0.62	0.59	0.33	0.50	0.47	0.09	0.58	0.18	0.28	0.11	0.58	0.25	0.32	0.06
7/13/2017	7	1	12:40	12:47	12:52	0.286	0.457	0.292	0.51	0.32	0.13	0.32	0.35	0.23	0.09	0.23	0.32	0.42	0.91	0.55	0.48	0.42	0.91	0.60	0.24
7/13/2017	7	2	14:32	14:37	14:43	0.273	0.254	0.394	0.32	0.13	0.08	0.17	0.25	0.11	0.06	0.14	0.67	0.81	0.92	0.80	0.67	0.81	0.92	0.80	0.24
7/13/2017	7	3	15:41	15:44	15:48	0.267	0.343	0.178	0.71	0.40	0.42	0.51	0.55	0.33	0.32	0.40	0.19	0.59	0.31	0.36	0.27	0.59	0.37	0.41	0.24
7/13/2017	7	4	16:24	16:26	16:29	0.337	0.406	0.387	0.86	0.76	0.75	0.79	0.71	0.62	0.59	0.64	0.04	0.19	0.12	0.12	0.06	0.19	0.23	0.16	0.24
7/13/2017	7	5	17:29	17:32	17:38	0.267	0.330	0.318	0.83	0.60	0.75	0.73	0.67	0.49	0.61	0.59	0.03	0.38	0.07	0.16	0.05	0.38	0.11	0.18	0.24
7/13/2017	7	6	18:20	18:22	18:25	0.260	0.387	0.279	0.84	0.75	0.36	0.65	0.67	0.62	0.30	0.53	0.03	0.11	0.77	0.31	0.04	0.11	0.77	0.31	0.06
7/14/2017	7	7	11:51	11:56	11:59	0.292	0.368	0.425	0.83	0.69	0.73	0.75	0.67	0.56	0.58	0.60	0.12	0.19	0.16	0.16	0.18	0.19	0.32	0.23	0.06
7/14/2017	7	8	12:20	12:25	12:31	0.318	0.368	0.203	0.80	0.67	0.23	0.57	0.64	0.53	0.21	0.46	0.09	0.35	0.70	0.38	0.14	0.35	0.70	0.40	0.06
7/14/2017	7	9	13:27	13:30	13:33	0.381	0.387	0.368	0.87	0.79	0.77	0.81	0.71	0.64	0.62	0.66	0.02	0.07	0.08	0.06	0.04	0.07	0.14	0.08	0.06
7/14/2017	7	10	14:38	14:40	14:45	0.368	0.400	0.362	0.87	0.66	0.66	0.73	0.72	0.55	0.54	0.60	0.04	0.40	0.24	0.23	0.07	0.40	0.41	0.29	0.06
7/14/2017	7	11	15:25	15:29	15:35	0.260	0.324	0.241	0.49	0.35	0.31	0.38	0.38	0.29	0.23	0.30	0.60	0.67	0.79	0.68	0.60	0.67	0.79	0.68	0.08
7/16/2017	6	1	11:16	11:18	11:23	0.368	0.533	0.438	0.08	0.12	0.03	0.07	0.05	0.08	0.02	0.05	0.93	0.79	0.99	0.90	0.93	0.79	0.99	0.90	0.23
7/16/2017	6	2	11:58	12:08	12:19	0.425	0.514	0.546	0.17	0.10	0.07	0.11	0.11	0.07	0.04	0.07	0.75	0.85	0.97	0.86	0.75	0.85	0.97	0.86	0.23
7/16/2017	6	3	13:09	13:13	13:16	0.298	0.540	0.387	0.11	0.08	0.12	0.10	0.08	0.06	0.08	0.07	0.79	0.84	0.82	0.82	0.79	0.84	0.82	0.82	0.23
7/16/2017	6	4	13:59	14:03	14:09	0.540	0.546	0.591	0.04	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.96	0.96	0.97	0.97	0.96	0.96	0.97	0.97	0.23
7/16/2017	6	5	15:02	15:06	15:10	0.311	0.483	0.616	0.04	0.05	0.03	0.04	0.03	0.04	0.02	0.03	0.97	0.95	0.98	0.96	0.97	0.95	0.98	0.96	0.28
7/16/2017	6	6	16:13	16:18	16:22	0.286	0.451	0.400	0.06	0.06	0.06	0.06	0.05	0.05	0.05	0.05	0.95	0.96	0.94	0.95	0.95	0.96	0.94	0.95	0.28
7/17/2017	6	7	10:21	10:25	10:29	0.356	0.438	0.502	0.09	0.09	0.10	0.09	0.06	0.06	0.07	0.06	0.91	0.90	0.92	0.91	0.91	0.90	0.92	0.91	0.28
7/17/2017	6	8	11:04	11:16	11:23	0.349	0.400	0.502	0.27	0.16	0.24	0.23	0.18	0.11	0.16	0.15	0.58	0.72	0.81	0.70	0.58	0.72	0.81	0.70	0.28
7/17/2017	6	9	12:23	12:27	12:31	0.476	0.578	0.502	0.06	0.05	0.08	0.06	0.05	0.04	0.07	0.05	0.95	0.87	0.89	0.90	0.95	0.87	0.89	0.90	0.28
7/17/2017	6	10	13:04	13:08	13:12	0.413	0.438	0.489	0.16	0.12	0.14	0.14	0.11	0.09	0.09	0.10	0.93	0.89	0.94	0.92	0.93	0.89	0.94	0.92	0.28
7/17/2017	6	11	13:48	13:53	14:04	0.425	0.476	0.489	0.48	0.28	0.30	0.35	0.33	0.19	0.21	0.24	0.29	0.50	0.80	0.53	0.59	0.50	0.80	0.63	0.28
7/24/2017	5	11	9:57	10:02	10:05	0.292	0.311	0.419	0.24	0.32	0.11	0.23	0.17	0.21	0.09	0.16	0.81	0.70	0.94	0.82	0.81	0.70	0.94	0.82	0.20
7/24/2017	5	10	11:26	11:36	11:40	0.286	0.273	0.298	0.38	0.41	0.24	0.35	0.26	0.28	0.16	0.23	0.60	0.42	0.91	0.64	0.60	0.42	0.91	0.64	0.20
7/24/2017	5	9	12:10	12:14	12:19	0.286	0.546	0.235	0.61	0.64	0.53	0.59	0.43	0.46	0.36	0.42	0.14	0.20	0.35	0.23	0.21	0.20	0.47	0.29	0.20
7/24/2017	5	8	13:46	14:00	14:05	0.381	0.318	0.540	0.14	0.11	0.20	0.15	0.11	0.10	0.16	0.12	0.72	0.79	0.54	0.68	0.72	0.79	0.54	0.68	0.20
7/24/2017	5	7	15:15	14:55	15:18	0.406	0.565	0.400	0.02	0.12	0.02	0.06	0.02	0.09	0.02	0.04	0.98	0.92	0.98	0.96	0.98	0.92	0.98	0.96	0.20
8/2/2017	5	6	11:34	11:43	11:46	0.318	0.514	0.470	0.77	0.78	0.77	0.77	0.60	0.61	0.59	0.60	0.05	0.04	0.08	0.06	0.08	0.04	0.18	0.10	0.15
8/2/2017	5	5	12:40	12:44	12:49	0.318	0.533	0.445	0.73	0.51	0.82	0.69	0.57	0.39	0.66	0.54	0.04	0.16	0.04	0.08	0.07	0.16	0.08	0.10	0.15
8/2/2017	5	4	13:05	13:15	13:20	0.286	0.375	0.464	0.74	0.70	0.50	0.64	0.56	0.53	0.39	0.49	0.06	0.06	0.52	0.22	0.09	0.06	0.52	0.23	0.15
8/2/2017	5	3	14:03	14:06	14:10	0.394	0.533	0.483	0.44	0.51	0.40	0.45	0.36	0.39	0.33	0.36	0.62	0.42	0.78	0.61	0.62	0.42	0.78	0.61	0.15
8/2/2017	5	2	14:45	15:04	15:07	0.318	0.438	0.470	0.60	0.61	0.54	0.58	0.47	0.47	0.44	0.46	0.50	0.42	0.75	0.56	0.79	0.42	0.75	0.66	0.15
8/2/2017	5	1	15:27	15:44	15:47	0.406	0.438	0.514	0.77	0.67	0.77	0.74	0.60	0.51	0.60	0.57	0.05	0.12	0.09	0.08	0.09	0.12	0.22	0.14	0.15
8/6/2017	4	11	10:38	10:44	10:49	0.483	0.489	0.445	0.08	0.11	0.05	0.08	0.06	0.09	0.05	0.07	0.96	0.92	0.95	0.94	0.96	0.92	0.95	0.94	0.45
8/6/2017	4	10	11:29	11:33	11:35	0.419	0.489	0.476	0.12	0.10	0.13	0.12	0.08	0.07	0.09	0.08	0.79	0.79	0.82	0.80	0.79	0.79	0.82	0.80	0.45
8/6/2017	4	9	12:02	12:06	12:10	0.445	0.413	0.495	0.10	0.02	0.11	0.08	0.07	0.01	0.08	0.05	0.93	0.94	0.96	0.94	0.93	0.94	0.96	0.94	0.45
8/6/2017	4	8	12:53	13:02	13:07	0.533	0.483	0.495	0.19	0.24	0.13	0.19	0.14	0.19	0.09	0.14	0.81	0.75	0.89	0.82	0.81	0.75	0.89	0.82	0.45
8/8/2017	4	7	9:38	9:45	9:49	0.337	0.381	0.445	0.23	0.15	0.08	0.15	0.17	0.10	0.06	0.11	0.86	0.89	0.97	0.90	0.86	0.89	0.97	0.90	0.45
8/8/2017	4	6	10:44	10:50	10:57	0.521	0.597	0.546	0.45	0.09	0.28	0.28	0.34	0.07	0.22	0.21	0.78	0.77	0.92	0.82	0.78	0.77	0.92	0.82	0.45
8/8/2017	4	5	12:06	12:11	12:14	0.406	0.394	0.540	0.06	0.05	0.07	0.06	0.05	0.05	0.05	0.05	0.89	0.91	0.94	0.91	0.89	0.91	0.94	0.91	0.45
8/8/2017	4	4	12:47	12:57	13:05	0.413	0.578	0.514	0.04	0.03	0.03	0.03	0.03	0.02	0.02	0.02	0.95	0.98	0.96	0.96	0.95	0.98	0.96	0.96	0.57

Date	Reach	Transect	Time of Photo			Lens Height (m)			Gap Fraction				Openness				Growing Season Shade (WinSCANOPY)								Growing Season Shade (LiDAR)
																	Variable Lens Height				Constant Lens Height				
			C	L	R	C	L	R	C	L	R	Avg	C	L	R	Avg	C	L	R	Avg	C	L	R	Avg	
8/8/2017	4	3	14:18	14:24	14:28	0.546	0.559	0.578	0.04	0.06	0.05	0.05	0.03	0.05	0.03	0.04	0.95	0.90	0.96	0.94	0.95	0.90	0.96	0.94	0.57
8/8/2017	4	2	14:42	14:45	14:47	0.433	0.546	0.502	0.09	0.09	0.08	0.09	0.06	0.06	0.05	0.06	0.94	0.89	0.93	0.92	0.94	0.89	0.93	0.92	0.57
8/8/2017	4	1	15:21	15:26	15:29	0.425	0.495	0.559	0.22	0.16	0.22	0.20	0.16	0.11	0.17	0.14	0.88	0.90	0.88	0.89	0.88	0.90	0.88	0.89	0.57
8/13/2017	1	1	10:14	10:20	10:25	0.222	0.279	0.216	0.81	0.50	0.42	0.57	0.66	0.40	0.34	0.47	0.07	0.44	0.44	0.32	0.09	0.44	0.56	0.37	0.07
8/13/2017	1	2	10:58	11:04	11:09	0.324	0.324	0.394	0.76	0.37	0.49	0.54	0.62	0.30	0.45	0.46	0.05	0.52	0.51	0.36	0.08	0.52	0.51	0.37	0.07
8/13/2017	1	3	11:53	11:58	12:01	0.362	0.356	0.394	0.51	0.51	0.60	0.54	0.66	0.40	0.48	0.51	0.08	0.45	0.36	0.30	0.14	0.45	0.67	0.42	0.07
8/13/2017	1	4	12:42	12:47	12:51	0.375	0.591	0.305	0.85	0.83	0.50	0.73	0.70	0.69	0.40	0.60	0.03	0.04	0.50	0.19	0.05	0.04	0.77	0.29	0.07
8/19/2017	1	5	10:07	10:13	10:16	0.298	0.254	0.241	0.74	0.42	0.38	0.51	0.59	0.33	0.32	0.42	0.15	0.42	0.80	0.45	0.22	0.42	0.80	0.48	0.07
8/19/2017	1	6	10:50	10:56	11:02	0.337	0.521	0.248	0.87	0.57	0.23	0.56	0.72	0.48	0.22	0.47	0.02	0.22	0.93	0.39	0.03	0.22	0.93	0.39	0.07
8/19/2017	1	7	11:42	11:48	11:57	0.267	0.279	0.178	0.74	0.41	0.53	0.56	0.58	0.30	0.43	0.44	0.09	0.25	0.46	0.27	0.13	0.25	0.55	0.31	0.07
8/19/2017	1	8	12:27	12:31	12:35	0.273	0.394	0.375	0.75	0.23	0.61	0.53	0.59	0.18	0.50	0.42	0.12	0.61	0.44	0.39	0.18	0.61	0.79	0.53	0.07
8/19/2017	1	9	13:06	13:10	13:14	0.260	0.229	0.286	0.69	0.49	0.22	0.47	0.54	0.37	0.17	0.36	0.20	0.32	0.84	0.45	0.28	0.32	0.84	0.48	0.05
8/19/2017	1	10	13:59	14:09	14:14	0.197	0.178	0.248	0.65	0.16	0.23	0.35	0.50	0.13	0.18	0.27	0.37	0.78	0.86	0.67	0.45	0.78	0.86	0.70	0.05
8/19/2017	1	11	14:36	14:42	14:49	0.311	0.260	0.241	0.74	0.33	0.55	0.54	0.59	0.27	0.46	0.44	0.11	0.59	0.52	0.41	0.18	0.59	0.52	0.43	0.05
8/29/2017	2	11	12:42	12:48	12:54	0.533	0.540	0.521	0.51	0.27	0.27	0.35	0.38	0.20	0.20	0.26	0.19	0.55	0.61	0.45	0.49	0.55	0.61	0.55	0.28
8/29/2017	2	10	13:34	13:39	13:42	0.546	0.616	0.584	0.29	0.31	0.25	0.29	0.23	0.24	0.19	0.22	0.59	0.60	0.64	0.61	0.59	0.60	0.64	0.61	0.28
8/29/2017	2	9	14:22	14:26	14:30	0.565	0.603	0.603	0.05	0.05	0.06	0.05	0.05	0.04	0.06	0.05	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.28
8/29/2017	2	8	15:23	15:28	15:31	0.489	0.711	0.654	0.12	0.22	0.04	0.13	0.12	0.18	0.04	0.11	0.86	0.67	0.94	0.82	0.86	0.67	0.94	0.82	0.28
8/29/2017	2	7	16:08	16:13	16:16	0.368	0.438	0.584	0.11	0.24	0.09	0.15	0.09	0.17	0.09	0.11	0.78	0.62	0.88	0.76	0.78	0.62	0.88	0.76	0.45
8/30/2017	2	6	9:29	9:37	9:43	0.483	0.591	0.489	0.31	0.36	0.10	0.26	0.23	0.27	0.08	0.19	0.32	0.30	0.78	0.47	0.73	0.30	0.78	0.60	0.45
8/30/2017	2	5	10:24	10:32	10:37	0.419	0.419	0.514	0.46	0.36	0.29	0.37	0.32	0.26	0.21	0.26	0.47	0.78	0.59	0.61	0.93	0.78	0.59	0.77	0.45
8/30/2017	2	4	11:22	11:26	11:30	0.387	0.432	0.413	0.44	0.43	0.27	0.38	0.33	0.32	0.21	0.29	0.55	0.58	0.72	0.61	0.55	0.58	0.72	0.61	0.45
8/30/2017	2	3	11:58	12:00	12:03	0.483	0.483	0.457	0.39	0.37	0.25	0.34	0.29	0.28	0.19	0.25	0.42	0.45	0.63	0.50	0.96	0.45	0.63	0.68	0.45
8/30/2017	2	2	12:32	12:39	12:45	0.438	0.552	0.514	0.33	0.28	0.28	0.30	0.24	0.20	0.20	0.21	0.58	0.65	0.65	0.63	0.58	0.65	0.65	0.63	0.45
8/30/2017	2	1	12:57	1:04	1:09	0.521	0.489	0.521	0.11	0.10	0.10	0.10	0.09	0.08	0.09	0.09	0.88	0.89	0.90	0.89	0.88	0.89	0.90	0.89	0.45
9/10/2017	3	0	11:13	11:19	11:23	0.438	0.400	0.495	0.81	0.70	0.40	0.64	0.64	0.55	0.31	0.50	0.09	0.22	0.38	0.23	0.19	0.22	0.89	0.43	0.03
9/10/2017	3	6	13:05	13:46	14:27	0.718	0.184	0.724	0.87	0.47	0.81	0.72	0.72	0.36	0.65	0.58	0.03	0.30	0.08	0.13	0.10	0.30	0.31	0.23	0.11
9/10/2017	3	6	13:09	13:53	14:35	0.578	0.292	0.584	0.84	0.55	0.76	0.72	0.68	0.42	0.60	0.57	0.04	0.29	0.16	0.16	0.12	0.29	0.45	0.29	0.11
9/10/2017	3	6	13:17	14:00	14:42	0.445	0.445	0.445	0.80	0.60	0.70	0.70	0.64	0.47	0.54	0.55	0.07	0.28	0.25	0.20	0.16	0.28	0.53	0.32	0.11
9/10/2017	3	6	13:28	14:11	14:51	0.318	0.565	0.305	0.77	0.64	0.62	0.67	0.60	0.50	0.47	0.52	0.10	0.23	0.28	0.20	0.16	0.23	0.44	0.28	0.11
9/10/2017	3	6	13:35	14:17	14:59	0.171	0.705	0.159	0.72	0.74	0.55	0.67	0.55	0.59	0.41	0.52	0.12	0.12	0.42	0.22	0.14	0.12	0.47	0.25	0.11
9/11/2017	3	9	10:07	10:49	11:22	0.711	0.178	0.711	0.85	0.25	0.77	0.62	0.69	0.21	0.63	0.51	0.03	0.67	0.09	0.27	0.11	0.67	0.34	0.38	0.06
9/11/2017	3	9	10:10	10:55	11:29	0.578	0.311	0.578	0.83	0.25	0.76	0.61	0.66	0.21	0.61	0.49	0.04	0.68	0.11	0.28	0.12	0.68	0.30	0.37	0.06
9/11/2017	3	9	10:16	11:01	11:32	0.445	0.445	0.451	0.80	0.26	0.73	0.60	0.63	0.21	0.57	0.47	0.06	0.72	0.17	0.32	0.12	0.72	0.37	0.40	0.06
9/11/2017	3	9	10:22	11:07	11:37	0.311	0.559	0.337	0.76	0.35	0.70	0.60	0.59	0.27	0.54	0.47	0.07	0.69	0.21	0.32	0.11	0.69	0.34	0.38	0.06
9/11/2017	3	9	10:39	11:16	11:49	0.184	0.711	0.171	0.74	0.37	0.65	0.59	0.56	0.30	0.50	0.45	0.08	0.45	0.28	0.27	0.10	0.45	0.33	0.29	0.06
9/12/2017	2	0	17:24	17:05	17:41	0.311	0.718	0.254	0.08	0.09	0.09	0.09	0.05	0.06	0.07	0.06	0.93	0.93	0.85	0.90	0.93	0.93	0.85	0.90	0.32
9/12/2017	2	0	17:28	17:10	17:45	0.400	0.565	0.330	0.08	0.09	0.09	0.09	0.06	0.07	0.07	0.06	0.92	0.92	0.85	0.90	0.92	0.92	0.85	0.90	0.32
9/12/2017	2	0	17:31	17:12	17:47	0.489	0.470	0.438	0.08	0.09	0.09	0.09	0.06	0.07	0.07	0.06	0.92	0.92	0.85	0.90	0.92	0.92	0.85	0.90	0.32
9/12/2017	2	0	17:35	17:16	17:51	0.603	0.330	0.718	0.09	0.09	0.09	0.09	0.06	0.06	0.07	0.06	0.92	0.92	0.87	0.90	0.92	0.92	0.87	0.90	0.32
9/12/2017	2	0	17:36	17:19	17:53	0.711	0.419	0.572	0.09	0.09	0.09	0.09	0.06	0.07	0.07	0.06	0.92	0.92	0.86	0.90	0.92	0.92	0.86	0.90	0.32
9/13/2017	4	5	12:59	12:34	13:24	0.711	0.318	0.413	0.07	0.06	0.07	0.07	0.05	0.06	0.05	0.06	0.86	0.87	0.94	0.89	0.86	0.87	0.94	0.89	0.45
9/13/2017	4	5	13:01	12:36	13:29	0.572	0.445	0.489	0.07	0.06	0.08	0.07	0.05	0.06	0.06	0.06	0.86	0.88	0.93	0.89	0.86	0.88	0.93	0.89	0.45
9/13/2017	4	5	13:08	12:45	13:31	0.445	0.222	0.565	0.08	0.06	0.08	0.08	0.06	0.06	0.06	0.06	0.85	0.87	0.92	0.88	0.85	0.87	0.92	0.88	0.45
9/13/2017	4	5	13:14	12:50	13:35	0.248	0.578	0.711	0.08	0.06	0.09	0.07	0.06	0.06	0.06	0.06	0.85	0.90	0.91	0.89	0.85	0.90	0.91	0.89	0.45
9/13/2017	4	5	13:18	12:54	13:37	0.324	0.711	0.635	0.07	0.05	0.08	0.07	0.06	0.05	0.06	0.05	0.88	0.93	0.91	0.91	0.88	0.93	0.91	0.91	0.45
9/14/2017	6	0	8:48	8:51	8:56	0.406	0.451	0.400	0.14	0.15	0.13	0.14	0.11	0.11	0.10	0.11	0.91	0.88	0.95	0.91	0.91	0.88	0.95	0.91	0.23

Position of photograph or observation denoted by: C = center, L = left, R = right (looking downstream)

APPENDIX D. SUITABLE PLANTS

The following list of plant species is provided as a reference for designers of shade restoration plans in the Brown's Creek watershed. The list is not all-inclusive, but characterizes species optimal for shading in Brown's Creek. These species are endemic to Washington County and suited to the hydric soils common in the Brown's Creek stream corridor. These species are common in riparian habitats such as streambanks, wetlands, floodplains, and meadows. In addition, species selection is based on shade benefit in terms of their height, canopy width, and growth rate. Ecological and design professionals should be consulted to determine a specific planting/seeding plan for each particular site.

Table 25. Plants Suitable for Planting in Brown's Creek Riparian Corridor

TREE			
Common Name	**Scientific Name**	**Wetland Status**	**Mature Height / Form**
Silver Maple	*Acer saccharinum*	FACW	30-32m / large canopy
River birch	*Betula nigra*	FACW	20m / slender to round crown
Tamarack	*Larix laricina*	FACW	20m / tapered crown
Bur Oak	*Quercus macrocarpa*	FAC	30m / broad crown
Peachleaf Willow	*Salix amygdaloides*	FACW	10-15m
Black Willow	*Salix nigra*	OBL	15-25m / broad crown
SHRUB			
Common Name	**Scientific Name**	**Wetland Status**	**Mature Height**
Speckled alder	*Alnus incana*	FACW	3-7.5m
Buttonbush	*Cephalanthus occidentalis*	OBL	1.25-4.5m
Silky dogwood	*Cornus amomum*	FACW	1.75-3.5m
Red-osier dogwood	*Cornus sericea*	FACW	1-2.5m
Swamp Rose	*Rosa palustris*	OBL	1.5-2.5m
Slender Willow	*Salix petiolaris*	OBL	2-3.5m
Nannyberry	*Viburnum lentago*	FAC	3-7.5m
GRASS			
Common Name	**Scientific Name**	**Wetland Status**	**Mature Height**
Big Bluestem	*Andropogon gerardii*	FAC	60-210cm
Rattlesnake Manna Grass	*Glyceria canadensis*	OBL	60-150cm
American managrass	*Glyceria grandis*	OBL	90-150cm
Prairie cord grass	*Spartina pectinata*	FACW	90-240cm
FORB			
Common Name	**Scientific Name**	**Wetland Status**	**Mature Height**
Turtlehead	*Chelone glabra*	OBL	60-120cm
Common boneset	*Eupatorium perfoliatum*	OBL	60-120cm
Spotted Joe-pye Weed	*Eutrochium maculatum*	OBL	60-300cm
Sawtooth sunflower	*Helianthus grosseserratus*	FACW	60-300cm
Cup Plant	*Silphium perfoliatum*	FACW	90-240cm
Blue vervain	*Verbena hastata*	FACW	30-180cm
Ironweed	*Vernonia fasciculate*	FACW	90-180cm

APPENDIX E. RIPARIAN SHADE MONITORING PLAN

The objective of this monitoring plan is to assess how shade along Brown's Creek changes after the implementation of shade restoration projects. This plan does not include a method for assessing the progress of enhancing the quality of plant communities overlapped by the shade restoration projects.

The high priority locations of shade restoration projects recommended in the Riparian Shading Study and previously implemented projects are shown in Figure 84. Segments 4, 6, and 8 are also included in this monitoring plan as the next priorities for monitoring and implementation. Additional locations may be added as small sites needing restoration are identified and/or invasive riparian vegetation management activities are performed along with shade restoration plantings.

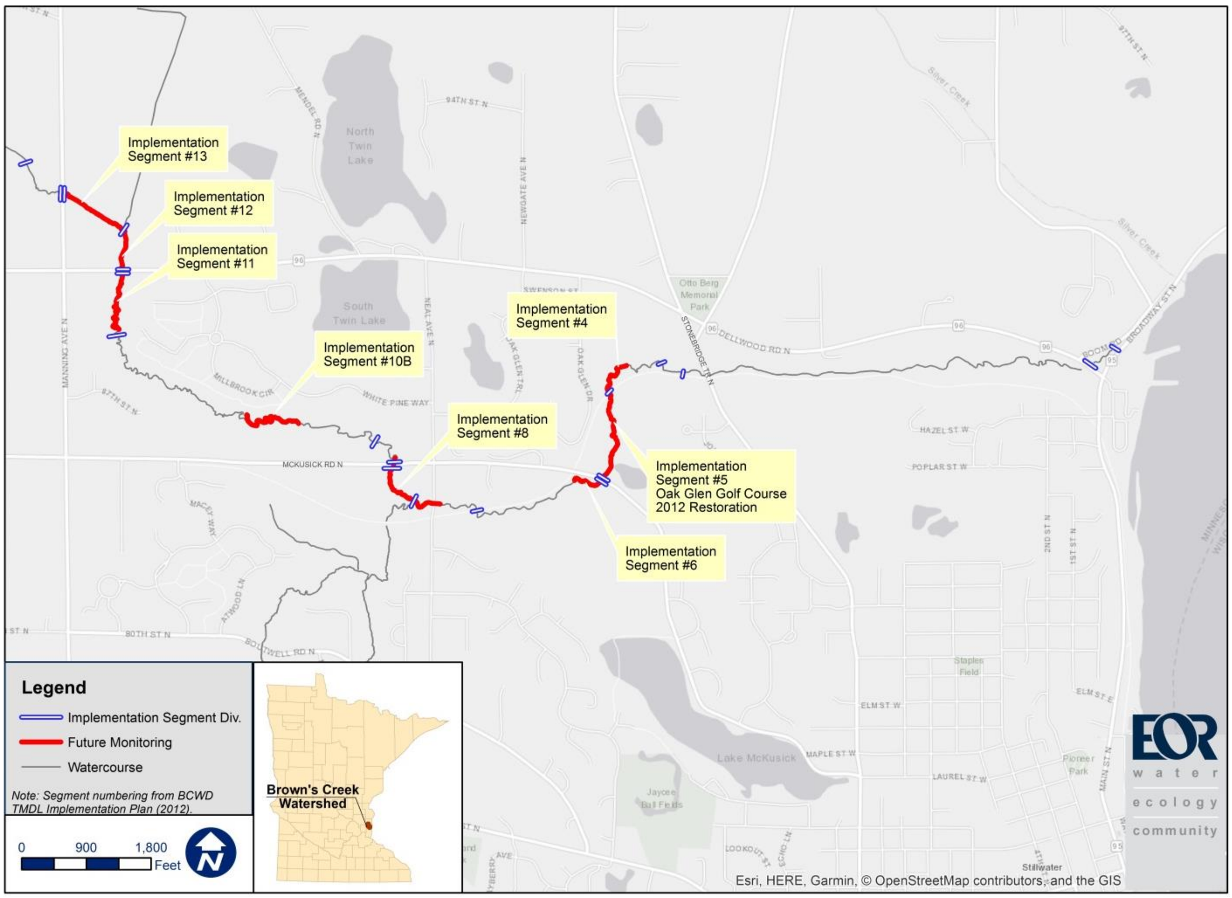

Figure 84. Locations for Riparian Shade Monitoring Program

E.1. Parameters

The key parameter to be assessed in this monitoring plan is the change in shade provided to the water surface of Brown's Creek due to the implementation of shade restoration projects. Additional parameters include the physical characteristics of the channel and riparian vegetation needed as diagnostic data for assessing the shade results and progress towards shade targets.

E.2. Method

The following outlines the method for collecting field data and assessing shade in Brown's Creek:

- After identifying a reach or small site that will undergo shade restoration or other changes to channel or vegetation characteristics, identify multiple transects (points along the length of the reach) spaced approximately 10 m apart with a total of at least 11 transects per reach. The sample reach and transect locations are already defined for the shade restoration projects prioritized in the Riparian Shading Study.
- Collect hemispherical photographs at each transect under baseflow conditions in June, July, or August. Take three photos at each transect from the center, left, and right (Figure 85) measured using a tape measure secured in place with pins (Figure 87). Identify the left and right sides of the transect when looking downstream. The fisheye lens of the camera must face skywards to capture the riparian canopy overhanging the stream (Figure 86). Adjust the tripod to lower the camera as close as possible to the water surface while keeping the camera dry. At the center photo location, collect a handheld global positioning system (GPS) point beside the camera and at the elevation of the lens. An equipment list is provided in Section E.2.1. Fill in the data form provided in Section E.2.2 for each day of field work, including additional characteristic assessment data. Access each transect from upstream or downstream of the sampled reach to avoid trampling the riparian vegetation.
- Pre-Restoration Frequency: Monitor location once before the shade restoration project or improvement is implemented. Note that this step is not necessary for the stream segments monitored in the Riparian Shading Study.
- Post-Restoration Frequency: Starting immediately after shade restoration/improvement activities, monitor every two years for a total of eight post-implementation visits. Note that for the Oak Glen Golf Course 2012 restoration site, the first of eight monitoring activities was conducted as part of the Riparian Shading Study.
- Enter all observations into the overall data collection spreadsheet on EOR's server[8]. Save copies of the completed field data forms here as well as retaining the original hard copies of the forms. Save and rename all photos with a reach, transect, and position (e.g. "R01T05M.jpg" for Reach 1, Transect 5, Middle Position).
- Analyze each photo in the software WinSCANOPY using the same parameter settings as the Riparian Shading Study. Save the analyzed photos and associated WinSCANOPY files in a separate folder in the BCWD Library on EOR's server[6]. Record the WinSCANOPY results for each photo in a spreadsheet containing all monitoring results, including: total site factor, total hemisphere gap fraction, and total hemisphere openness.
- In the results spreadsheet, calculate the shade estimated by WinSCANOPY in each photo as 1 minus the total site factor. Calculate the average shade at each transect (i.e. the average of shade at the left, middle, and right positions) and the average across the sampled reach.

Analysis of the collected data and WinSCANOPY analysis results is detailed in the next section.

[8] X:\Clients_WD\041_BCWD\LIBRARY\Monitoring_data\Shade

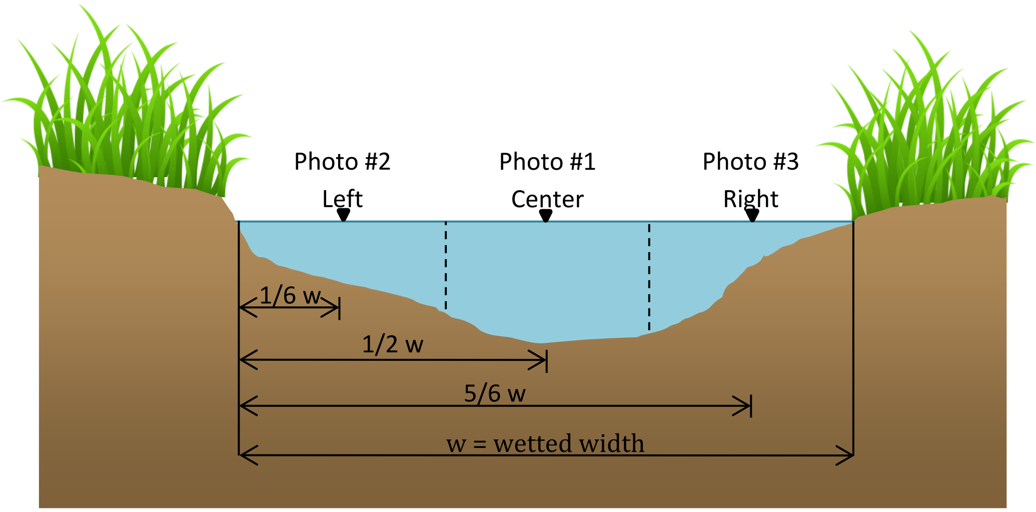

Figure 85. Example Transect with Photograph Locations

Figure 86. Example of Hemispherical Photograph

Figure 87. Setup for Center Photo

E.2.1. Equipment List

All equipment is available through the BCWD's engineering consultant, Emmons & Olivier Resources.

Long Tape Measure

Pins

Short Tape Measure

Surveyor's Rod

Compass

GPS Handheld

Tripod

Camera, O-Mount, and Remote

Clipboard

Pen

Data Forms (Section E.2.2)

E.2.2. Data Form

Date	Wind: Constant Motion (CM) or Still (S)
Page of	Light: Overcast (O), Partly Cloudy (PC), Cloudy (C), Sunny (S)
Surveyor(s)	Photo Location: Left (L), Middle (M), Right (R) (looking downstream)

Reach #	Transect # [1]	Stream Azimuth[2] (°)	Wetted Width (m)	Thalweg Depth (m)	Width of Exposed Bank (m)	Width of Overhanging Bank (m)	Height of Bank Adjacent to Stream (m)	Mode Height of Herbaceous Vegetation (m)	Width of Overhanging Herbaceous Vegetation (m)	Density of Vegetation [3]	Dominant Under & Overstory Species[5]	Distance to Nearest Tree[4] (m)	Photo Location (L, M, R)	GPS Point Location[6] (L, M, R)	Time of Photo	Lens Height above Stream (m)
					L	L	L	L	L	L	L	L	L	L	L	L
					R	R	R	R	R	R	R	R	R	R	R	R
													M	M	M	M
					L	L	L	L	L	L	L	L	L	L	L	L
					R	R	R	R	R	R	R	R	R	R	R	R
													M	M	M	M
					L	L	L	L	L	L	L	L	L	L	L	L
					R	R	R	R	R	R	R	R	R	R	R	R
													M	M	M	M

(1) Begin numbering transects at upstream end of sampled reach.
(2) Measure the direction that the stream is flowing at the transect relative to due north.
(3) On a scale of 0 to 1 where 0 represents low density of vegetation (e.g. mowed turfgrass) and 1 represents high density vegetation (e.g. no sunlight penetrating through canopy).
(4) Measured if tree is within 15 m of stream.
(5) Visible from stream
(6) Collect a GPS point at one of the three photographs collected across each transect.

All heights measured relative to water surface.

At each transect, note activities within the riparian area influencing plant establishment, such as beavers, grazing, mechanical disturbance, development, etc.

Review the tree planting plan and confirm the number of trees that have survived.

E.3. Reporting Results and Recommending Corrective Actions

Updates on the shade trends will be included in the Washington Conservation District's annual monitoring reports. The results should include trends in average shade at each transect and averaged across the sampled reaches over time. From the shade trend analysis and additional field data, the reporting should discuss potential corrective actions, if necessary, and update the estimated lag time (e.g. Figure 61) until target shade will be achieved. Continued monitoring of shade at the same transect locations over time will provide the data needed to assess the lag time from the time of planting to reaching target shade levels. The characteristic assessment data will also provide the necessary information to diagnose issues with shade establishment by tracking changes in morphology and plant establishment. Corrective actions may include planting new trees due to mortality or loss from beaver activity, beaver management, and additional herbaceous plantings to enhance near-stream canopy structure. Particular attention is needed to the height of herbaceous vegetation, exposed streambank, and success of tree establishment as shade is very sensitive to these characteristics. The recommended timing and cost of corrective actions should also be presented in these reports.

Every five years, at the same time as the BCWD's hydrologic and hydraulic model update, it is also recommended that the Brown's Creek Stream Temperature Model in CE-QUAL-W2 be updated using the observed shade. Pertinent model results include simulated daily maximum and mean stream temperatures as well as the number of hourly and daily exceedances of the threat temperature.

E.4. Implementation

Washington Conservation District staff will incorporate data collection from this monitoring plan into their ongoing monitoring activities in the Brown's Creek watershed. Their team is well suited to take on this task and can establish the necessary capacity as they bring in and train new staff. BCWD will procure further assistance where needed from EOR and the Saint Anthony Falls Laboratory to process the hemispherical photographs and periodically update the stream temperature model.