DEPARTMENT OF TRANSPORTATION

Assessing Culverts in Minnesota: Fish Passage and Storm Vulnerability

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Culverts at road-stream crossings can create barriers to movement within a stream network that can have dramatic consequences for fish populations by fragmenting habitat. Culverts can become barriers when flow conditions exceed fish swimming ability, e.g., for drop at the outlet and insufficient depth or excess flow velocity. In this project, we use a simple modelling framework to assess 50 culverts throughout Minnesota to: a) determine what fraction of these culverts currently present a fish passage barrier for both high flows (velocity barrier) and low flows (depth barrier) and b) to summarize design parameters that most affect passibility (e.g., culvert width). The estimated high and low flows are fed into the HY-8 culvert hydraulics model, and the resulting velocity and depths are compared to published fish swimming capabilities. We also assess future (2061-2080) high- and low-flow fish passage conditions for five culvert sites using global climate model outputs, Hydrologic Simulation Program Fortran (HSPF) runoff models, and the fish passibility modelling framework. Both low- and high-flow conditions in streams are very responsive to future climate, with either positive or negative future changes, depending on which global climate model is used. This study concludes that maintaining a low-flow channel or embedded culvert barrel will make culverts more passable during changes in low flows and ensuring culvert widths equal to or greater than the bankfull channel width in combination with embedded sediment will help mitigate increases in high fish-passage flows and high peak flows.

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LIST OF ABBREVIATIONS

QLP: Low passage flow. This represents the lowest discharge for which fish passage is required. 90th percentile based on the annual flow duration series. This represents the lowest 10% of the flows over a year.

QHP: High passage flow. This represents the upper bound of discharge at which fish are believed to be moving. 5th percentile based on the annual flow duration series. This represents the highest 5% of the flows over a year.

Q1.5, Q2, Q50, Q100: Peak flows based for each statistical return interval (1.5, 2, 50, and 100 yr return intervals).

Overtopping flow: Discharge where road crossing is overtopped.

HY-8: Culvert hydraulic modeling software (https://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/) published by the Federal Highway Administration

EXECUTIVE SUMMARY

In Minnesota and much of the country, culvert design is moving away from traditional hydraulically designed culverts to those that accommodate aquatic organism passage (see Hernick et al. 2019). Often, these designs result in a larger culvert barrel and one or more barrels being set below the stream bed elevation with the goal of maintaining a continuous stream bed through the culvert. Because of their larger size, these culverts are often more expensive, but recent research (O'Shaughnessy et al. 2016; Gillespie et al. 2014; Christiansen et al. 2014) indicates that in many cases, despite higher upfront costs, the ecologically designed culverts are more cost-effective due to their longer life span, reduced need for maintenance, and improved flood resiliency.

This project was designed to answer two main research questions: 1) What is the scope of fish passage concerns across the state? and 2) How vulnerable are conventional and fish passage designs to current and potential climate scenarios? It should be noted that this project focused on a sensitivity analyses of culvert design parameters spanning a large number of culverts and not accurate designs of individual culverts. The techniques and data required for use in this modeling study were not intended as a methodology for culvert designers to use in design.

To model culvert hydraulics across a range of flows, 50 culverts in 10 different watersheds across Minnesota were surveyed for dimensions, slope, tailwater elevation, and sediment characteristics. HY-8, a culvert hydraulics model developed by the Federal Highway Administration, was used to model depth, velocity, and shear stress within the culvert barrels. These model results were used to evaluate fish passage at high and low fish passage flows and were used to evaluate the relative depths, velocities, and shear stresses within culvert barrels and the streams. Together, these results supported guidance for culvert designs that match the stream channel characteristics, width, depth, velocity, shear stress, and sediment, and illustrated the importance of considering passage at both high and low flows. A subset of these culverts was selected to model the response to projected future climate.

To model the response of stream flow and fish passage to projected future climate, HSPF (Hydrologic Simulation Program Fortran) rainfall-runoff models were assembled and calibrated for the catchments of five culverts: two culverts in the Beaver River (Superior Northshore), a culvert in a tributary of the Snake River (mid-state), a culvert in the Root River (Southeast Minnesota), and a culvert in a tributary of the Cottonwood River (Southwest Minnesota). The runoff models were used to project future changes in the flow parameters related to fish passage, sediment transport, and culvert overtopping. The runoff models for each catchment were used to perform both continuous flow analysis to analyze future changes in the fish passage and sediment flow parameters and discrete storm-event analysis to analyze future changes in overtopping flows. The simulated flow rates from the runoff models were compared to the fish passage, sediment, and culvert overtopping thresholds from the culvert hydraulic models to project future changes in culvert fish passibility and overtopping frequency.

For future flow analysis, the rainfall-runoff models used the outputs of downscaled global climate models (GCMs) for the period of 2061-2080. Each of the 20-plus GCMs outputs available gave somewhat different projections of future rainfall and air temperature patterns. To put bounds on future streamflow conditions, the runoff simulations were run for four GCMs with varying degrees of change in mean annual air temperature and mean annual precipitation. Simulated low-flow fish passage conditions (the lowest 10% of all flows) in streams were very responsive to future climate and projected to change anywhere from -90% to +220%, depending on the GCM used and the site. In addition, 1.5-year return period flows, which were used to analyze sediment mobility in culverts, were projected to change from -56% to +260%. High fish passage flow conditions (the highest 5% of all flows) were also responsive to future climate, changing anywhere from -42% to +74%. For road overtopping analysis, an Environmental Protection Agency (EPA) database of future storm sizes was used to simulate storms with 25-, 50-, and 100-year return periods. Projected future storm size increases of up to 18% led to increases in peak flow of up to 88%.

A novel feature of this study was the ability to use the continuous rainfall-runoff simulations to assess the average number of days per year that a particular culvert presents either a velocity barrier or a depth barrier to fish passage. Three climate scenarios with low to moderate increases in rainfall led to increases in the number of days with a depth barrier for the two study culverts that currently present potential depth barriers. The wettest climate scenario led to decreases in depth barriers but an increase in velocity barriers of up to 20 days per year.

Both low-flow depth barriers and high-flow velocity barriers present concerns for fish passage in Minnesota across culvert types based on the results of this study. In summer, shallow depths can limit fish movement to areas such as thermal flow refugia and can block both upstream and downstream movement. High velocities can limit upstream movement in critical spawning times, especially for low endurance swimmers such as Northern Pike. Specific culvert design concerns identified in the screening-level analysis of 50 culverts include:

1. High bankfull width ratios (culvert opening width/bankfull channel width) > approximately 2 can create shallow flows that are a concern for low-flow depth barriers.
2. Low bankfull width ratios (culvert opening width/bankfull channel width) <1 can create flow constrictions that are a concern for high-flow velocity barriers.
3. High slope (>1%) culverts had more low-flow depth barriers and more high-flow velocity barriers.
4. Even for culvert widths > bankfull widths, velocity can be a concern in steeper culverts and roughness (embedded sediment) is important for resting areas and decreasing velocities.
5. Embedded culverts reduced but did not eliminate barriers, suggesting that other considerations, such as culvert width, slope, and cross-section are also important.

There is significant uncertainty over future climate scenarios and the corresponding hydrology. Yet, these scenarios provide bounds for potential future flow rates with which to evaluate culvert resiliency. The following conclusions were based on the detailed hydrologic/hydraulic analyses of future flow conditions in five culverts:

1. Future hydrologic scenarios across Minnesota are particularly sensitive to changes in low flow. Maintaining a low-flow channel or embedded culvert barrel can help fish navigate culverts

during low flows. Backwatering the culvert with a passible downstream grade control can also help to mitigate this effect.

2. Ensuring culvert widths equal to or greater than the channel width in combination with embedded sediment can help mitigate increases in high fish passage flows by reducing velocities and providing resting areas.
3. Culverts with bankfull width ratios < 1 are particularly susceptible to decreases in the overtopping return interval (more frequent overtopping by more frequent large storms).
4. Culverts with shear stresses significantly more or less than the channel are susceptible to scour or deposition. Designing the crossing similar to the channel helps alleviate these issues.

In general, these conclusions emphasize that culvert designs that maintain stream connectivity (Hernick et al. 2019) are more resilient to effects of changing climate. This study provides support that a culvert designed at bankfull width or slightly greater is more resilient to current and future large flow events than a traditional hydraulic design. Culvert designs that that have some capacity to adjust (embedded culverts) are also likely more resilient in terms of fish passage to high and low flows. This study also highlighted limitations of current guidance including the need for better information on low-flow channel design, the inclusion of floodplain culverts for large flow events, and the limitations of the reliance on bankfull channel width as a design parameter. Current guidance relies on an accurate estimate of bankfull width, but this parameter is challenging to measure in the field, especially in situations where local hydrology is changing.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

In Minnesota and much of the country, culvert design is moving away from traditional hydraulically designed culverts to those that accommodate aquatic organism passage (see Hernick et al. 2019). Often these designs result in a larger culvert barrel and one or more barrels being set below the stream bed elevation with the goal of maintaining a continuous stream bed through the culvert. Because of their larger size, these culverts are often more expensive, but recent research (O'Shaughnessy et al. 2016; Gillespie et al. 2014; Christiansen et al. 2014) indicates that in many cases, despite higher upfront costs, the ecologically designed culverts are more cost-effective due to their longer life span, reduced need for maintenance, and improved flood resiliency.

This project is designed to answer two main research questions: 1) What is the scope of fish passage concerns across the state? and 2) How vulnerable are conventional and fish passage designs to current and future climate scenarios? This project evaluates culvert design parameters with a simplified modelling study intended to identify trends spanning a large number of culverts (and not an accurate design of a single culvert). The hydraulic and hydrologic modelling techniques and data required for use in this modeling study are not intended as a methodology for culvert designers to use in design.

CHAPTER 2: SUMMARY OF METHODS

2.1 OVERVIEW

The goals of this project are to evaluate the impact of culvert design on fish passage and culvert resiliency at current and projected future hydrologic scenarios. Culvert design parameters evaluated include culvert dimensions, culvert slope, number of barrels, ratio between channel width and culvert opening width, and recessed or embedded barrels. Culverts are recessed if a culvert barrel is set below stream grade and are embedded if sediment is placed or present within the recessed culvert barrel. A traditional hydraulic culvert design is a culvert sized to pass discharge of a specified return interval (i.e. 50-yr return interval flow). Culvert design guidance to accommodate fish passage generally promotes channel spanning culverts (width great than or equal to the channel width) with one or more recessed or embedded barrels (Hernick et al. 2019). The goal of these designs is to match the culvert characteristics (depth, velocity, sediment mobility, and habitat) to the stream characteristics to ensure uninhibited fish passage across a range of flows. The design of existing culverts in Minnesota is highly variable and this project is designed to evaluate trends between culvert design parameters (relative width, slope and embeddedness) to fish passage, stream connectivity and resiliency in current and future scenarios. The first phase of this project was to screen a large number of culverts (50) across Minnesota to identify potential fish passage barriers, similar to a study conducted in Northeast Ohio (see Rayamajhi et al. 2012; Baral 2013). The second phase was to conduct a more detailed analysis of four culverts to evaluate the resiliency of these culvert designs to future hydrologic scenarios.

Fish passage screening (Phase I, 50 culvert sites):

1. Is culvert velocity less than velocity criteria based on the swimming ability of a target fish species or community of fish at a specified high fish passage flow?
2. Is culvert depth greater than depth criteria based on the depth requirements for a target fish species or community of fish at a specified low fish passage flow?
3. Is the depth and velocity within the culvert barrel similar to the stream at key passage flows?
4. Is the sediment mobility within the culvert barrel similar to the stream at flows?

Resiliency to current and future hydrologic scenarios (Phase II, 5 culvert sites):

1. At what return interval will the road-stream crossing overtop under current and future flows?
2. How do fish passage barriers change under current and future flows?
3. How does stream connectivity change under current and future flows?

A combination of hydraulic modeling and hydrologic modeling were used to evaluate these questions. Input to the analysis included: culvert design (dimensions, slope, material, embeddedness, etc.), hydrologic variables (high and low fish passage flow, peak flows at 1.5, 25, 50 and 100 yr return intervals for current and future hydrologic scenarios), fish swimming criteria (prolonged and burst speeds for a range of Minnesota fish) and sediment characteristics (grain size distribution) (Figure 1). Because this study relies on simplified hydraulic and hydrologic modeling, the results of this study are not intended to evaluate the performance of any particular culvert site, but intended to identify trends that can be used to inform culvert design (Hernick et al. 2019).

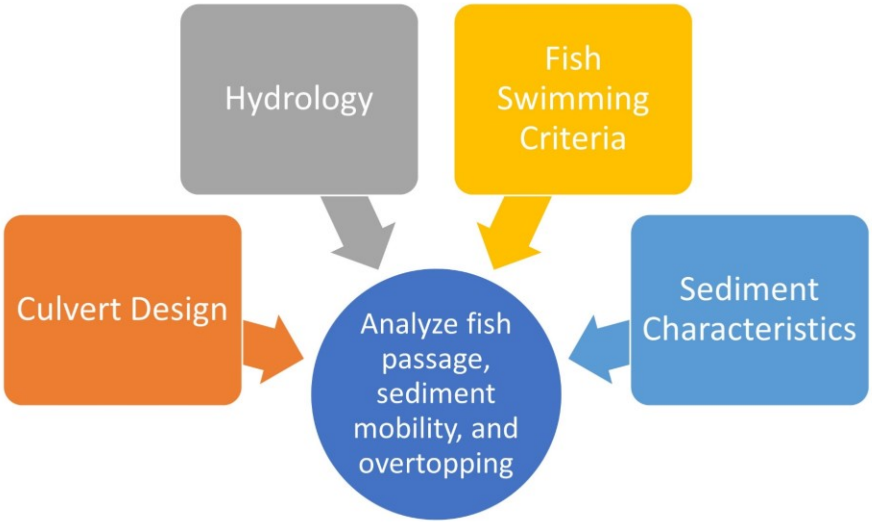


Figure 1. Overall project layout combining field data collection of culvert and stream characteristics with modeled current and future hydrology with a database of Minnesota fish swimming abilities to analyze fish passage, sediment mobility and overtopping frequency.

2.2 DESCRIPTION OF HYDROLOGIC VARIABLES

Relevant flow rates need to be defined to evaluate culvert performance. For this study, fish passage was evaluated at representative high and low passage flows (QHP and QLP). These flows represent the highest and lowest discharges for which fish passage is required. Different states and regions have different criteria to define these flows (Kilgore et al. 2010), but Minnesota does not have a statewide standard. For this study, fish passage flows were calculated based on the annual flow duration series as described below (Hotchkiss and Frei, 2007).

QLP: Low passage flow. This represents the lowest discharge for which fish passage is required and is calculated as the 90th percentile based on the annual flow duration series. This represents the flow where 90% of the daily flows are greater over a year.

QHP: High passage flow. This represents the upper bound of discharge to evaluate fish movement and is calculated as the 5th percentile based on the annual flow duration series. This represents the flow where 5% of the daily flows are greater over a year.

For current conditions, fish passage flows were estimated from StreamStats (https://streamstats.usgs.gov/ss/; Ziegeweid et al. 2015). For future scenarios, fish passage flows were estimated from modeled future flow duration curves.

Discharge rates for key return interval storms were extracted from relevant peak flow analyses as defined below. For current conditions, peak flows were estimated from StreamStats (https://streamstats.usgs.gov/ss/; Lorenz et al. 2010). For future scenarios, fish passage flows were estimated from modeled peak flow as described in Section 6.3.

Q1.5, Q2, Q50, Q100: Peak flows based for each statistical return interval (1.5, 2, 50, and 100 yr return intervals).

To evaluate culvert resiliency, the discharge at which the road-stream crossing was overtopped was used. This value was estimated using the HY-8 hydraulic modeling for each culvert site (https://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/).

Overtopping flow: Discharge where road crossing is overtopped.

2.3 HYDRAULIC MODELING

To evaluate culvert performance, depth, velocity, and shear stress are required at different flow rates. While FishXing (https://www.fs.fed.us/biology/nsaec/products-tools.html) is designed to evaluate culverts for fish passage, a standard engineering software, HY-8, was utilized in this study to model culvert hydraulics. The output depth and velocity profiles were then compared to fish swimming criteria and the output shear stress was used to estimate sediment mobility.

Input to HY-8 consists of culvert dimensions, a tailwater cross section, culvert and tailwater slope, and culvert and tailwater roughness. These data were measured in the field, but carefully checked with the following adjustments. LiDAR data were downloaded from MNTopo (http://arcgis.dnr.state.mn.us/maps/mntopo/) and were used to verify tailwater slope, tailwater cross-section, or roadway data or to estimate these variables where the information was missing. For some sites, the surveyed tailwater cross-sections did not extend onto the floodplain enough to contain the QHP flow. LiDAR data were used at these sites to extend the cross-sections to include a larger portion of the floodplain. At sites where the stream was deeper than was safe to enter, LiDAR data were used to estimate the tailwater cross-section and slope. Because LiDAR cannot accurately measure topography below the water's surface, care was taken to ensure the tailwater elevation remained reasonable in these circumstances and this elevation was adjusted when necessary. The elevation of tailwater cross-sections for some sites were also adjusted to better match the observed outlet conditions. For some culverts this meant raising the bottom elevation using the tailwater slope, and for other sites the cross-section was adjusted to match the elevation of downstream grade control structures. Roadway data were extracted from the LiDAR by comparing the elevation of the streambank and the roadway. The difference in elevation was used to establish roadway elevations in the survey coordinates for sites where that information was missing.

Sediment within culverts can only be modeled as a layer of even thickness in HY-8. As a result, some of the culvert invert data were altered so that the culvert slope would match the sediment slope. Adding an even layer of sediment would then result in the culvert having the proper roughness, elevation, and slope that was observed in the field.

The Manning's roughness of the tailwater cross-sections were user selected using photos taken at each site and a reference table for Manning's n values for channels (Chow~~,~~ 1959). Roughness values were estimated separately for the floodplains and the channel.

2.4 PASSAGE BARRIERS BY SPECIES

Passage barriers for fish were identified for water velocity, depth, and if the culvert was perched. HY-8 results were compared to fish swimming information contained in a database compiled from FishXing and other peer- reviewed sources. The database in FishXing was updated in 2006; however, since this time, many new studies have addressed swimming speeds and a comprehensive review of available studies for all Minnesota fish species was conducted (see Appendix A; Table 1). The barrier comparisons were conducted for the fish species within each of the major basins in Minnesota (Hatch 2015). The average swimming speed or calculated swimming speed for the average fish length reported in each reference was used as a representative speed. Swimming performance is typically assessed using swim tunnels or flumes and is broken down into burst, prolonged, or sustained swimming capabilities (Cano-Barbacil et al. 2020). Burst swimming are maximum speeds for short periods (<20-30 s) and sustained swimming is for long periods of time (>200 minutes). Prolonged swimming speeds can be maintained for intermediate intervals of time. There can be significant variation within and between reported values for individual species due to fish length, experimental methods, temperature, etc. and the values in Table 1 should be verified with the source reference before use in other studies to ensure that the appropriate swimming criteria is used. Taken together, however, these values provide a range of typical swimming criteria for Minnesota fish species.

Table 1. Estimated Fish Swimming Criteria (see Appendix A for sources).

Common Name		**Mean Speed (ft/s)**	
	Mean Length (in)	**Prolonged**	**Burst**
Minnesota State Listed Invasive			
Alewife	9.3	1.6	3.9
Carp, Bighead	3.7	0.8	
Carp, Common	6.0	2.8	3.7
Carp, Grass		3.6	
Carp, Silver	29.3	3.3	
Goby, Round		1.2	3.2
Goldfish	8	1.7	4.5
Lamprey, Sea	12.9	0.8	
Smelt, Rainbow		1.3	
White Perch	9.9	1.9	
Minnesota State Listed Special Concern			
Chub, Lake		1.0	
Dace, Redside	1.6		2.5
Eel, American		0.7	
Minnow, Suckermouth	2.6	1.5	2.8
Shiner, Redfin	1.8		1.8
Shiner, Topeka	1.7	1.3	2.5
Sturgeon, Lake	6.2	1.3	
Minnesota State Listed Threatened			

Common Name		Mean Speed (ft/s)	
	Mean Length (in)	Prolonged	Burst
Topminnow, Plains	2.2	1.2	2.6
Extirpated Native			
Shiner, Ghost	1.4	1.5	
Minnesota State Listed Non-Native			
Salmon, Atlantic	24.9	0.5	7.8
Salmon, Chinook	29.7	5.1	14.0
Salmon, Coho	23.0	3.2	13.8
Salmon, Pink	21.6	4.5	11.4
Stickleback, Threespine	2.2	1.2	
Trout, Brown	8.0	4.2	6.9
Trout, Rainbow	7.2	2.6	6.4
Minnesota State No Conservation Status			
Bass, Largemouth		1.3	
Bass, Smallmouth	12.4	2.5	4.5
Bluegill		0.9	1.4
Buffalo, Smallmouth		2.0	
Bullhead, Black	2.7	1.1	2.1
Burbot			2.0
Catfish, Channel	5.8	2.0	
Chub, Creek	2.8	1.7	3.0
Chub, Hornyhead (SGCN)	1.8		2.2
Dace, Longnose	2.8	1.4	2.5
Dace, Northern Redbelly	2.2	1.3	2.5
Darter, Iowa	1.9	1.2	2.4
Darter, Johnny	2.4	1.2	2.1
Goldeye	8.9	2.0	
Killifish, Banded	2.6	1.1	2.8
Minnow, Bluntnose	1.8		2.2
Minnow, Brassy	2.4	1.4	3.0
Minnow, Fathead	2.5	1.3	2.2
Northern Pike	14.6	1.2	
Pumpkinseed	5.0	1.2	
Redhorse, River	23.9	5.0	
Redhorse, Shorthead	16.0	4.3	
Redhorse, Sliver	20.5	3.6	
Sauger			4.1
Sculpin, Mottled	2.5	1.7	5.1
Sculpin, Slimy	3.1		
Shiner, Common	2.4		2.1
Shiner, Emerald	1.6		2.7
Shiner, Golden	2.6	1.5	
Shiner, Mimic	1.4	1.4	
Shiner, Red	1.9	1.8	2.3
Shiner, Sand	1.7		2.2
Shiner, Spotfin	2.4	2.2	2.0
Shiner, Spottail		0.7	
Shiner, Weed (SGCN)	1.6	1.3	
Stickleback, Brook	2.5	1.0	2.3
Stickleback, Ninespine		0.7	

Common Name		Mean Speed (ft/s)	
	Mean Length (in)	Prolonged	Burst
Stonecat		1.7	2.0
Stoneroller, Central	2.1	1.2	2.2
Sturgeon, Shovelnose	7.7	1.2	
Sucker, Longnose (SGCN)	10.0	2.0	6.0
Sucker, White		2.1	
Sunfish, Green	3.0	1.3	2.6
Trout, Brook	4.4	1.0	3.1
Trout, Lake	4.2	1.3	
Trout-perch	2.8	1.8	
Walleye	15.6	2.6	7.5
Whitefish, Lake	11.6	1.7	3.5

For determining velocity barriers, fish swimming speeds were compared to culvert water velocities. This comparison was done for two different swimming modes, prolonged and burst. Mean (of reported data) prolonged swimming speeds were compared to mean (along the length of the culvert) water modeled water velocities, and mean burst speed were compared to the maximum modeled water velocities. The comparisons could yield three different results, passable, impassable for average velocity, and impassable for maximum velocity. These results were then used to calculate the percentage of fish species that were able to pass through each culvert based on velocity. Fish with no data on swimming speed were given the value NR for "no record".

Due to a lack of information on fish dimensions, particularly fish body depth, depth barriers were assumed to occur if the minimum water depth in the culvert was less than 0.2 feet. The decision flow chart is shown in Figure 2.

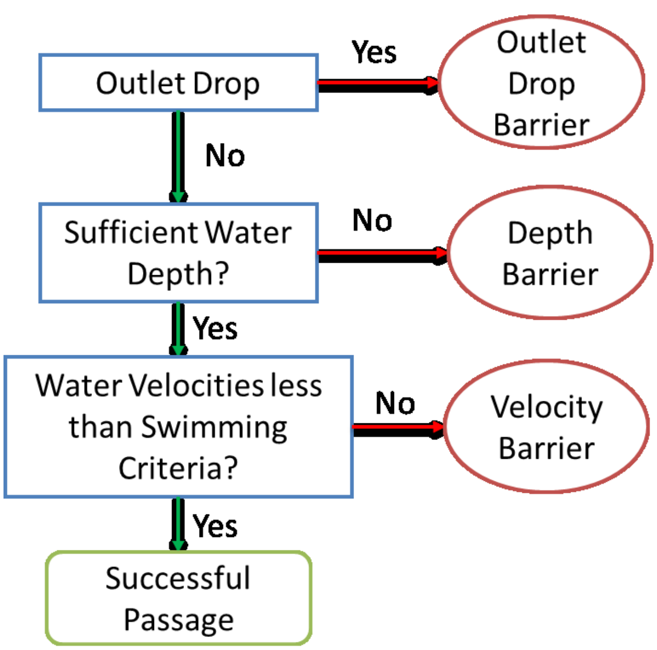


Figure 2. Flow chart for determining potential barriers or successful passage using HY-8 model results.

2.5 EVALUATING PASSAGE BARRIERS AND CULVERT DESIGN

To investigate the effect of culvert design (depth, slope, material, embedded, or offset barrels) on fish passage, culverts were classified based on modeled depth and velocity at QLP and QHP flows. A culvert was considered to be passible for depth if the modeled depth was greater than 0.2 ft in any barrel. A culvert was considered to be passible for velocity if the modeled velocity was less than 2.0 ft/s in any barrel with > 0.2 ft depth, or in the case of a culvert with depths < 0.2 ft, the velocity in the barrel with the greatest depth. These criteria were selected based on general assumptions (see Hillman 2015) of Minnesota fish swimming ability and do not capture the full diversity of swimming abilities. For the Minnesota fish species with available data (not including invasive species), the median prolonged swimming speed is 1.4 ft/s and the mean swimming speed is 1.8ft/s. Many species cannot swim above 1.5 ft/s for prolonged periods (Figure 3); however, based on the available data, the velocity criterion of 2.0 ft/s (the 75th percentile of available swimming criteria) provides a reasonable value to evaluate culvert velocities for potential swimming barriers. A velocity of 2.0 ft/s exceeds the mean prolonged swimming criteria for 75% of the species for which data are available. Historically, as a rule of thumb, MNDNR recommended that to be passible, velocities within culvert barrels needed to be < 2.0 ft/s at the 2-yr flow event. This recommendation remains a starting point for comparing current and proposed conditions (per. Comm. P. Leete).

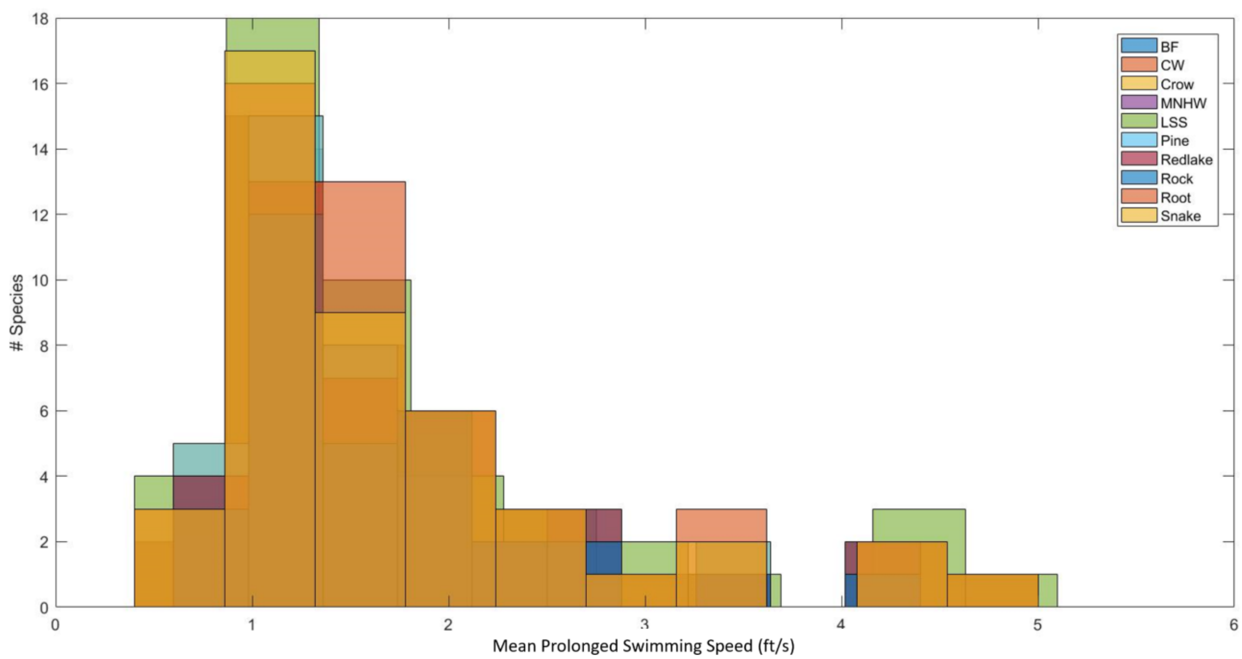


Figure 3. Histogram of prolonged swimming speeds for Minnesota fish species by watershed (Big Fork (BF), Cottonwood (CW), N. Fork Crow (Crow), Minnesota Headwaters (MNHW), Lake Superior South (LSS), Pine, Red Lake (Redlake), Rock, Root, Snake). Note that the distribution of swimming speeds is similar across watersheds included in this study.

CHAPTER 3: SITE SELECTION AND DATA COLLECTION

Culvert site selection was based on: i) data availability, ii) input from the technical advisory panel and other stakeholders, iii) field visits and data collection, and iv) a range of fish communities, existing culvert types and geomorphic settings. To ensure that iv was met, 50 culverts were selected from ten different HUC8 watersheds. Potential culverts were identified using all available culvert location databases including MnDOT (http://dotapp9.dot.state.mn.us/bridgeinfo3/) and MNDNR (https://www.dnr.state.mn.us/watersheds/culvert_inventory/index.html. These watersheds were dispersed across the major basins used to delineate fish communities in Minnesota (Hatch 2015) as well as Minnesota level 3 ecoregions and incorporated special areas of interest, like Topeka Shiner habitat. Within each watershed, the culverts were selected at random. The distribution of culvert sizes and types was also evaluated when selecting the sites. This was done to ensure that the sites chosen were a representative sample of the culverts in Minnesota. The map in Figure 4 shows the locations of the culverts.

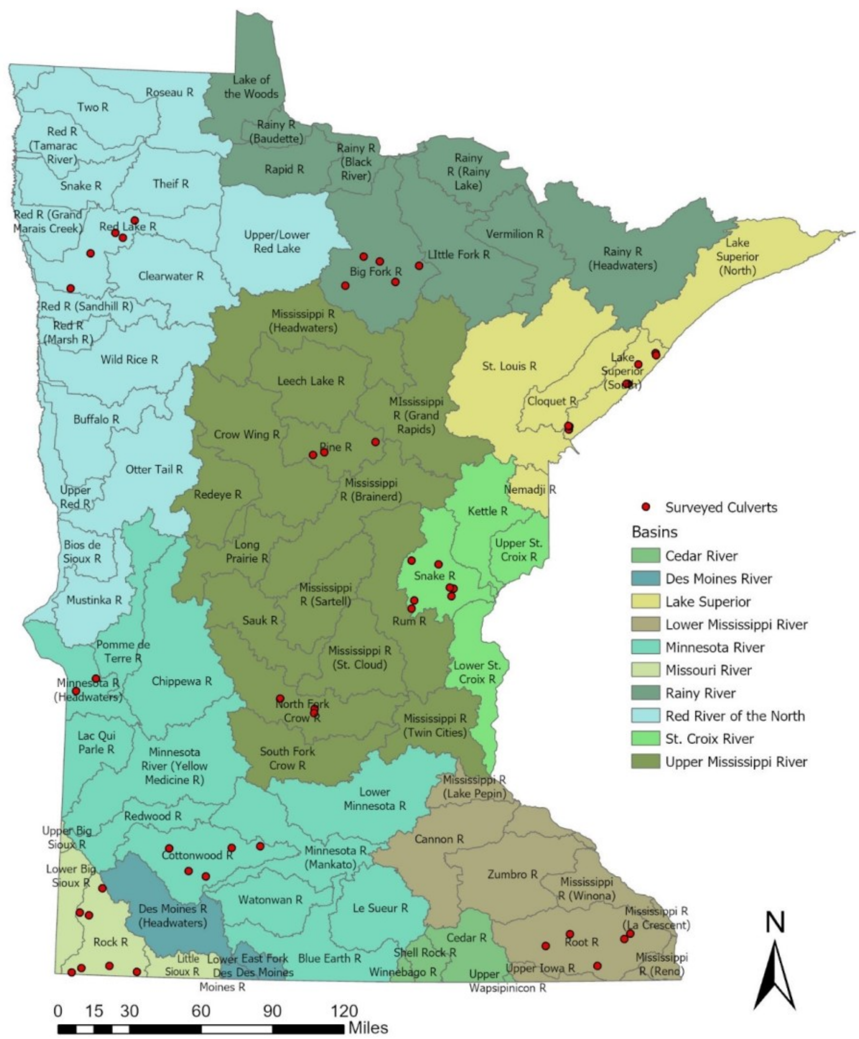


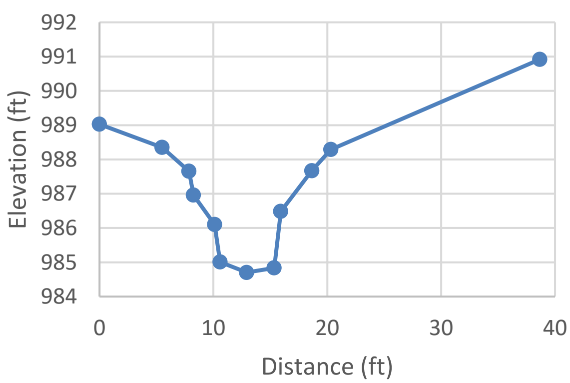
Figure 4. Map of culvert locations.

3.1 DATA COLLECTED

3.1.1 Culvert Data

At each site, the research team recorded culvert type, shape, material, dimensions, inlet configuration, and sediment. Any passage concerns at the time of data collection were noted. The field datasheet used can be found in Appendix B. Each data sheet included a sketch of the sediment distribution within the culvert barrel and of any unusual features in the vicinity of the culvert. The datasheet used was created based on the MNDNR Full Assessment Datasheet found in Hillman (2015) with modifications for data collection focused on requirements for HY-8.

At each site, a robotic total station was used to measure the relative elevations of culvert inverts to calculate culvert slope and a tailwater cross-section with roughness descriptions was surveyed to calculate stream flow characteristics (Figure 5). In addition, stream thalweg elevations were measured to estimate tailwater slope. Site conditions were documented with photographs at each site (Figures 6 and 7).



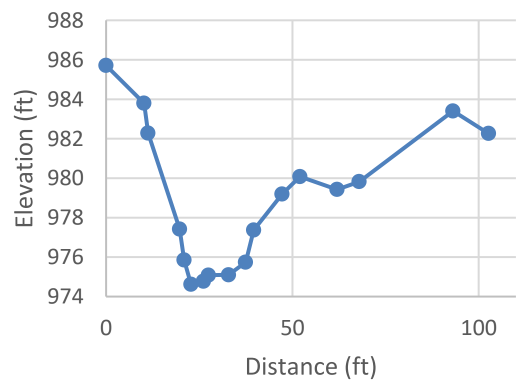


Figure 5. Tailwater cross-section from culverts in the Root River (left) and Red Lake River (right). Both the elevation and distance are relative measurements

The site selection for this project was designed to gather information about culverts across the state with a range of watershed sizes, culvert types, slopes and designs. The USGS StreamStats tool was used to calculate the drainage area for each culvert. The majority of the visited culverts fell within the range of 2-12 mi^2 with a median watershed size of 9.2 mi^2 and a minimum of 0.4 mi^2. Similarly, most of the culverts surveyed were on local roads as would be expected by a stratified random culvert selection. More than half of the surveyed culverts had more than one barrel. Culvert slopes were calculated using the surveyed inverts. The median slope of the culverts was 0.3% with a maximum slope of 2%. There were a number of culverts with negative slopes. The majority of the culverts surveyed had outlets with 0 or less than 0.5 ft of perch. Other information recorded at each site, including sediment data (descriptions and samples), was used to estimate roughness characteristics for hydraulic modeling and was used to estimate sediment mobility.

Figure 6. Photo documentation of culvert inlets (top) and outlets (bottom) from the Root River (left) and Red Lake River (right).

Figure 7. Photos of two cross-sections surveyed at sites in the Root River watershed (left) and in the Red Lake River (right).

3.2 CHANNEL DIMENSIONS AND SEDIMENT CHARACTERISTICS

In addition to the tailwater characteristics (cross-section, slope and sediment characteristics), an estimate of bankfull width is required to analyze the effect of relative culvert width. The width ratio used in this study is the total culvert width divided by the channel bankfull width. Bankfull widths were estimated from regional curves (Hillman et al. 2015). Bankfull determination, a key component for sizing culvert width (Hernick et al. 2019) is a challenge to measure in the field. For this study, the focus on data collection was to measure parameters necessary for HY-8, and bankfull width was not always measured due to: deep or unsafe flows, lack of access, or lack of time by the survey crew.

CHAPTER 4: SCREENING FOR POTENTIAL AOP BARRIERS

The goal of this Phase was to screen a large number (50) of culverts across Minnesota to identify potential fish passage barriers and trends in culvert design that lead to passage barriers. A stream flow estimator (USGS StreamStats) was used to estimate high and low flows for each study site. The hydrologic model output was used as input to a culvert model (HY-8) to obtain the flow velocities, depths, and sediment mobility in each study culvert. The in-culvert flow conditions were then compared to available data on passage needs for the fish species relevant for each study site.

4.1 STREAMSTATS FOR FLOW ESTIMATES

Culvert hydraulics were modeled for two fish passage flows, low: QLP, and high: QHP, using HY-8. These flows were obtained using the USGS StreamStats batch processor. To use the StreamStats batch processor, the culvert locations were edited in GIS to lay directly on the Minnesota stream grid used by StreamStats. Aligning the culvert locations with the stream grid ensures that each watershed is correctly delineated and that the estimated flow statistics match the culvert's drainage area. The output files included flow duration statistics necessary for modeling to estimate QLP and QHP. Table 2 shows StreamStats Peak Flows (1.5, 2, 50, and 100 yr return intervals), 5% and 90% exceedance from annual flow duration (QHP and QLP), and overtopping flow (from HY-8).

Table 2. Peak flows and 5% (D5) and 90% (D90) exceedance from annual flow durations estimated by StreamStats. MN HW is the Minnesota River Headwaters.

		Peak Flows (cfs)				D5	D90
	Culvert ID	1.5 yr	2 yr	50 yr	100 yr	QHP	QLP
Big Fork	BF1	55	78	397	490	24	0.3
	BF5	93	131	590	717	43	0.6
	BFBU1	108	133	329	373	128	4.2
	BFBU2	134	186	779	939	63	1.1
	BFBU4	49	70	350	432	21	0.2
N. Fork Crow	Crow2	93	128	579	713	65	0.2
	CrowBU1	111	160	849	1060	73	0.2
	CrowBU2	101	140	637	785	73	0.2
Cottonwood	CW1	96	143	894	1140	31	0.0
	CW2	47	72	458	579	5	0.0
	CW3	88	138	947	1210	9	0.0
	CW4	84	126	806	1020	27	0.1
	CWBU1	67	104	686	869	9	0.0
Lake Superior	LSS12	31	41	198	250	7	0.2
	LSS14	337	442	2010	2530	40	1.0
	LSS16	373	488	2190	2750	49	0.7
	LSS18	24	32	155	196	6	0.1

	Culvert ID	Peak Flows (cfs) 1.5 yr	2 yr	50 yr	100 yr	D5 QHP	D90 QLP
	LSS21	801	1030	4190	5200	101	2.1
	LSS22	811	1020	3700	4500	146	3.8
	LSS4	34	47	286	376	4	0.1
	LSS8	136	182	928	1190	15	0.5
MN HW	MNHW1	86	140	1170	1520	20	0.0
	MNHWBU2	39	64	560	731	18	0.2
Pine	Pine1	82	113	478	578	45	0.8
	Pine2	92	121	393	460	76	1.0
	PineBU3	80	106	376	446	64	1.3
Red Lake	RL1	248	402	3030	3850	42	0.0
	RL2	38	54	202	233	4	0.0
	RL5	43	63	309	371	4	0.0
	RLBU1	31	45	219	262	3	0.0
	RLBU3	418	658	4040	4970	83	0.0
Rock	Rock1	43	76	730	1070	1	0.0
	Rock3	36	64	608	910	1	0.0
	Rock4	121	199	1870	2520	7	0.0
	Rock7	73	125	1170	1650	2	0.0
	RockBU5	72	125	1160	1640	2	0.0
	RockBU6	239	365	3490	4430	28	0.1
	RockBU7	60	114	978	1440	1	0.0
Root	Root2	43	71	661	878	0.4	0.0
	RootBU3	171	252	1390	1730	4	0.2
	RootBU4	434	640	3450	4260	20	1.6
	RS1	214	352	2960	3880	5	1.8
	RS4	110	181	1580	2080	1	1.1
Snake	Snake1	115	159	673	811	46	1.0
	Snake10	120	167	740	897	44	0.6
	Snake11	33	48	271	339	9	0.2
	Snake2	181	238	775	907	124	2.8
	Snake4	299	400	1360	1590	186	4.5
	Snake9	52	75	394	488	17	0.3
	SnakeBU2	64	89	385	467	29	0.3

4.2 POTENTIAL AOP BARRIERS

Potential barriers for each crossing were identified by using model results for the most passible culvert barrel for multi-barrel culverts. The most passible barrier was identified by: minimum depth >0.2 ft followed by the lowest velocity. In general, at low flow (QLP), depth barriers were more prominent while at high flow (QHP), velocity barriers dominated. At QLP, 64% of the studied culverts had modeled minimum depths <0.2 ft compared to 8% shallower than 0.2 ft at QHP. It should be noted that the simple geometry of HY-8 did not account for an inset low flow channel if one existed. Only one of the 50 culverts surveyed had a low flow channel constructed in a single barrel. The modeled QLP depth was close to 0 for many culverts in all modeled watersheds (Figures 8 and 9). However, at QHP, the modeled velocity exceeded many fish species swimming abilities limiting the movement of some, or all species (Figures 10 and 11). Seven culverts were considered to be fully passible at high flows for all non-invasive fish species with available swimming criteria data, while only four culverts were considered to be completely impassible for all non-invasive fish species with data, due to depth/perch and/or velocity. Four total culverts visited for this study (6%) were perched and thus created barriers for all non-jumping, or weak jumping fish species.

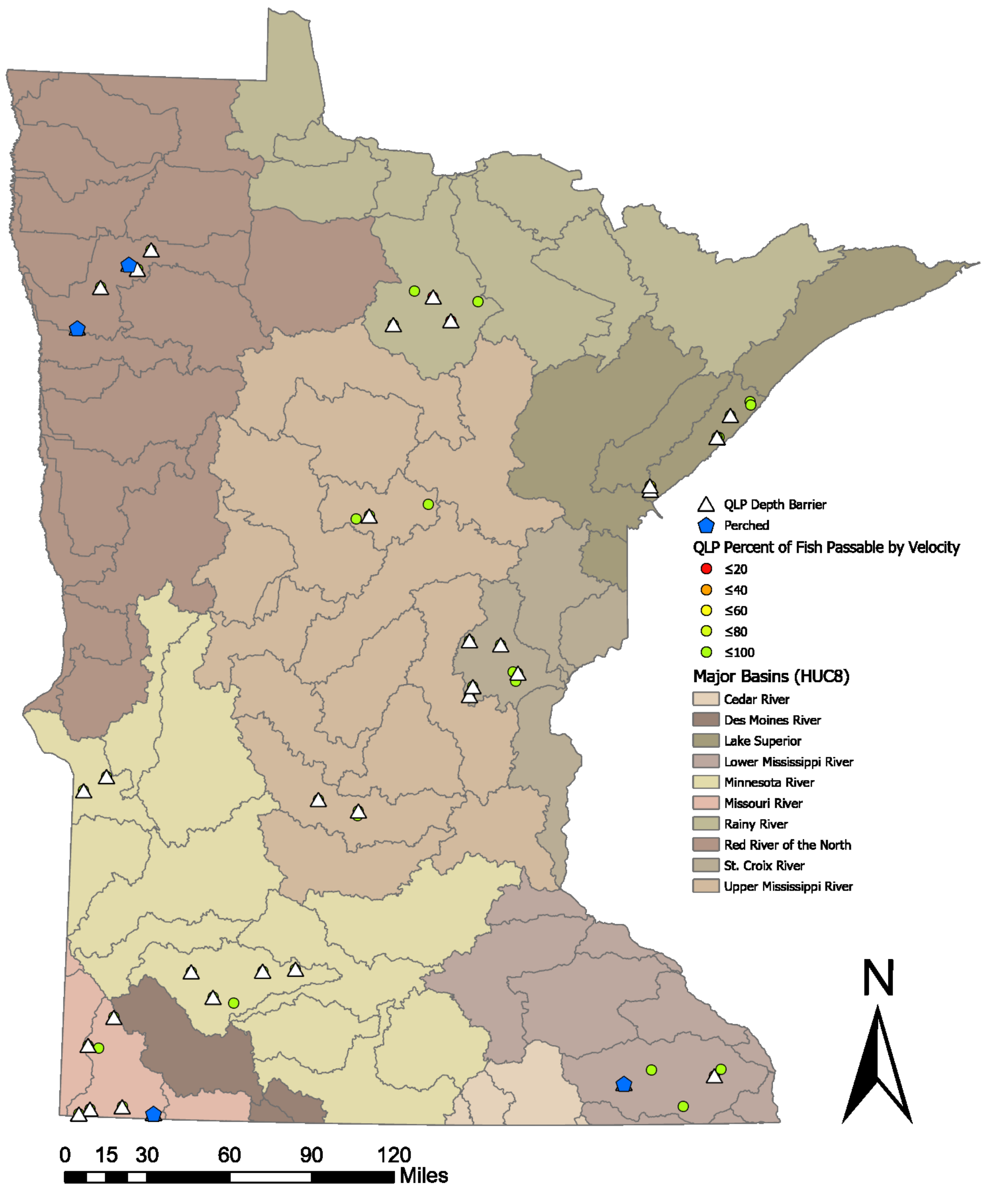


Figure 8. Map of depth barriers, and % of fish species that meet velocity criteria for culvert models at QLP. Note that of the culverts that meet the depth criterion, no culverts were significant velocity barriers.

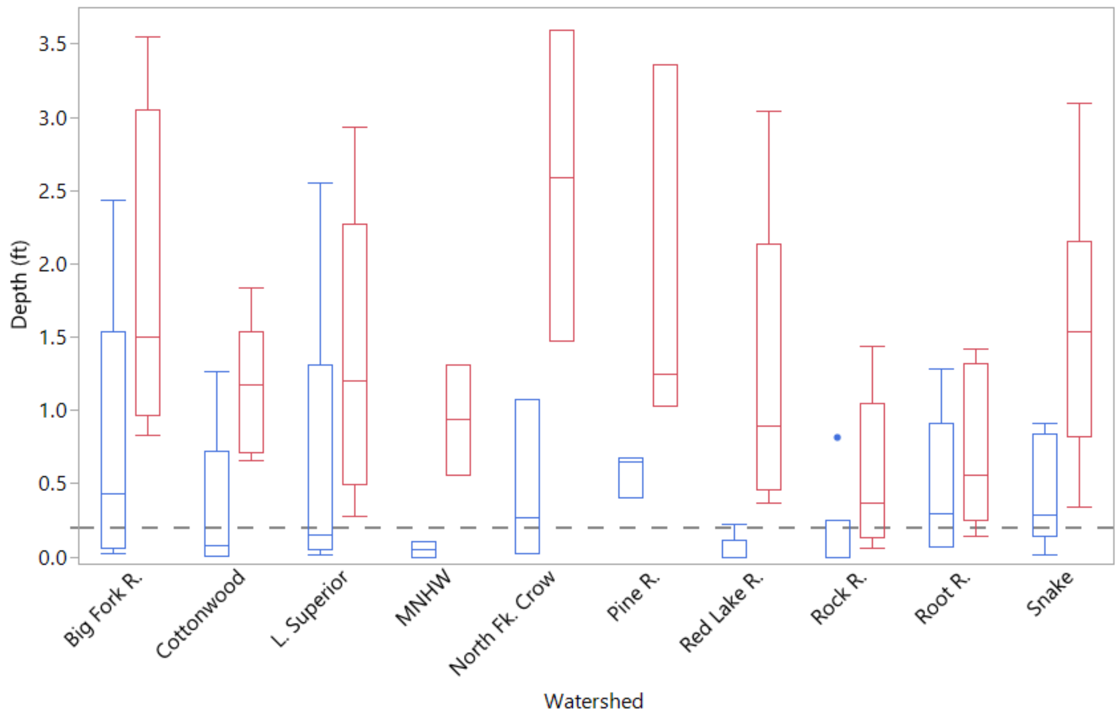


Figure 9. Modeled passage depth at low (blue) and high (red) passage flows, QLP and QHP, by watershed.

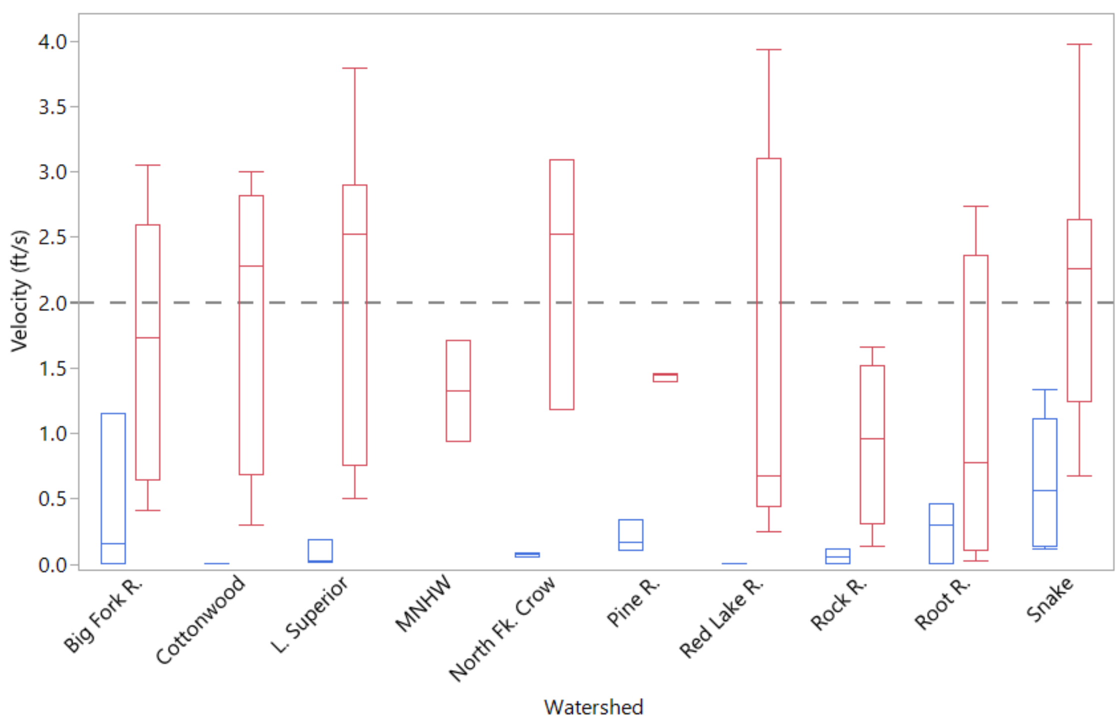


Figure 10. Modeled passage velocity at low (blue) and high passage (red) flows, QLP and QHP, by watershed. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

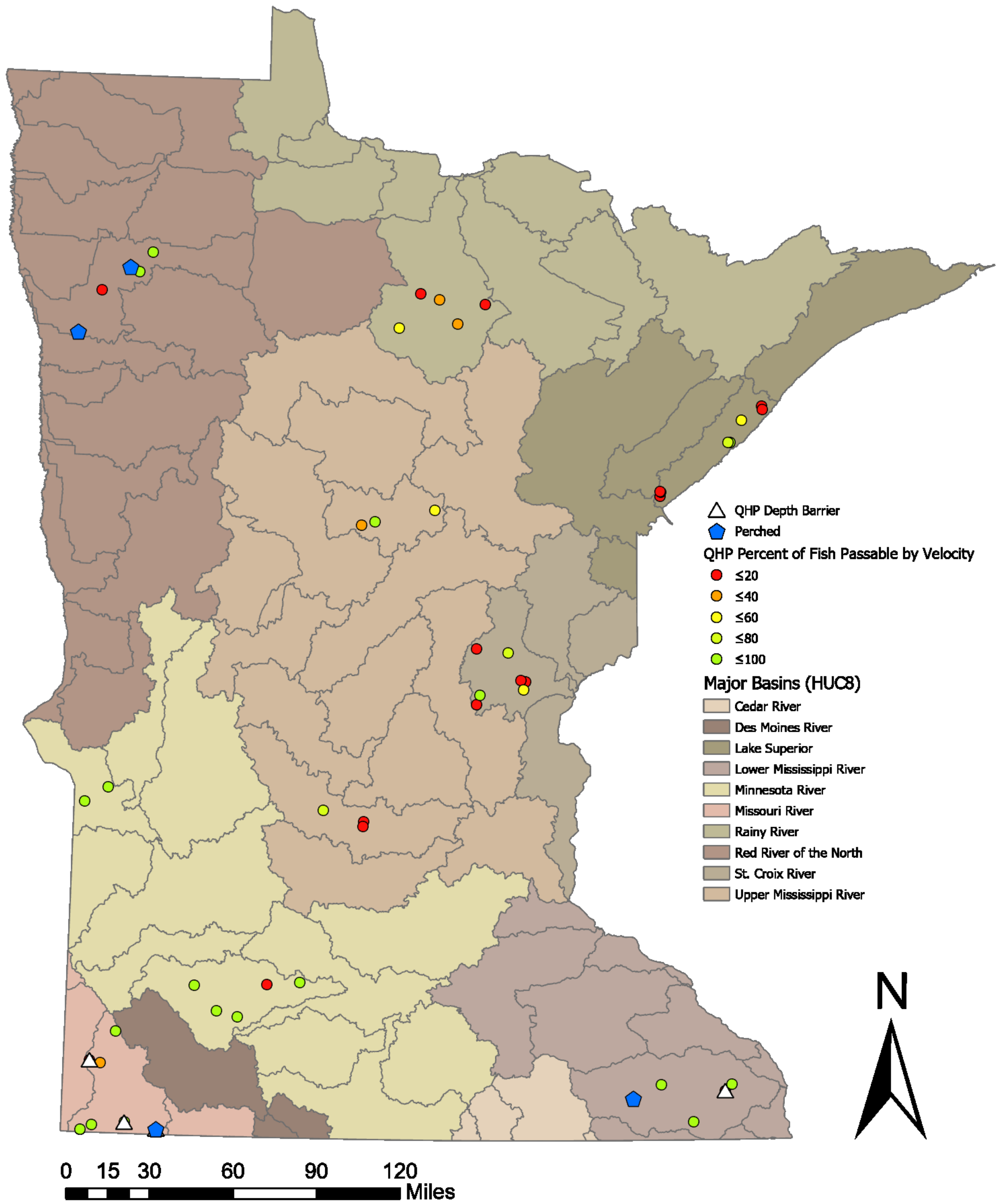


Figure 11. Map of depth barriers, and % of fish species that meet velocity criteria for culvert models at QHP.

4.3 FISH PASSAGE AND CULVERT DESIGN

A simplified analysis with thresholds for culvert depth and velocity was used to evaluate trends in fish passage with culvert design. At QLP, 64% of the modeled culverts were shallower than 0.2 ft. No culverts with depth > 0.2 ft had velocities > 2.0 ft/s. At QHP, 8% of culverts were shallower than 0.2 ft and 41% of the remaining culverts were faster than 2 ft/s, resulting in a total of 46% of culverts a concern for high-flow barriers.

Because shallow depths dominated at low flow and high velocities dominated at high flow, the low-flow depth and high-flow velocities barrier classifications can be combined resulting in 72% of the modeled culverts a concern for fish movement at either high or low flows.

4.3.1 Culvert Type

Six different culvert types were included in this study: concrete box culverts, concrete circular, concrete pipe arch, steel circular, steel open bottomed arch, and steel pipe arch. Because of the large number of categories and relatively small number of culverts within each category, it is difficult to draw conclusions on the influence of type of culvert on potential fish passage barriers (Figures 12 and 13). Very shallow flows and high velocities occur across all culvert types. Because HY-8 models 1-dimensional culvert hydraulics, we were unable to model low flow channels. However, culverts without a low flow channel, especially box culverts, are more prone to very shallow low flows.

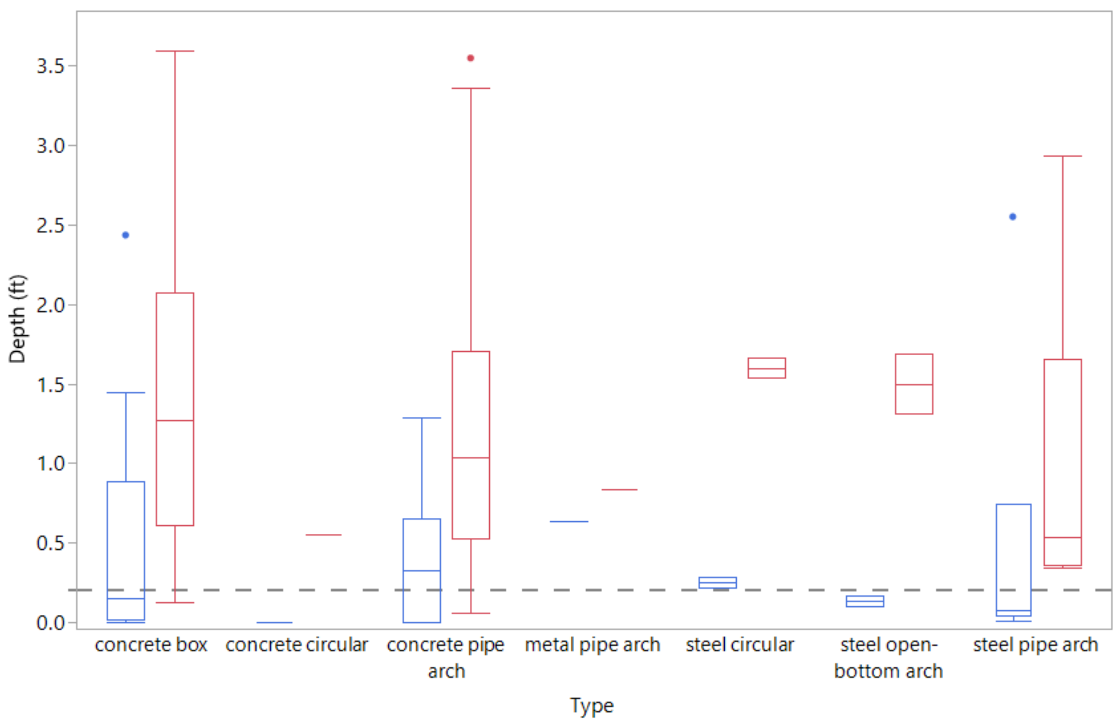


Figure 12. Modeled depth by culvert type for QLP (blue) and QHP (red). Dashed line indicates depth criterion.

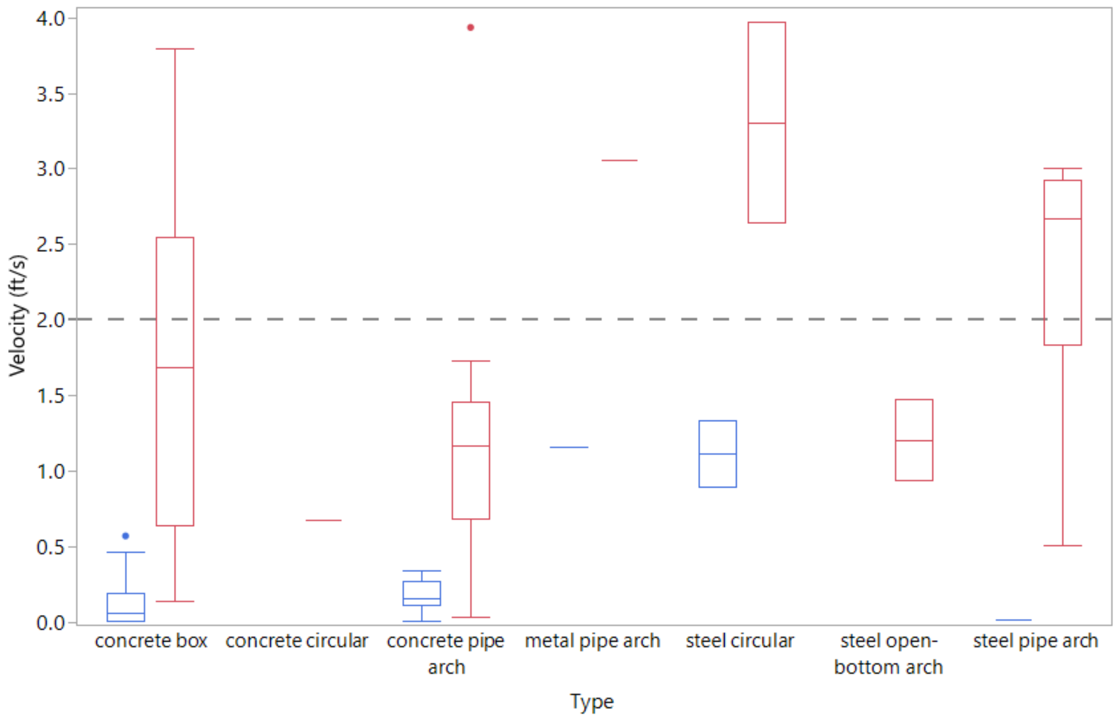


Figure 13. Modeled velocity by culvert type for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

4.3.2 Culvert Width

Culvert width was normalized by the typical bankfull width for each culvert site. These bankfull widths were estimated from the regional curves (Hillman et al. 2015). Some trends begin to emerge when the percent of culverts that exceed the depth or velocity criteria are compared with the ratio of culvert width to bankfull width (Figures 14 and 15). The QLP depth barriers were most pronounced for bankfull ratios > 2. Depth barriers at high flow were more likely to occur at bankfull width ratios above 1.0 and increased with increasing ratio. Conversely, potential velocity barriers generally decreased with increasing bankfull width ratios. Combined, these trends support the typical guidance of designing culverts to approximately bankfull width under current climate conditions or slightly wider and reemphasize that very narrow or very wide culverts relative to the bankfull width can create issues at both high and low flows (see Hernick et al. 2019). At low flows, a culvert set wider than bankfull width likely has a greater cross-sectional area, allowing flow to spread out and become shallow, so to accommodate this, a low flow cross section is needed.

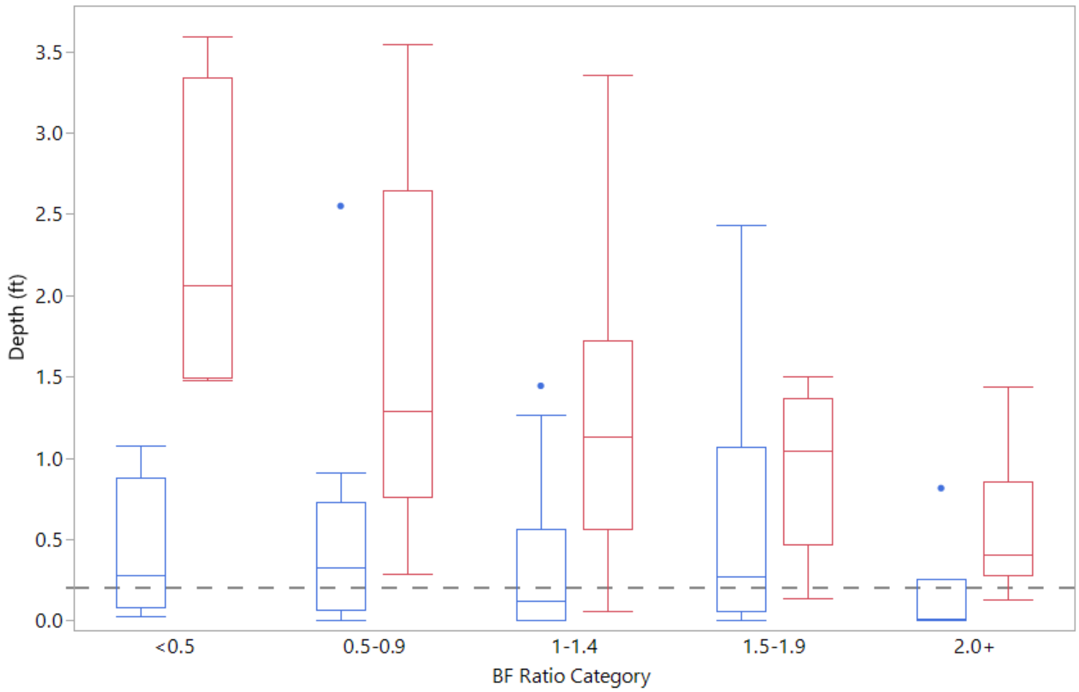


Figure 14. Modeled culvert depth in each bankfull ratio (culvert width/bankfull width) category less than depth criterion (0.2 ft) for QLP (blue) and QHP (red).

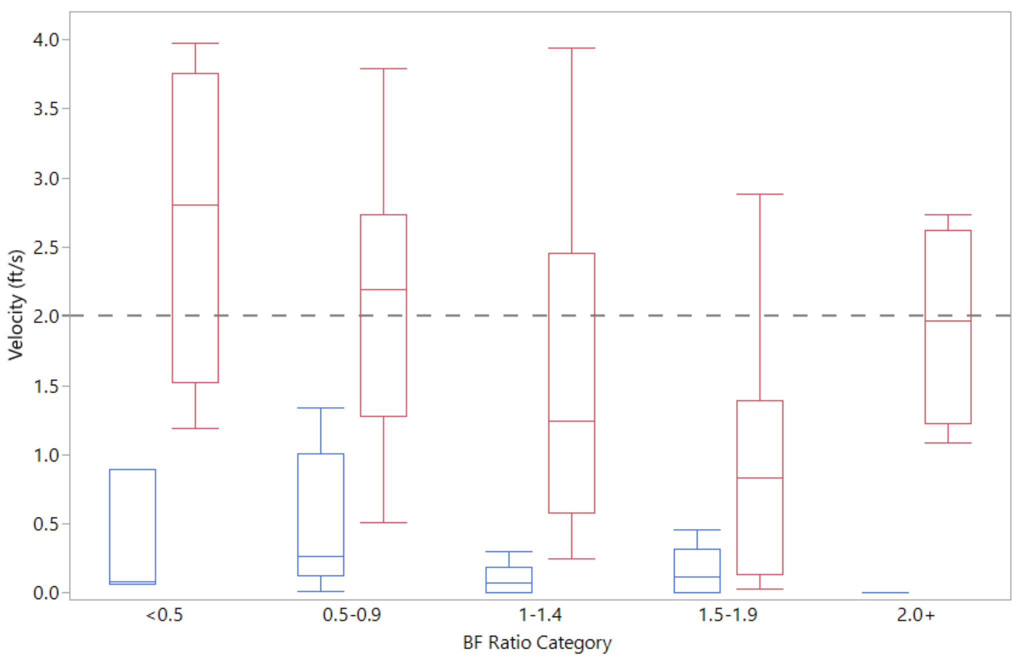


Figure 15. Modeled velocity by bankfull width ratio for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

4.3.3 Slope

Both QLP depth and QHP velocity barriers were less frequent at negative and low slopes within the culvert barrel. Generally, velocity barriers at QHP and depth barriers at QLP increased with increasing slope (Figures 16 and 17).

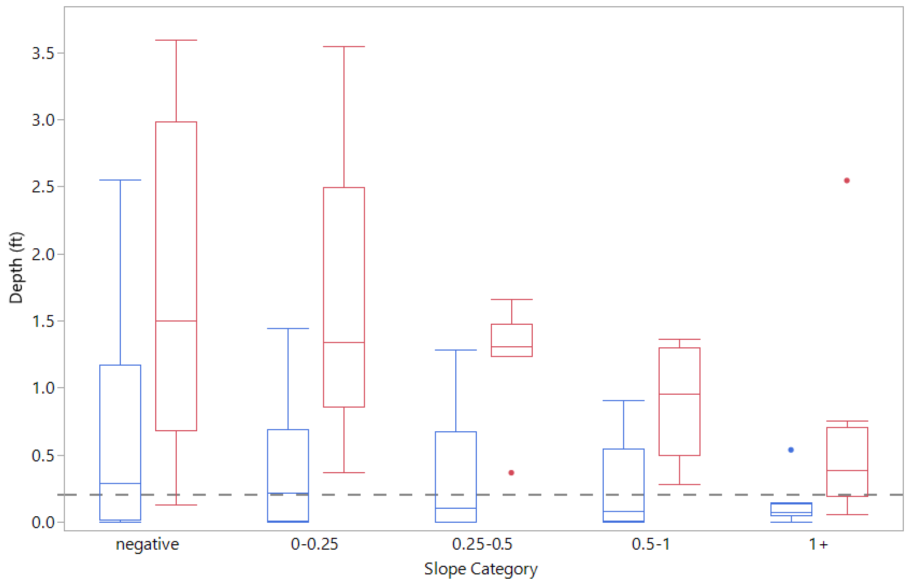


Figure 16. Modeled depth by slope category for QLP (blue) and QHP (red). Dashed line indicates depth criterion.

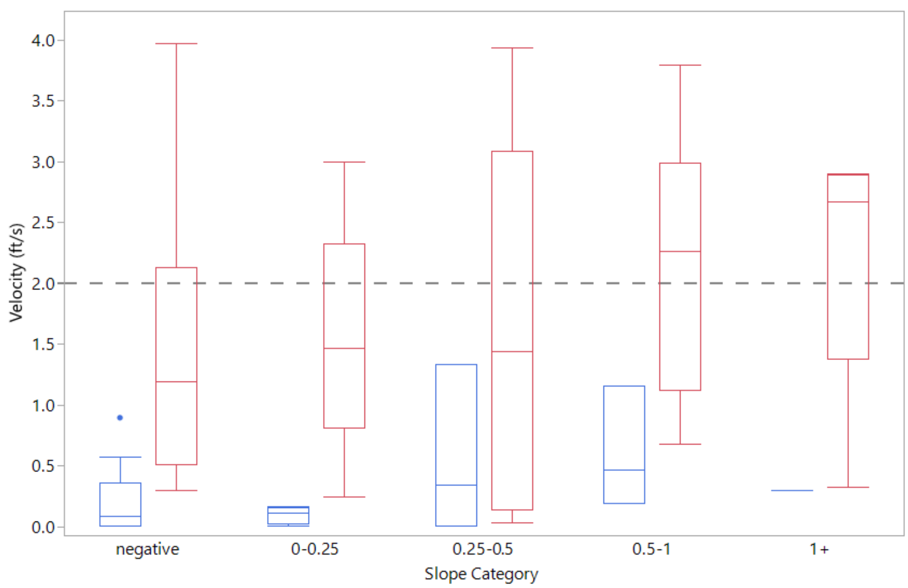


Figure 17. Modeled velocity by slope category for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

4.3.4 Embedded Culverts

Generally, embedded culverts had reduced occurrences of both depth and velocity barriers when compared to those not embedded (Figures 18 and 19). However, not all embedded culverts met the depth and velocity criteria.

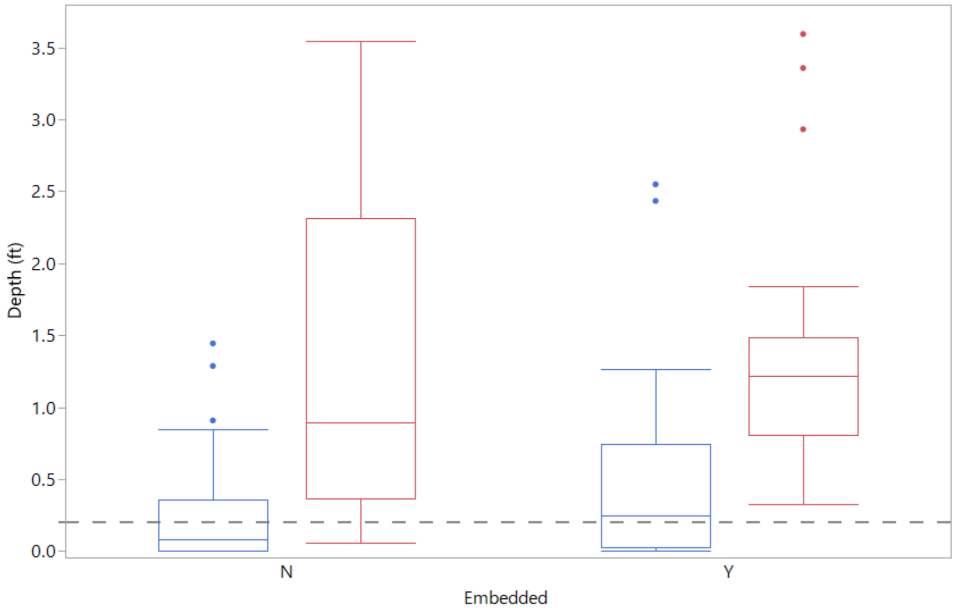


Figure 18. Modeled depth by embedded category for QLP (blue) and QHP (red). Dashed line indicates depth criterion.

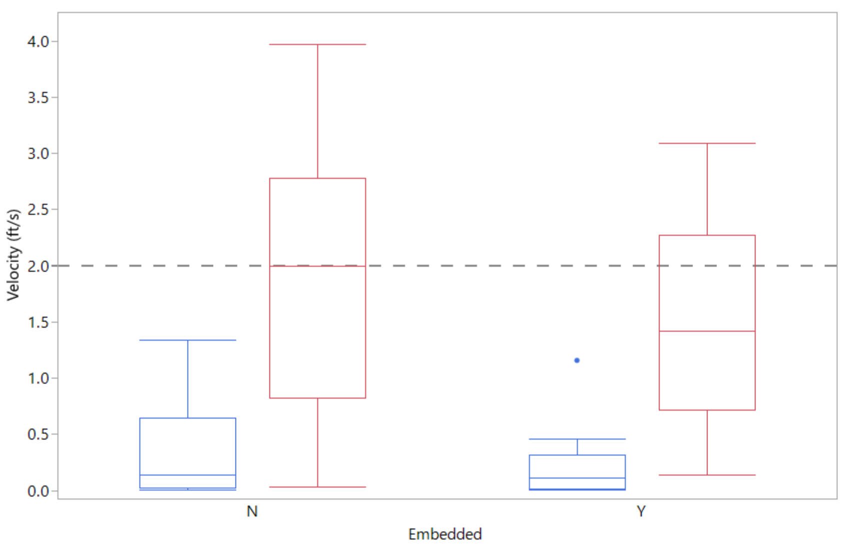


Figure 19. Modeled velocity by embedded category for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

4.3.5 Multibarrel Culverts and Offset Barrels

Twenty eight of the fifty culverts had two or three barrels. At QLP, 54% of the multibarrel culverts were less than the depth criterion. At QHP, 4% of the multibarrel culverts were still below the depth criterion and 32% exceeded the velocity criterion for 36% total potential barriers. When low-flow depth and high-flow velocity barriers are combined, 71% of multibarrel culverts are labeled a potential barrier. This is similar to the culvert set as a whole. But this analysis does not consider other additional issues with multibarrel culverts that can create fish passage barriers such as catching debris. For the surveyed sites, the number of barrels does not seem to affect the depth or velocity criterion passibility (Figure 20 and 21).

While single opening crossings that span the bankfull channel are preferred (FSSWG 2008), when multiple barrels are installed, one or more of multiple barrel culverts should be vertically offset to keep low flow confined to increase depth and thus passibility (Hernick et al. 2019). Examining the effect of vertically offsetting one or more of the multiple barrels, there is a slight, but statistically insignificant increase in depth in multibarrel culverts with vertical offsets (Figure 22). There is also a small, but statistically insignificant increase in velocity with vertical offsets (Figure 23). Multiple barrel culverts can be designed to have a single box to carry bankfull width with additional boxes for higher flows or several boxes to make up bankfull width. These types were not separated in this analysis.

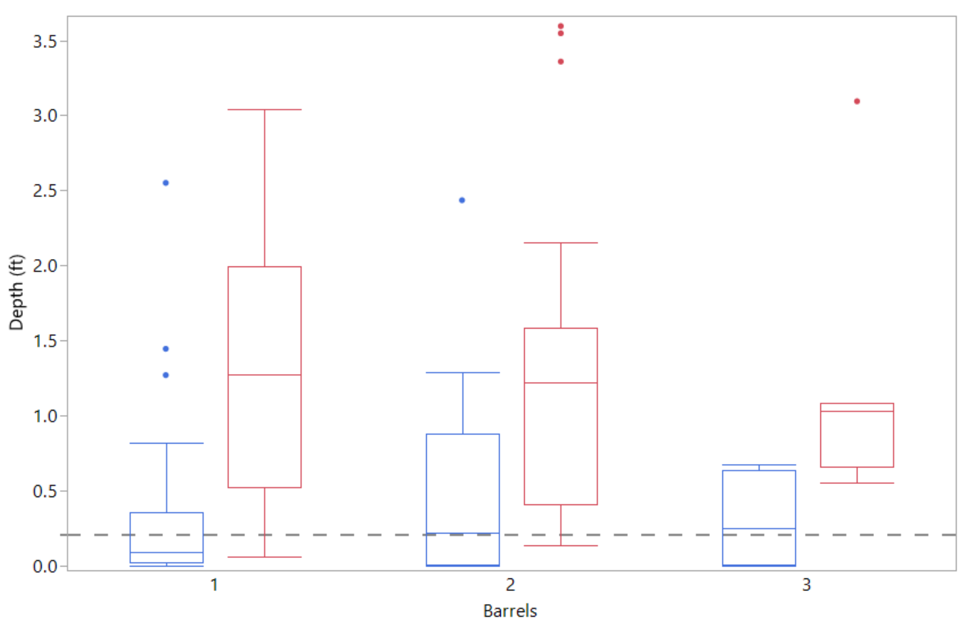


Figure 20. Modeled depth by number of barrels for QLP (blue) and QHP (red). Dashed line indicates depth criterion.

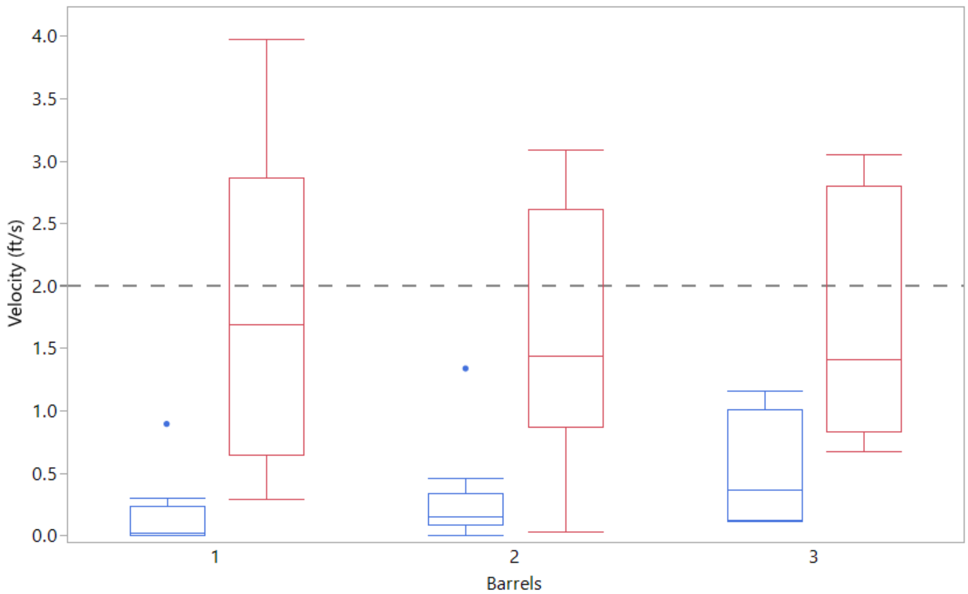


Figure 21. Modeled velocity by number of barrels for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

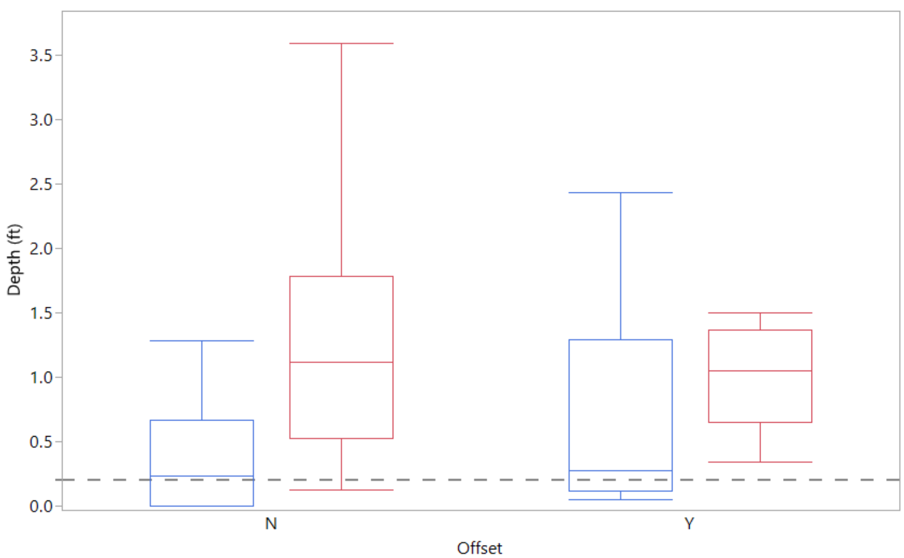


Figure 22. Modeled depth by offset category for QLP (blue) and QHP (red). Dashed line indicates depth criterion.

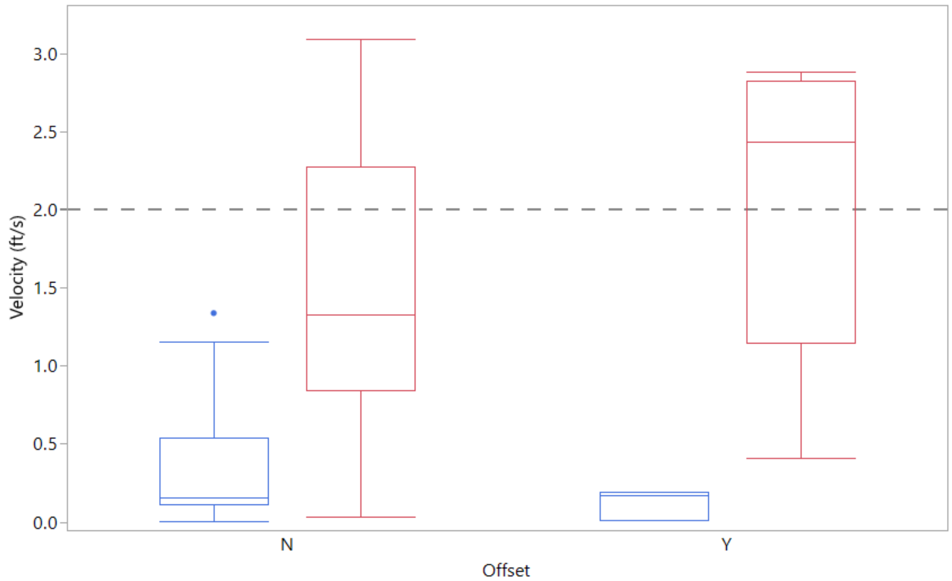


Figure 23. Modeled velocity by offset category for QLP (blue) and QHP (red). Dashed line indicates velocity criterion. Note that for very low flow depth (<1 in) modeled velocities could be very high and thus culverts that did not meet depth criterion were not included in the velocity analysis.

4.3.6 Comparison of Culvert Depth and Velocity to Tailwater Cross Section

To put potential fish passage barriers into context, culvert minimum depths and mean (along the length of the culvert) velocities were compared to the modeled velocities and depths from the tailwater cross section (Figures 24-27). At QLP, the presence of a large number of backwatered culverts is visible as a minimum culvert depth >> tailwater depth (Figure 24). However, for culverts below the depth criterion, most were also less than the tailwater depth (below the 1:1 line), indicating that these very shallow culverts were more shallow than tailwater depth. While the differences were small, ~0.1-0.4 ft, this additional depth at low flow can greatly assist organisms, emphasizing the need for evaluating low flows in the culvert design process. Most culvert velocities were less than the tailwater velocities at QLP with four exceptions (Figure 25).

For QHP, while there were a few remaining depth barriers, culvert depth generally tracked tailwater depth (Figure 26). The culverts with very low depths at QHP had very low predicted discharge from StreamStats, even for QHP. Most of the culverts that exceeded the velocity criterion (2 ft/s) at QHP also exceeded the velocity in the tailwater cross section, but those that were less than 2.0 ft/s in the cross section and greater than 2.0 ft/s in the culvert indicate a likely flow constriction leading to excess velocity (Figure 27).

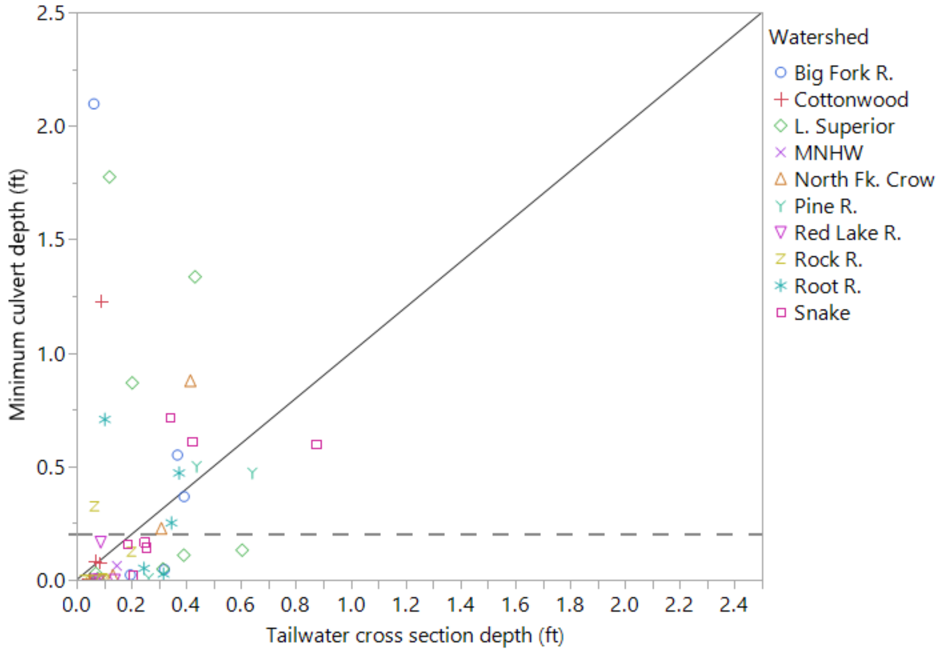


Figure 24. Modeled minimum culvert depth compared to the modeled tailwater depth for QLP. The diagonal line is the 1:1 relationship, and the dashed line is the depth criterion (0.2 ft).

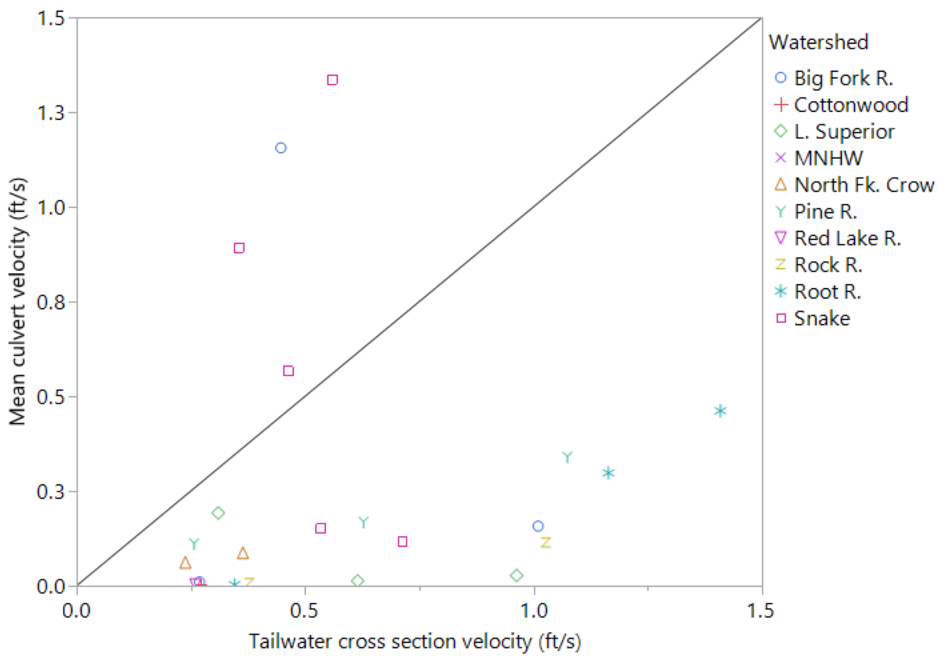


Figure 25. Modeled mean velocity compared to the modeled tailwater velocity for QLP. The diagonal line is the 1:1 relationship, and the dashed line is the velocity criterion (2 ft/s).

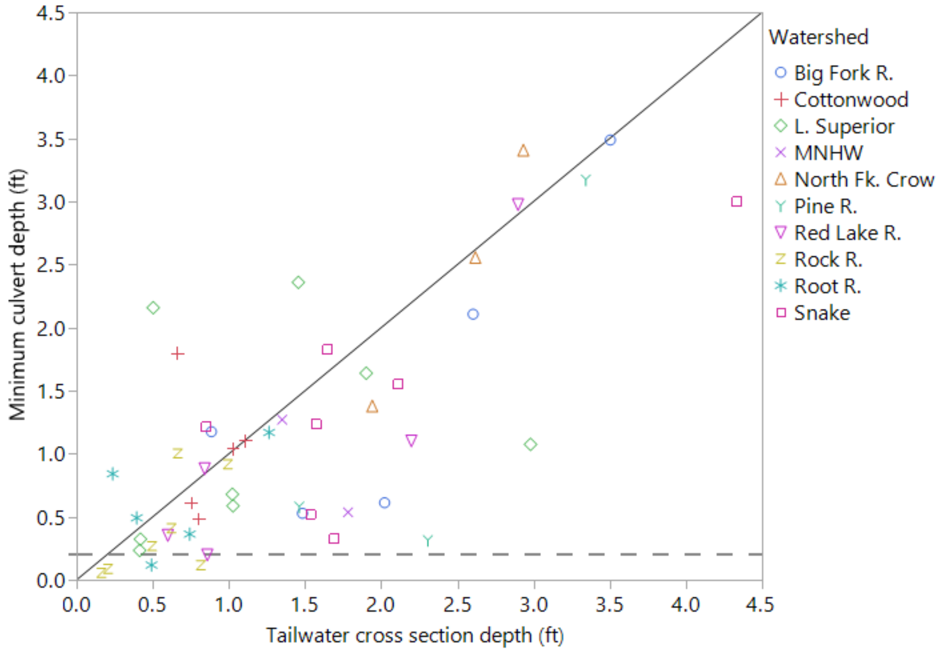


Figure 26. Modeled minimum culvert depth compared to the modeled tailwater depth for QHP. The diagonal line is the 1:1 relationship, and the dashed line is the depth criterion (0.2 ft).

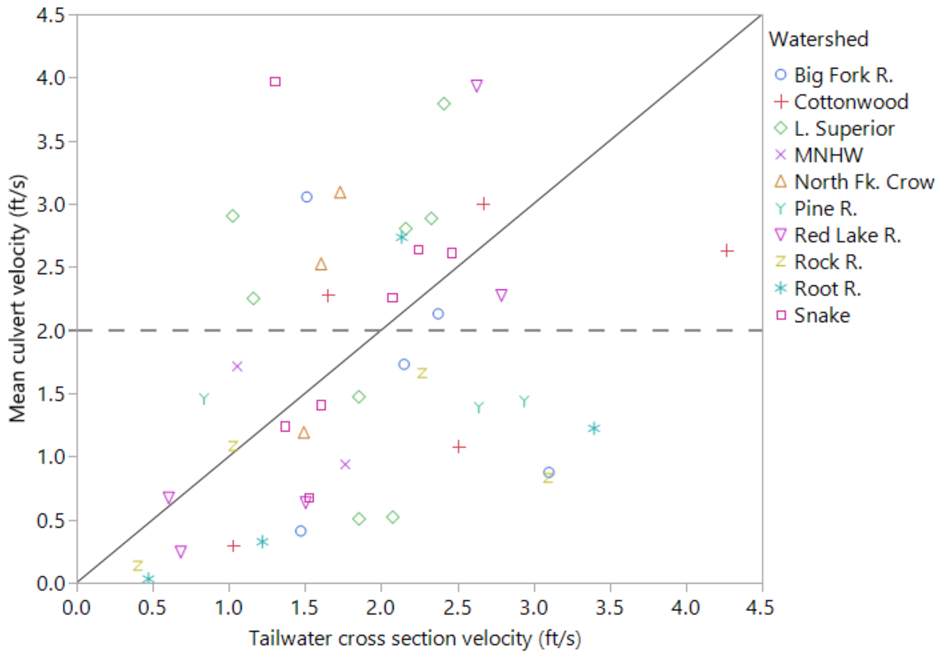


Figure 27. Modeled mean velocity compared to the modeled tailwater velocity for QHP. The diagonal line is the 1:1 relationship, and the dashed line is the velocity criterion (2 ft/s).

4.3.7 Sediment Mobility

The maximum calculated shear stress from model output was compared to shear stress in the tailwater cross section (Figures 28-29) for the 1.5, and 50-yr return interval flows. The maximum shear stress was selected based on the recommendation from HEC-26 to use the maximum shear stress along the length of the culvert barrel. For both the near bankfull flow (1.5-yr return interval) and 50-yr peak flow, the culvert shear stress was predominantly below the tailwater shear stress. This may be an indicator of potential sedimentation issues if the mobile sediment carried by the stream is much larger than what is mobile within the culvert barrel. For the culverts where shear stress is greater than channel shear stresses under current conditions, embedded culverts are unlikely to be successful. However, more information about sediment transport within a reference reach is needed for design of sediment transport requirements within an embedded culvert.

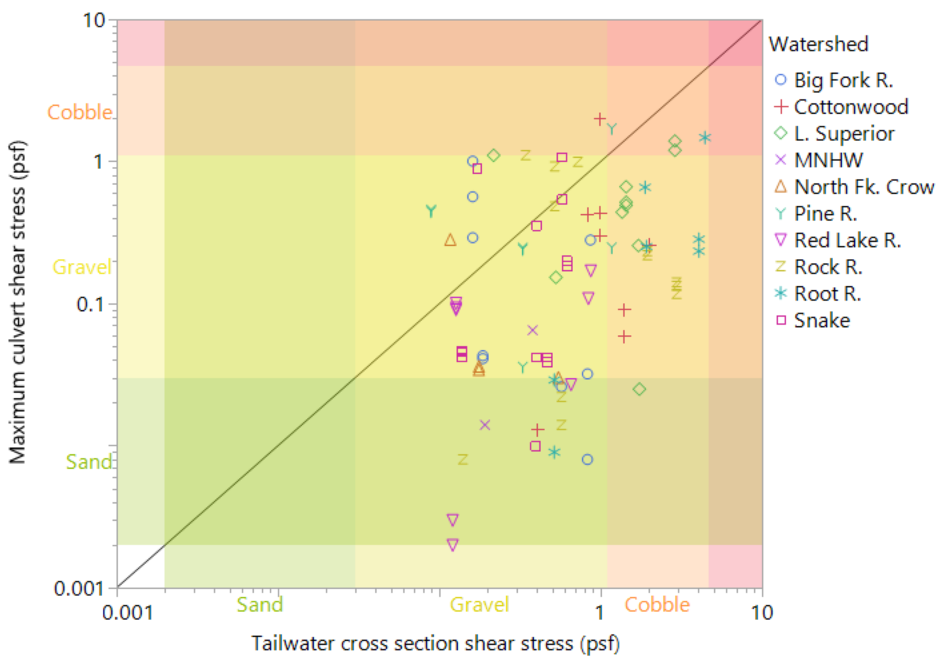


Figure 28. Modeled maximum culvert shear stress compared to the modeled tailwater shear stress for Q1.5. The diagonal line is the 1:1 relationship. Colors represent ranges of critical shear stress for sediment size classes (Fischenich 2001).

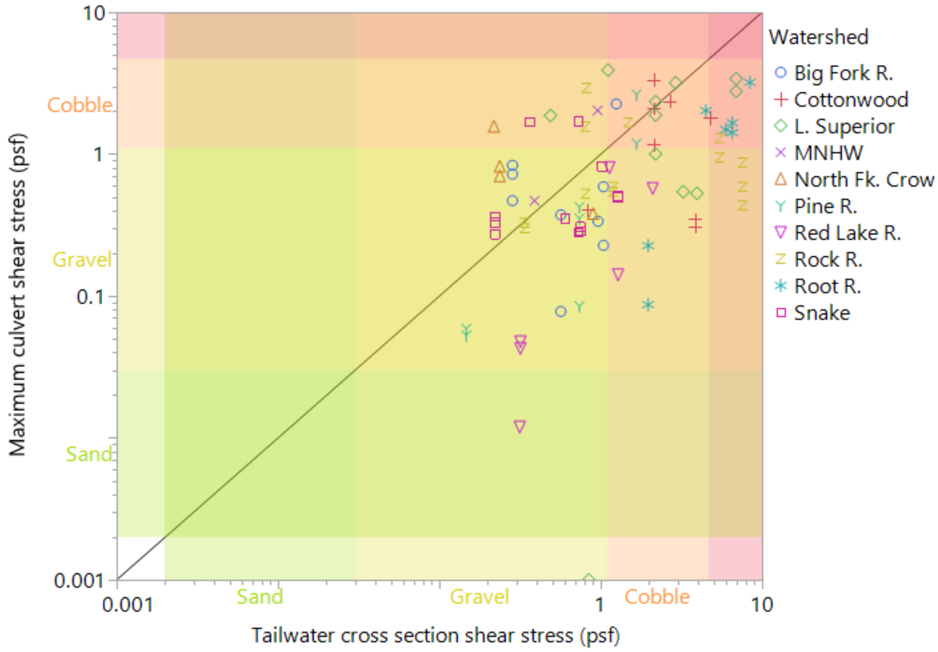


Figure 29. Modeled maximum culvert shear stress compared to the modeled tailwater shear stress for Q50. The diagonal line is the 1:1 relationship. Colors represent ranges of critical shear stress for sediment size classes (Fischenich 2001).

CHAPTER 5: HYDRAULIC MODELING ACROSS A RANGE OF FLOWS

To evaluate culvert performance under current and future flows, culvert hydraulics were modeled across a range of flows for a select subset of culverts. For each site, HY-8 results were used to calculate three key flow variables: a threshold stream flow discharge that resulted in a mean 2 ft/s velocity; a threshold stream flow discharge that resulted in a minimum 0.2 ft depth; and the overtopping stream flow discharge. These threshold values were used to evaluate potential fish passage barriers for future hydrologic scenarios (Chapter 6). In addition, curves were created for each culvert barrel for depth, velocity, and shear stress across a range of flow rates. This allows for the comparison of the effect of changing flow rates on fish passage and sediment mobility.

5.1 SITE DESCRIPTIONS

From the larger 50 culverts studied in Phase I, five culverts were selected for additional consideration (Table 3). These sites were selected to cover different areas of the state, but it was critical that sites were in close proximity to flow gages for calibration of hydrologic models. These culverts represent typical culvert setups present in the larger set of 50 culverts, but do not capture all possible culvert characteristics. Two culverts were located on the East Branch of the Beaver River (LSS21 and LSS22), one on Mud Creek (Snake 4), one on the South Fork of the Root River (Root2), and one on an unnamed tributary of Dry Creek which flows into the Cottonwood River (CW2). All of the selected culverts were concrete, four were box culverts, and one was a pipe arch. Three had embedded barrels and culvert widths ranged from 0.8 to 1.9 times the channel bankfull width.

Table 3. Culvert Characteristics.

ID	Shape	Material	Barrels	Size (ft)	Embedded	Offset	Length (ft)	Sediment	Culvert Slope (%)	Tailwater Slope (%)	Total Width (ft)	Bankfull Width (ft)	BW width ratio
LSS21	box	concrete	2	12x10,12x12	Y	Y	80	Gravel/Cobble/Silt	0.5	0.02	24	31.1	0.8
LSS22	box	concrete	3	14x11D,14x13	Y	Y	100	Boulders	0.85	0.43	42	38.0	1.1
Root2	pipe arch	concrete	2	14.1x8.9	N	N	100	Muck/Sand/Gravel	0.7	0.6	28.2	14.6	1.9
Snake4	box	concrete	3	12x6T	N	N	42	Sand/Muck	<0	0.04	36	42.5	0.8
CW2	Box	concrete	2	10x10	Y	N	50	Muck	<0	0.004	10	7.9	1.3

5.1.1 East Branch Beaver River (Lake Superior Watershed)

The East Branch of the Beaver River is a designated trout stream (https://www.dnr.state.mn.us/fishing/trout_streams/northeast.html). The two culverts located on this reach are identified in this study as LSS21 and LSS22 (Figure 30). Both were constructed in 2007 and both culverts have an embedded barrel with other barrels vertically offset.

Figure 30. Relative location of LSS21 and LSS22.

LSS21 is a double box culvert (12x10 and 12x12 ft) located upstream of LSS22 where EB Beaver Creek crosses under CSAH 4. The approach to this culvert was very skewed which led to a buildup of woody debris at the culvert entrance (Figure 31); however, skew was not explicitly modeled in this project. One barrel is offset by two feet and the other barrel is embedded (Figure 31). The culvert width is approximately 0.8 times the channel bankfull width (as estimated from regional curves). At the time of surveying (September 27, 2019), the offset barrel was dry and filled with a gravel/cobble mix (Figure 32). Grade control was provided by a rock weir downstream of the culvert (Figure 33).

Figure 31. Aerial image of LSS21 showing skewed culvert entrance. Flow is from left to right (left). Woody debris caught on culvert entrance (right).

Figure 32. Photos of embedded barrel (left; barrel 2) and offset barrel (right; barrel 1). September 27, 2019.

Figure 33. Grade control was provided by a weir downstream.

LSS22 is a triple barrel box culvert (14x11, 14x13, and 14x11 ft) where EB Beaver Creek crosses under CSAH 5 (Figure 34). The two side barrels are vertically offset by 2 feet and the middle barrel is embedded (Figure 35). The total culvert open width is approximately 1.1 times the channel bankfull width (as estimated from regional curves). At the time of the survey, one of the offset barrels was dry and the other had very shallow flow. Grade control was provided by a rock weir downstream of the culvert (Figure 36).

Figure 34. Aerial image of LSS22. Flow is from top to bottom.

Figure 35. Photos of embedded barrel (center) and offset barrels. September 27, 2019. Barrel 1 (left) has no sediment, barrel 2 (middle) is embedded with large boulders, and barrel 3 (right) has large cobble and some boulders. Barrels 1 and 3 are vertically offset.

Figure 36. Grade control was provided by a weir downstream.

5.1.2 Mud Creek (Snake River Watershed)

Mud Creek is a tributary to the Snake River. In 2013, the MPCA conducted a Stressor Identification study on this watershed and identified key stressors: excess sediment, low dissolved oxygen, habitat alteration, ditching and flow alteration as likely causes for the biological impairment (https://www.pca.state.mn.us/sites/default/files/wq-iw6-11n.pdf). Hornyhead Chub are identified as a

fish species of interest in this watershed due to their declining statewide populations. The Mud Creek culvert that passes under TWP 129 is identified in this study as Snake4 (Figure 387). This culvert consists of a triple barrel concrete box culvert (12x6 ft) and all barrels are equally sized and set at the same elevation. Flow was deep and slow moving at the time of survey (August 2, 2019; Figure 38). The total culvert open width is equal to approximately 0.8 times the channel bankfull width (as estimated from regional curves).

Figure 37. Aerial image of Snake4. Flow is from bottom to top.

Figure 38. Culvert entrance (left) and exit (right). August 2, 2019. No barrels were embedded or offset.

5.1.3 South Fork Root River

The South Fork of the Root River is a designated trout stream; however, the designated area is located downstream of the study culvert (https://www.dnr.state.mn.us/fishing/trout_streams/south_mn_maps.html). This culvert (Root2) consists of a concrete double barrel pipe arch where the South Fork of the Root River crosses under CSAH 18 (Figure 39). Both barrels are set at the same elevation. However, one barrel is significantly sedimented in and was carrying no flow at the time of survey (Figure 40). The total culvert width is approximately 1.9 times the bankfull width (as estimated from regional curves).

Figure 39. Aerial image of Root2. Flow is from top to bottom.

Figure 40. Culvert exit. August 14, 2019. Barrel 2 had significant sedimentation.

5.1.4 Unnamed Tributary to Dry Creek

This unnamed tributary to Dry Creek is in the Cottonwood Watershed. A single barrel box culvert is located where this stream crosses under CSAH 10 (Figures 41-42). The culvert has a large pool downstream that is backwatered through the culvert and the culvert has sedimentation (mucky) within the barrel. This tributary flows into an adjacent creek, Dry Creek, less than 0.25 miles downstream. The Dry Creek culvert has a gage that was used for hydrologic model calibration. Species found in Dry Creek and its tributary include: Bigmouth Shiner, Blacknose Dace (wester), Bluntnose Minnow, Central

Stoneroller, Common Shiner, Creek Chub, Fathead Minnow, Johnny Darter, and White Sucker (2017 sampling retrieved from Fishes of Minnesota Mapper; https://www.dnr.state.mn.us/maps/fom/index.html).

Figure 41. Aerial image of CW2. Flow is from bottom to top (South to North).

Figure 42. Unamed tributary culvert in the Cottonwood River watershed. August 8, 2019.

5.2 HYDRAULIC MODELING: RATING CURVES

HY-8 models set up for each culvert site in Phase I were used to model velocity, depth and sediment mobility across a much wider range of flows in Phase II. For each site, HY-8 results were used to calculate three key flow variables: a threshold stream flow discharge that resulted in a mean 2 ft/s velocity; a threshold stream flow discharge that resulted in a minimum 0.2 ft depth; and the overtopping stream flow discharge (Table 4). These threshold values were used with the continuous hydrologic modeling to determine the effect of changing hydrology on the number of days each culvert presented a depth or velocity barrier. Three of the culvert sites, LSS21, Root2, and CW2 were sufficiently backwatered such that with any flow >1 cfs, depth did not create a barrier. The overtopping flow was also used in the hydrologic analysis to evaluate the resiliency of each culvert site at current and future scenarios.

Table 4. Stream flow discharge values for velocity threshold (> 2 ft/s) and depth threshold (< 0.2 ft). Overtopping flow discharge value when flow begins to overtop roadway.

Culvert	Velocity Threshold (cfs)	Depth Threshold (cfs)	Overtopping flow (cfs)
LSS21	87.2	backwatered	2772
LSS22	78.3	7.7	7849
Snake4	475.7	1.8	1158
Root2	116.9	backwatered	3147
CW2	50.2	backwatered	1148

For each culvert site and each culvert barrel, the model results for depth, velocity and shear stress in each barrel were plotted as a function of stream flow discharge (Figures 43-47). Min depth is the minimum depth in the culvert, mean velocity is the velocity averaged over the length of the culvert, and shear stress is the maximum shear stress over the length of the culvert. Depth, velocity, and shear stress in the tailwater cross section were averaged over the cross section. This allows a comparison of each parameter to the modeled parameter in the tailwater cross section by stream flow discharge. Key observations are summarized below. Note that HY-8 is limited at very low stream flow discharge values (< 1 cfs) and thus this was the lowest stream flow discharge modeled.

LSS21 (Figure 43)

- The culvert is backwatered for flows above 1 cfs.
- Velocity and shear stress in both culvert barrels far exceed the velocity and shear stress modeled in the tailwater cross section.

LSS22 (Figure 44)

- Depth in the culvert barrels is less than that modeled in the tailwater cross section. Barrel 1 (with no sediment) is shallower than barrels 2 (embedded) and 3.

- Velocity in the culvert barrels is greater than that modeled in the tailwater cross section. Barrel 1 (with no sediment) is faster than barrels 2 (embedded) and 3. Both barrels 2 and 3 have significant roughness (sediment cobble to boulder size).
- Shear stress is less in the culvert barrels than the tailwater cross section until approximately 3500-4500 cfs.

Snake4 (Figure 45)

- Depth in the culvert barrels closely tracks the depth in the tailwater cross section until full pipe conditions are reached.
- Velocity in the culvert barrels also closely tracks the velocity in the tailwater cross section until full pipe conditions are reached. After full pipe conditions are reached, the velocity in the culvert exceeds the velocity in the tailwater cross section.
- Shear stress in the culvert barrel is less than the tailwater cross section until approximately 900 cfs.

Root2 (Figure 46)

- Depth in the culvert barrels closely tracks the depth in the tailwater cross section.
- Velocity in the culvert barrels is less than the tailwater cross section until approximately 1000 cfs.
- Shear stress is significantly less in both culvert barrels compared to the tailwater cross section.

CW2 (Figure 47)

- The culvert is backwatered for flows above 1 cfs.
- At low flows, the velocity in the culvert and cross-section are similar, however, after ~50 cfs, the velocity in the culvert barrel increases significantly.
- Shear stress is less in culvert barrel than in channel cross section.

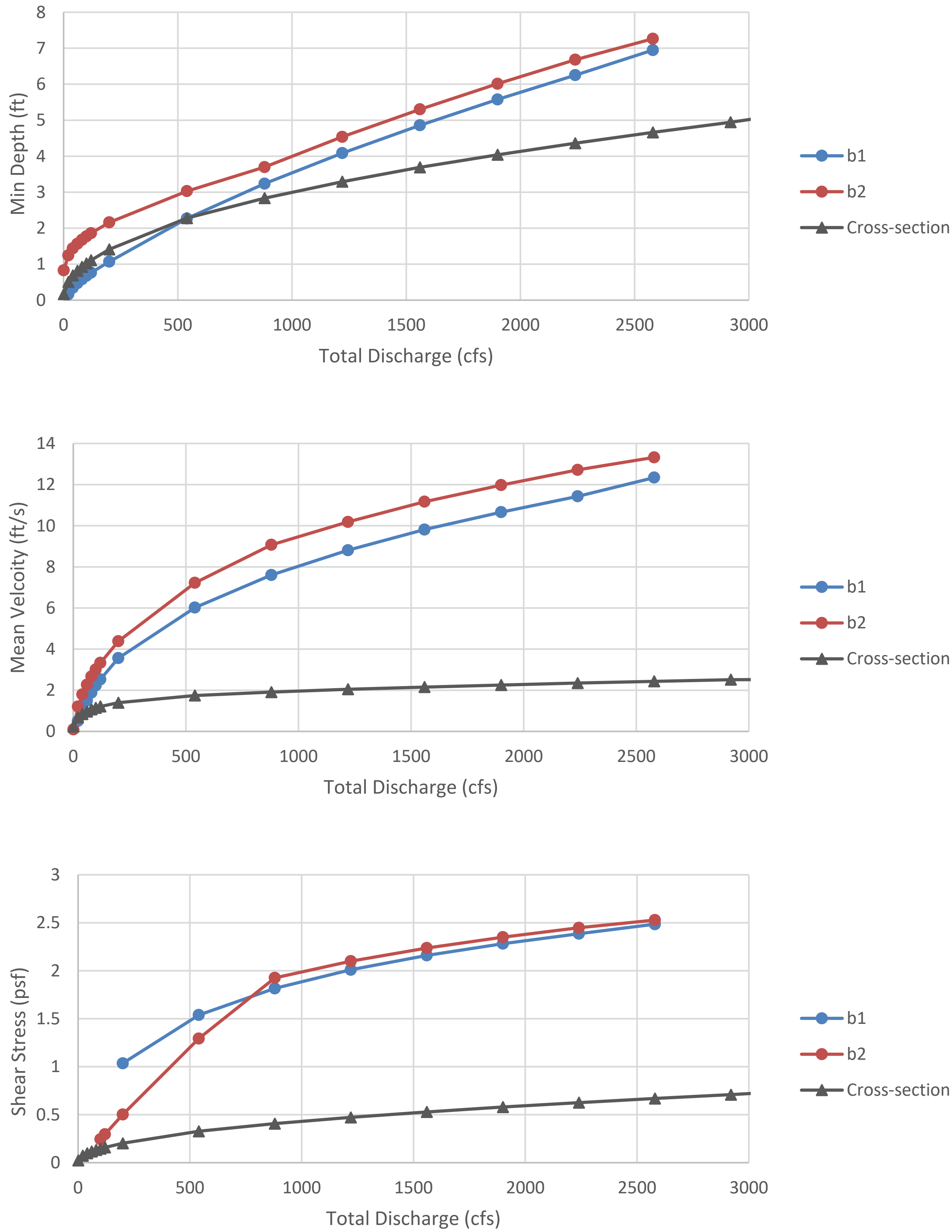


Figure 43. Depth, velocity and shear stress in each barrel and in the tailwater cross section for LSS21. Barrel 2 (b2) is embedded and barrel 1 (b1) was vertically offset. See Figures 30-33 for photographs.

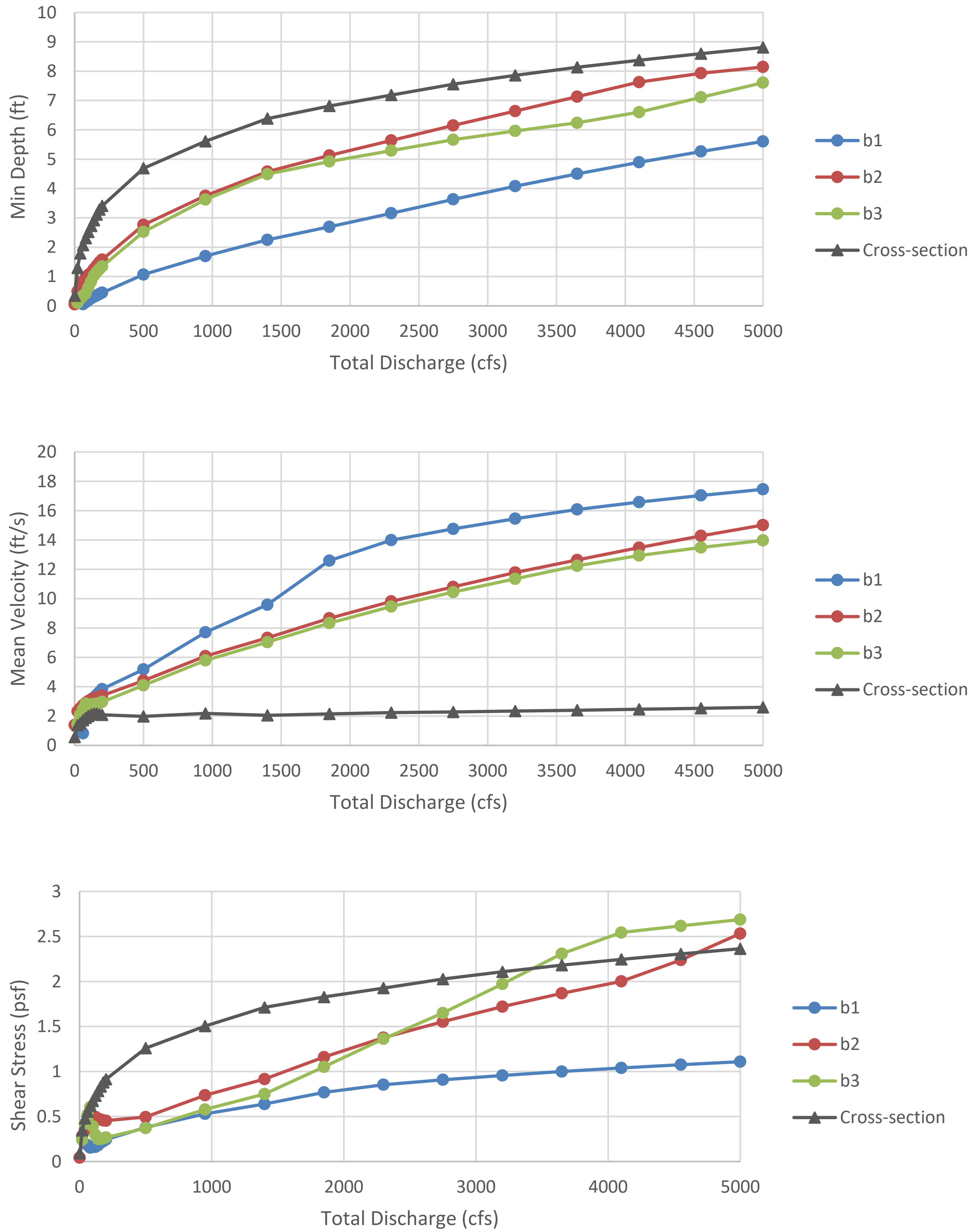


Figure 44. Depth, velocity and shear stress in each barrel and in the tailwater cross section for LSS22. Barrel 2 (b2) is embedded (middle barrel) and barrels 1 (b1) and 3 (b3) are vertically offset. See Figures 34-36 for photographs.

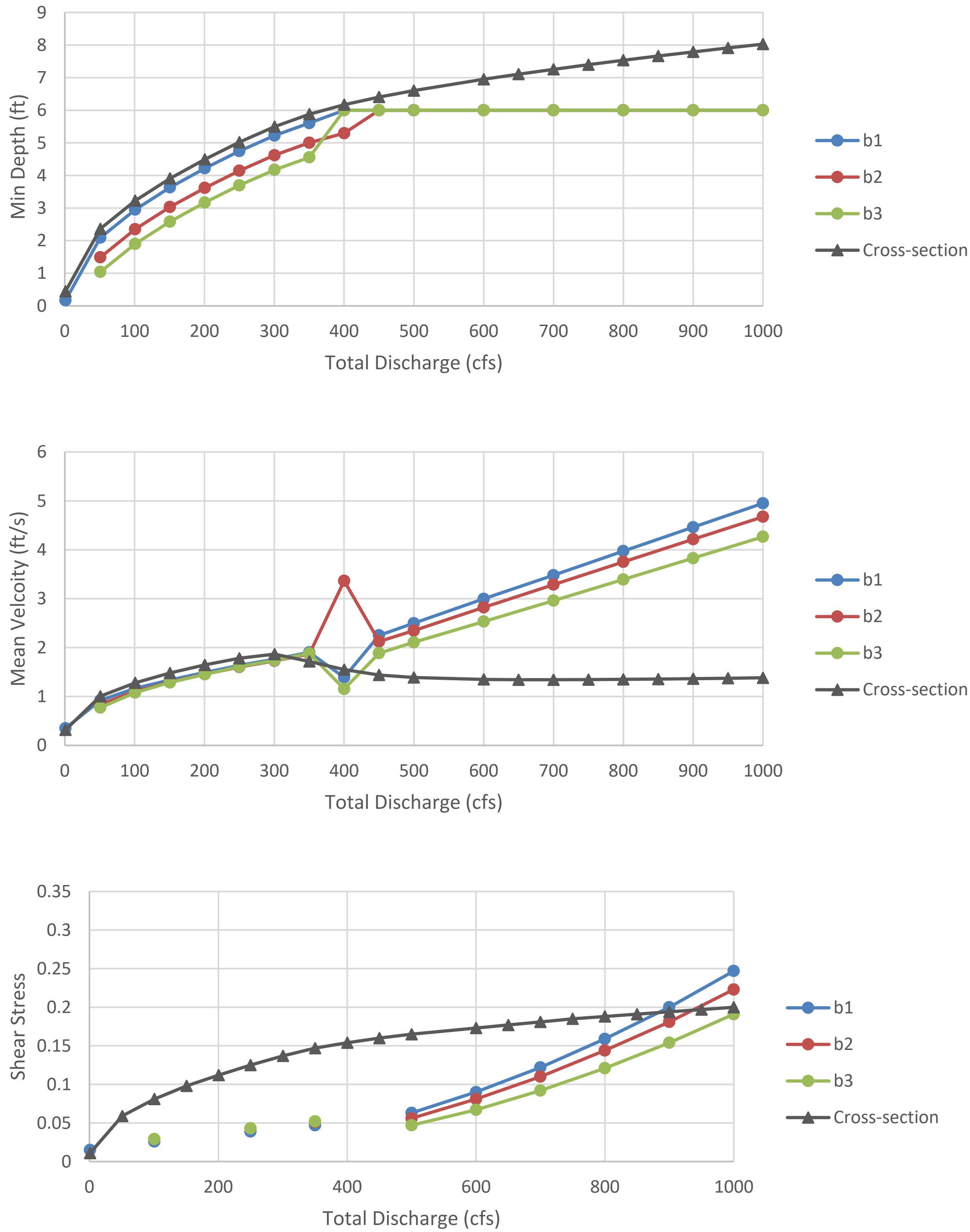


Figure 45. Depth, velocity and shear stress in each barrel and in the tailwater cross section for Snake4. Note instability where flow transitions to full pipe flow at around 400 cfs. No barrels were embedded and no barrels (b1, b2 or b3) were offset. See Figures 37-38 for photographs.

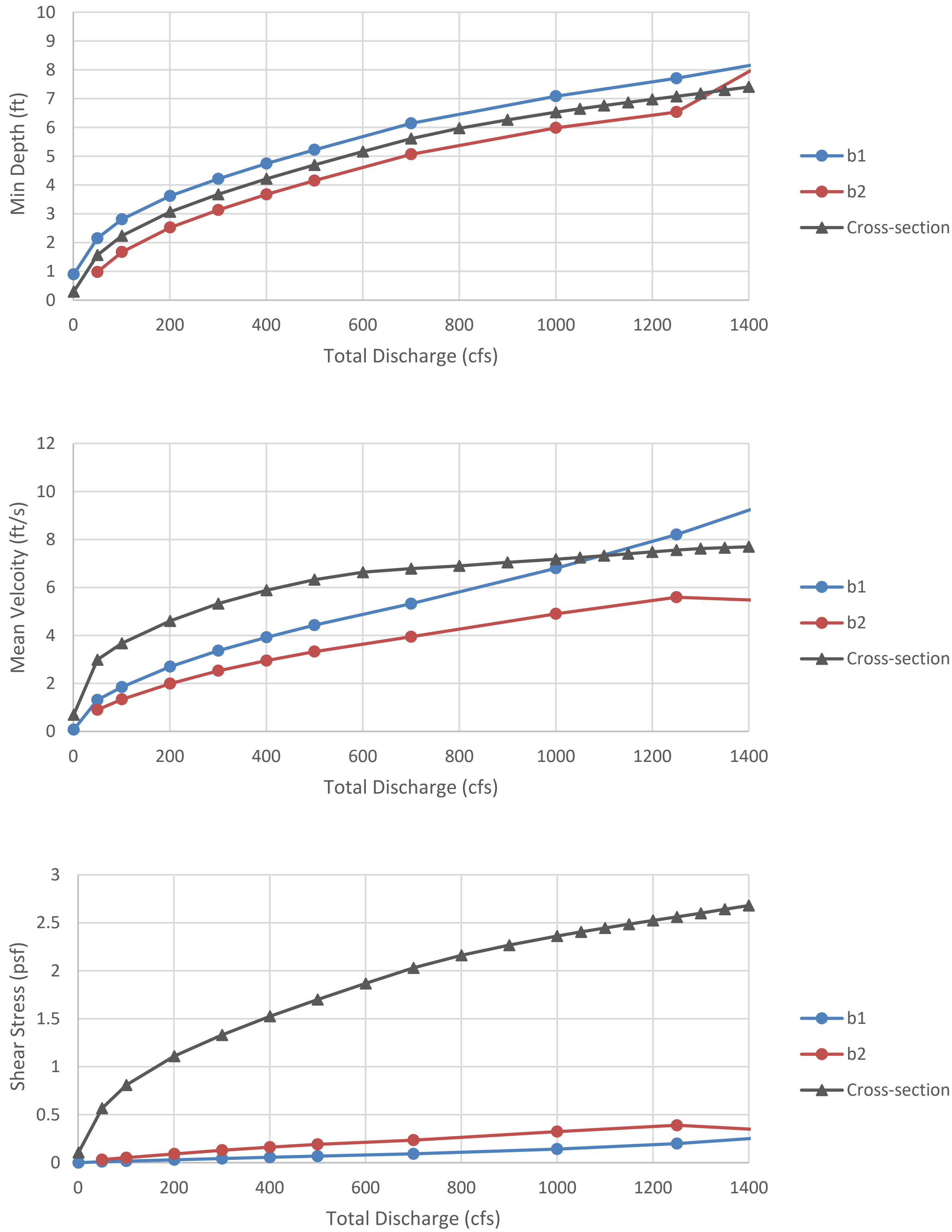


Figure 46. Depth, velocity and shear stress in each barrel and in the tailwater cross section for Root2. No barrels were embedded, although barrel 2 (b2) had significant sedimentation. See Figures 39-40 for photographs.

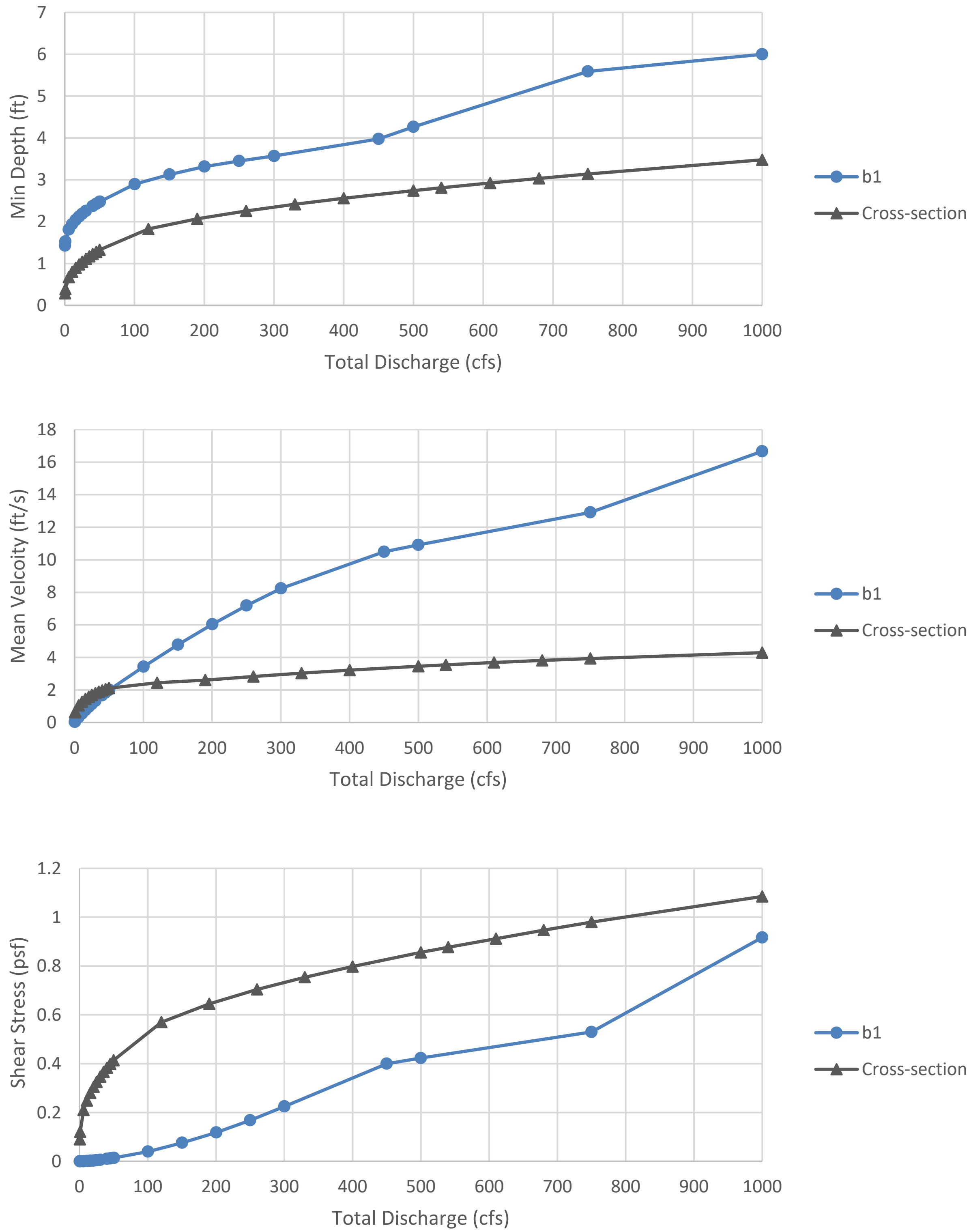


Figure 47. Depth, velocity and shear stress in each barrel and in the tailwater cross section for CW2. No barrels were embedded, although barrel 2 (b2) had significant sedimentation. See Figures 41-42 for photographs.

CHAPTER 6: FUTURE CLIMATE SCENARIOS

6.1 SUMMARY OF METHODS

To model the response of stream flow to projected future climate, HSPF (Hydrologic Simulation Program Fortran, Imhoff et al. 1997) rainfall-runoff models were assembled and calibrated for the catchments of four culverts. The HSPF models were used to project future changes in the flow parameters related to fish passage, sediment transport, and culvert overtopping. The HSPF models for each catchment were used to perform both continuous flow analysis to analyze future changes in the fish passage and sediment flow parameters, and discrete storm event analysis to analyze future changes in overtopping flows, as summarized in Figure 48. The simulated flow rates from the HSPF models are compared to the fish passage, sediment, and culvert overtopping thresholds from the culvert hydraulic models to project future changes in culvert fish passibility and overtopping frequency.

An important component of the hydrologic analysis was selecting future climate data as inputs to the HSPF models. For continuous analysis, daily timestep climate time series from downscaled Global Climate Model (GCM) outputs were obtained for four GCMs, to represent the range of projected changes in precipitation and air temperature from all GCMs (see Figure 52). For discrete storm event analysis, a US EPA database (CREAT) of future storm sizes was used – this database gives projected future changes in storm sizes for three generic scenarios (Warm/Wet, Median, Hot/Dry) which attempt to cover the range of responses from all GCMs. These EPA scenarios are defined based on mean annual precipitation and mean annual air temperature, and the scenario with the largest increase in mean annual precipitation (Warm/Wet) does not necessarily give the largest increase in storm size (see Table 8). We maintained the names of the EPA scenarios in our analysis so that the source of data for each scenario is clear and reproducible.

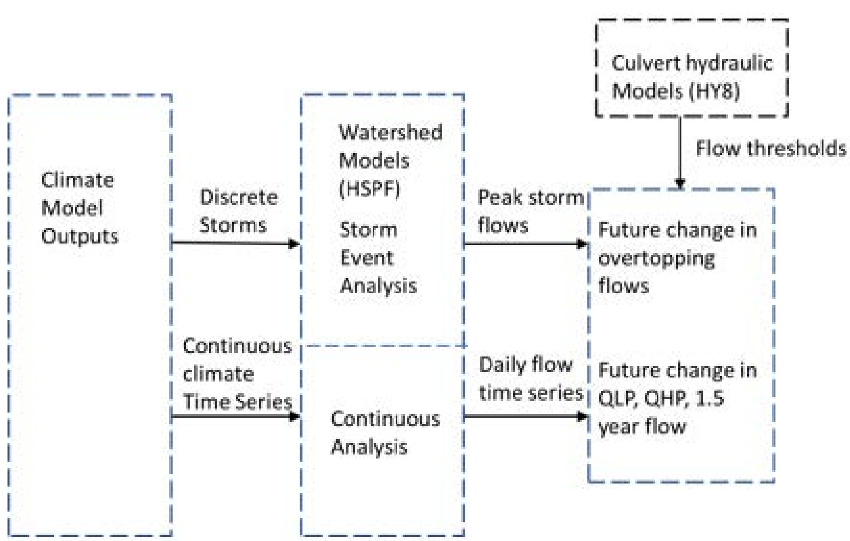


Figure 48. Diagram of the data and model workflow for the hydrologic modeling work.

6.2 CONTINUOUS FLOW ANALYSIS

Hydrologic information such as catchment area, slope, and land cover was compiled for the catchments draining to the four study culverts. The relative size and location of the catchments is shown in Figure 49, and the catchment characteristics are summarized in Table 5. The Beaver River and Snake River study sites both have a hydrologically important lake in the drainage network, which were included in the hydrologic models.

Table 5. Catchment characteristics.

Study Catchment	Culvert	Area (km^2)	Average Slope (%)	Dominant Land Covers
Cottonwood	CW2	5.8	2.7	Ag
East Branch	LSS21	76	2.3	Forest
East Branch	LSS22	120	5.0	Forest
Snake River (Mud	Snake4	156	0.84	Forest, Ag
South Fork Root	Root2	47	3.3	Ag

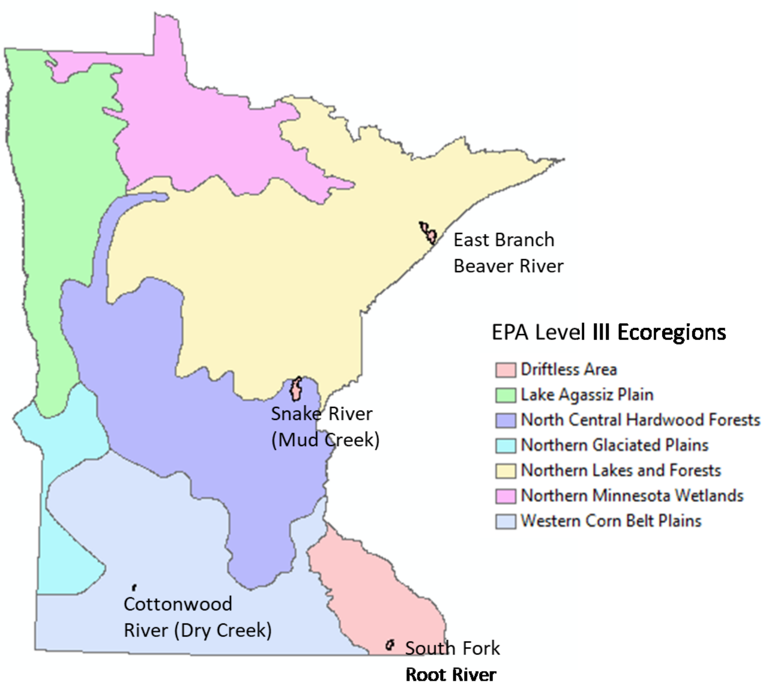


Figure 49. Locations of the three study sites and EPA Level III Ecoregions.

HSPF (Hydrologic Simulation Model Fortran) models were assembled and calibrated for the three study catchments containing four surveyed culverts. The models were assembled based on the NHDPlus V2 hydrography data set (https://www.epa.gov/waterdata/get-nhdplus-national-hydrography-dataset-plus-data), which was used to delineate the model sub-catchments and the stream channel drainage network. The model sub-catchments and drainage network for the three study catchments are shown in Figure 50.

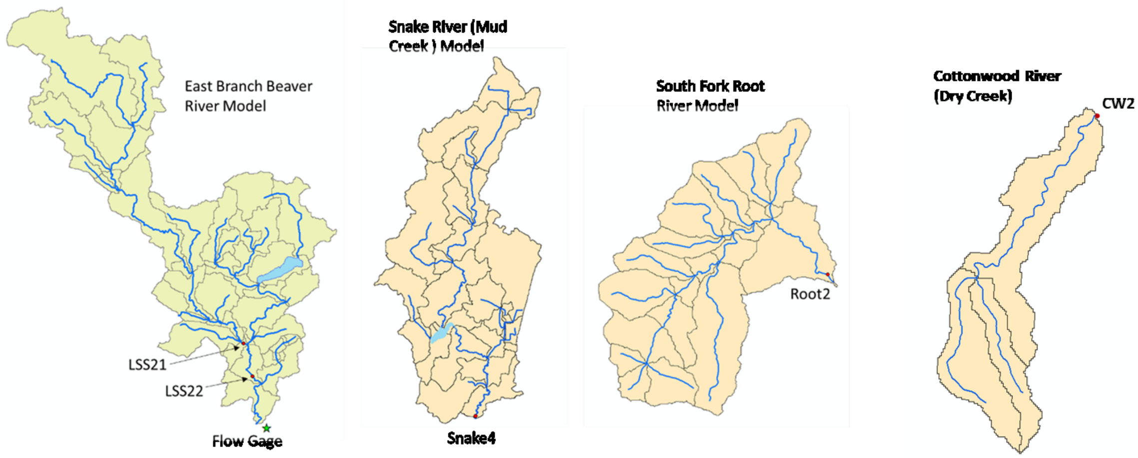


Figure 50. HSPF model sub-catchments and drainage network for the Beaver River, Snake River, Root River, and Cottonwood River study sites.

The HSPF models were calibrated using local climate data and available flow gaging data (Table 6), either from within the same watershed or from a nearby watershed with similar characteristics. In all cases, the observed flow data was linearly scaled based on the ratio of the catchment size of the gage and the catchment size of the study catchment. Hourly historical climate data (air temperature, dew point temperature, wind speed, solar radiation, cloud cover) were obtained for each site from the NOAA gridded climate data, NLDAS (https://ldas.gsfc.nasa.gov/nldas). Better flow calibration results were achieved by adjusting the gridded hourly precipitation data based on daily precipitation data taken from the closest co-operative rain gage (Harmony, Minnesota, for the Root River; Mora, Minnesota, for the Snake River; Wolf Ridge for the Beaver River, and Jeffers, Minnesota, for the Cottonwood River).

In addition to the climate variables, HSPF requires an input for potential evapotranspiration (PET), which includes plant water use for photosynthesis (transpiration), direct evaporation from the soil surface, and the evaporation of rainfall captured by the plant canopy. The ASCE-Penman method (Walter et al. 2000) was used to estimate daily PET for each site – the ASCE-Penman method takes into account humidity; therefore, the effect of future changes in humidity on PET were taken into account in projected stream flows.

Table 6. Summary of flow gages used for HSPF model calibration. The flow gages were identified from the MNDNR/MPCA co-operative flow gage network

Study Catchment	Flow Gage	Flow Gage Contributing Area (km^2)	Distance to Culvert site (km)	Gage Record
Cottonwood	Dry Creek near Jeffers, Minnesota	8.2	0.7	6/1982 —11/1985
East Branch	Beaver River near Beaver Bay (CSAH4)	321	2.9	4/2011-present
Snake River (Mud	Mud Creek nr Grasston (CR5)	170	4.0	1/2010-10/2011
South Fork Root	South Fork Root River at Amherst	57.5	2.3	4/2008 – 11/2015
South Fork Root	Crystal Creek near Harmony (TWP315)	15.3	16	3/2010-present

Where possible, spatial data were used to estimate HSPF parameters, to reduce the number of calibration parameters. The SSURGO soil data set (Soil Survey Staff 2015) was used to estimate the infiltration and soil water storage parameters for each sub-catchment of each model. The NCLD 2016 land cover layer (https://www.mrlc.gov/national-land-cover-database-nlcd-2016) was used to estimate impervious surface area in each sub-catchment and forest cover, used to set shading and canopy storage parameters in HSPF. Each model was then calibrated as follows:

1) The overall water balance (mean annual flow) was adjusted by scaling the estimated PET
2) The monthly water balances were adjusted using the monthly lower zone evapotranspiration parameters
3) Peak flows were calibrated by adjusting the soil infiltration rate
4) Low flows were adjusted using the groundwater recession rate parameters

While the ability of the models to match the observed flow time series were measured using R^2 and the Nash-Sutcliffe parameter as is standard in many modeling studies (Motovilov et al. 1999), emphasis was placed on reproducing the observed flow duration curve over the period of record, meaning the model reproduces the observed high, medium and low flow statistics. The observed and simulated flow duration curves for each site are given in Figure 51. The model calibration and subsequent data analysis focused on mean daily flows, rather than sub-daily flows. The daily time step flows align with the StreamStats flow estimates used elsewhere in the study and are an appropriate time scale for fish passage analysis.

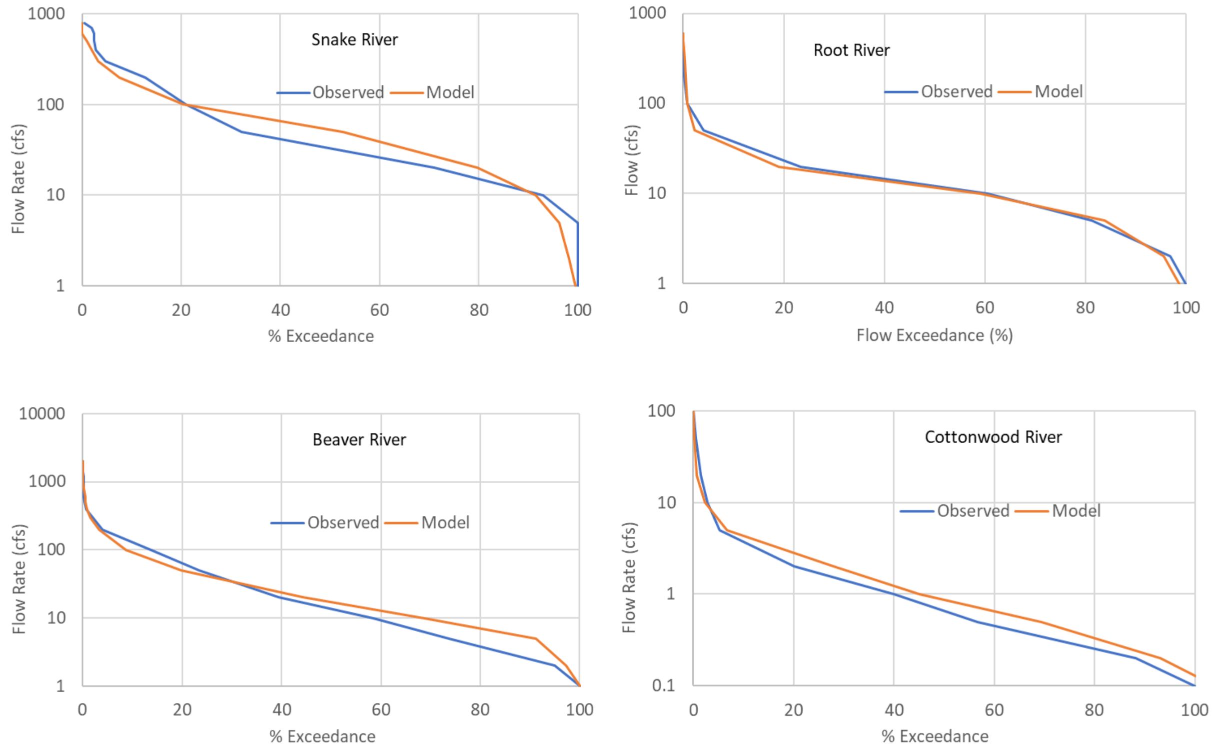


Figure 51. Simulated and observed flow duration curves for the Snake, Root, Beaver, and Cottonwood River sites.

6.2.1 Climate Scenario Preparation

We selected the 1/16° University of Idaho statistically downscaled data set (Abatzoglou et al. 2012) as the source for global climate model (GCM) data in this project, mainly because it includes projections for humidity, solar radiation and wind speed, in addition to precipitation and air temperature. Downscaled global climate model (GCM) output data were downloaded for each location from the MACA site (http://maca.northwestknowledge.net/) for both a historical period (1981-2000) and a future period (2061-2080). The climate data were downloaded for four GCMs from the CMIP5 model set (Taylor et al. 2012), for the RCP85 emissions scenario (high CO_2 emissions). The GCMs were selected to span a range of projected changes in mean annual air temperature and mean annual precipitation (Figure 52): Hadley GEM2-CC365 (hot dry), GFDL-ESM2G (warm, wet) and the intermediate MIROC5 and Nor models. The downscaled climate change projections can have significant gradients in projected changes over Minnesota (Figure 53).

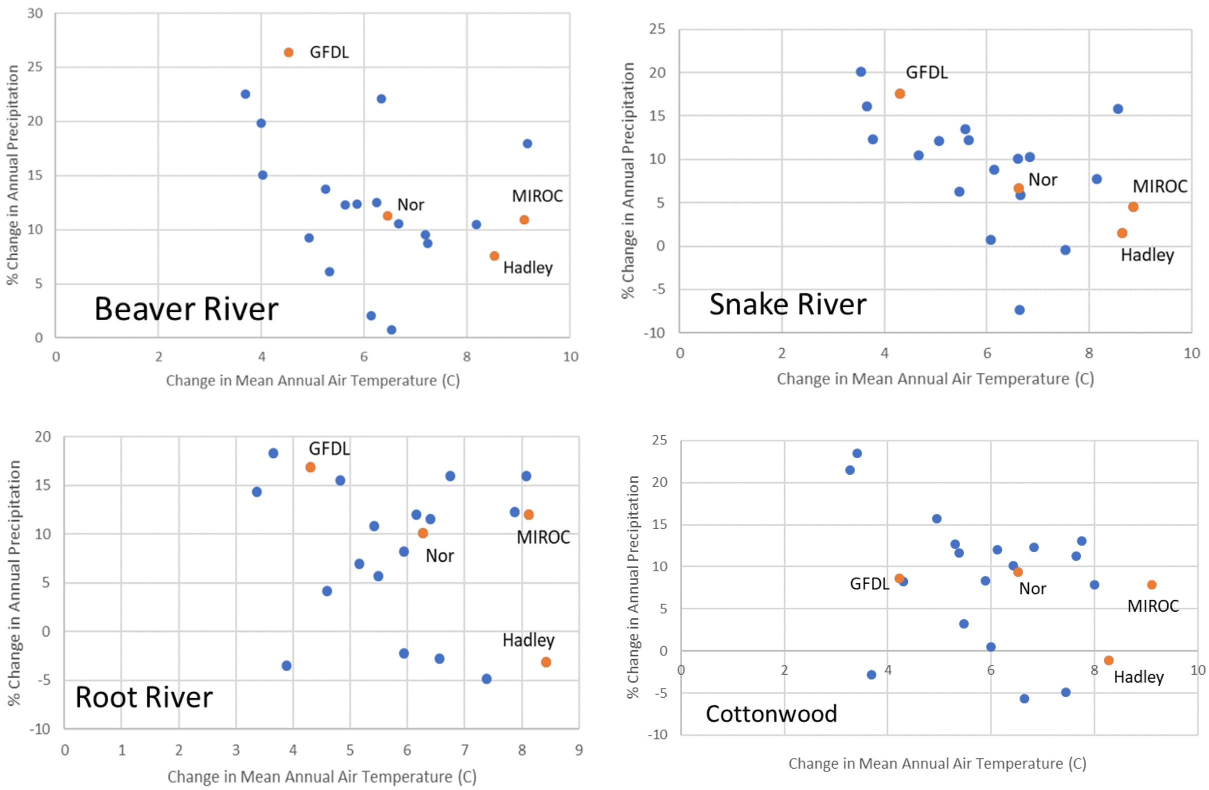


Figure 52. Projected change in mean annual precipitation versus projected change in mean annual air temperature from 1981-2000 to 2061-2080, for 34 GCM models in the CMIP5 set for the four study watersheds. The four GCMs used in this study are highlighted (in orange) and labeled.

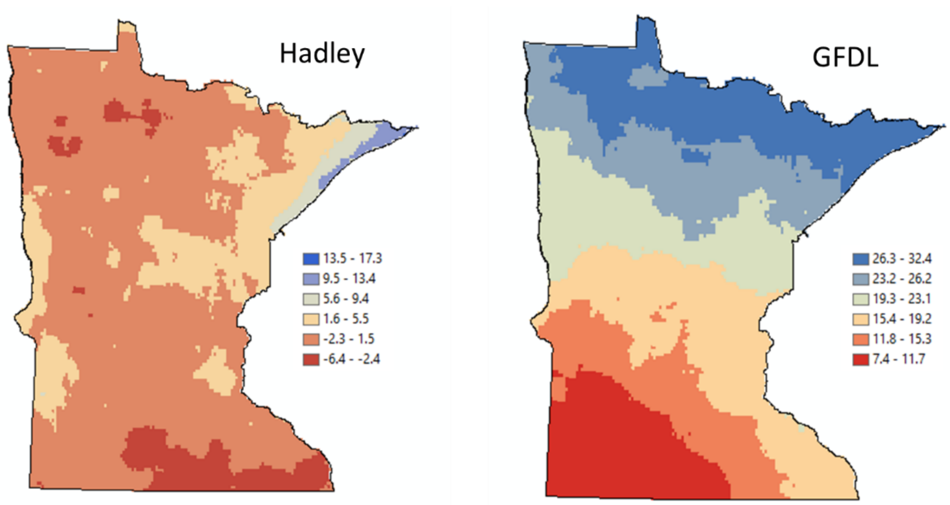


Figure 53. Projected changes (%) in mean annual precipitation (from 1971-2000 to 2071-2100) across Minnesota for the Hadley and GFDL models.

Each GCM model has bias in its outputs – model simulations for historical periods do not match observations at a local scale, even when averaged over 20 years. The GCM model outputs for the historical period (1981-2000) were used to de-bias each climate variable. Monthly-averaged climate variables were calculated for each GCM and for the climate observations for each location (Lorenz et al. 2016). For precipitation, the (mean observed/mean simulated) ratio was calculated for each month, and used to correct both the historical and future GCM precipitation data. For air temperature, the GCM data were corrected based on monthly differences (mean observed - mean simulated). Humidity, solar radiation, and cloud cover were also corrected using monthly multiplicative corrections, in a similar manner to precipitation.

The de-biased GCM outputs also needed to be disaggregated from daily values to hourly value for input to the HSPF models. Because of the emphasis in this study on mean daily flows, relatively simple algorithms for disaggregation built into the HSPF tool were used to disaggregate the GCM climate outputs. In particular, daily precipitation was disaggregated using an assumed triangular distribution of hourly precipitation. Much more sophisticated methods for disaggregating daily precipitation that attempt to preserved the sub-daily storm patterns of a region are a topic of current research (e.g. Lee & Park 2017), but were out of scope for this study.

6.2.2 Historical and Future Flow Statistics

The four calibrated HSPF models were run for both the historical and future climate scenarios from the GCMs, along with a 20-year observed record of climate for each location (1981—2000). For the Root, Snake, and Cottonwood river models, daily flow data time series were saved for the outlet of the catchments (the locations of the stream gages) and also the locations of the study culverts. For the Beaver River model, daily flow data time series were saved for two locations within the drainage network for the two study culverts (LSS21 and LSS22, see Figure 50). Typical modeled flow time series for the Root River site are illustrated in Figure 54. Figures 55 and 56 give examples of how the flow duration curves for each site shift from current conditions to the future climate scenarios. Figure 55, which gives results for all four culverts in response to the Hadley scenario, shows that the response of low flows to the Hadley scenario is stronger in the Northshore area compared to the central and southern portions of the state. For the Snake River, only the GFDL scenario projects future increases in streamflow, with the other three climate scenarios projected decreases in both high and low flows (Figure 56).

The daily flow data for each site and scenario were then processed to look at future changes in flows relevant for culvert fish passage: the velocity barrier flow rate, the depth barrier flow rate, the low fish passage flow (QLP; 90th percentile flow duration) and high fish passage flow (QHP; 5th percentile flow duration) passage flows, and the 1.5 year return period flow (Q1.5) used to characterize sediment movement and substrates. For the velocity and depth barrier flows, the simulated flow time series were processed to count the number of days that flow was equal to or greater than the velocity barrier flow rate and the number of days that flow was equal to or lower than the depth barrier flow rate (Figure 57). For the 1.5 year return period flow, a log-Pearson type III distribution (Mays 2001) was fit to the 20 year time series, as follows:

- The maximum flows for each year were calculated, and the base 10 log was calculated
- The mean, standard deviation, and skew of the log annual maxima was calculated
- Based on the skew and the return period, the K value was interpolated from Table 10.4.1 in May (2001).
- The 1.5 year return period flow (Q_T) was then calculated as: Log (Q_T) = y + K·S

Where y and S are the mean and standard deviation of the log annual maxima, respectively.

Although the GCM climate data were de-biased, flow simulations run using the GCM-generated historical climate data are still biased, i.e. the 1.5 year return period flows calculated based on observed climate do not match the 1.5 year return period flows calculated based on the historical climate data from the GCMs. This is due to variations in the distribution of daily precipitation depth between the GCM models. To reduce these bias errors in the future flow projections, a percent change in the flow rate from historical to future was calculated for each GCM using Eq. 1:

$$\% \text{ Change} = 100*(Qf-Qh)/Qh \qquad (1)$$

Where Qf is the flow statistic based on future GCM climate and Qh is the flow statistic based on the historical GCM climate. These % Change values were than applied to the observed flow rates for each site, to yield unbiased, estimated future flows. The projected changes in the 1.5 year return period flow, QLP (90% duration flow) and QHP (5% duration flow) are summarized in Figures 58 and 59. Tabular results are given in Appendix D, Tables D1 and D2. For both QLP and QGP, the GFDL scenario leads to future increases, and the Hadley and MIROC scenarios lead to decreases in flow, but the amount of change varies substantially among the four study sites.

The results for depth and velocity barriers are summarized in Figure 60. Tabular results are given in Appendix D, Table D3. The wet GFDL scenario led to decreases in the number of days with depth barriers and increases in the number of days with velocity barriers, while the Hadley, MIROC, and Nor scenarios had the opposite effect.

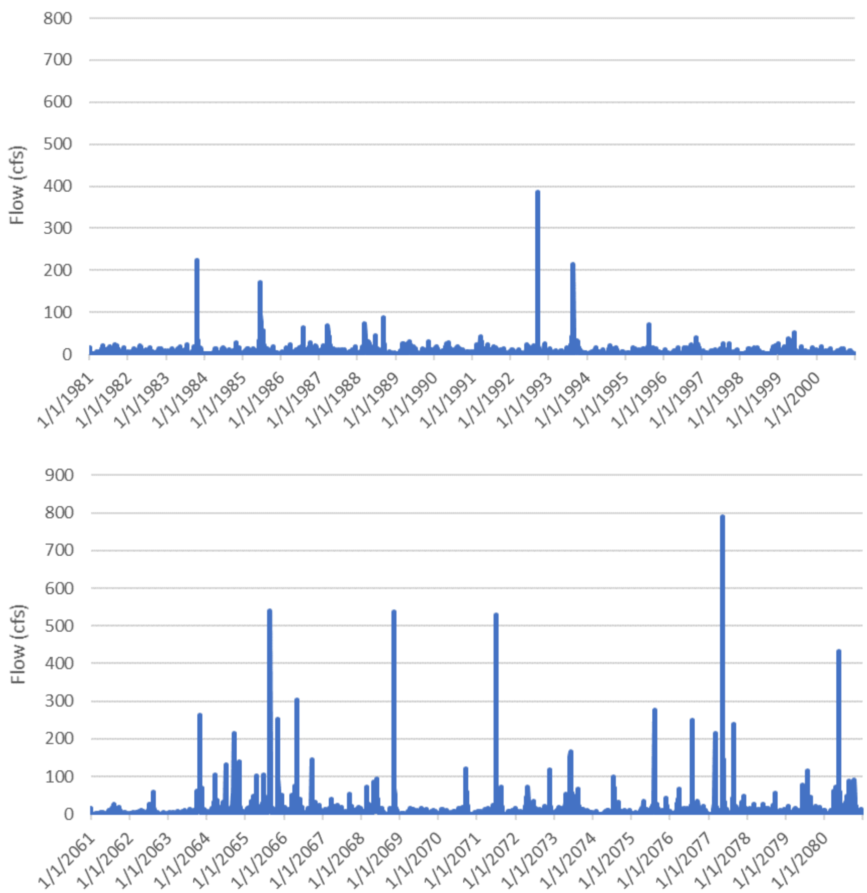


Figure 54. Simulated daily flows in the South Fork of the Root River (culvert Root2) for historical (top panel) and future (bottom panel) climate data from the GFDL model. Under the GFDL scenario, mean annual flow increases from 4.6 cfs to 7.2 cfs.

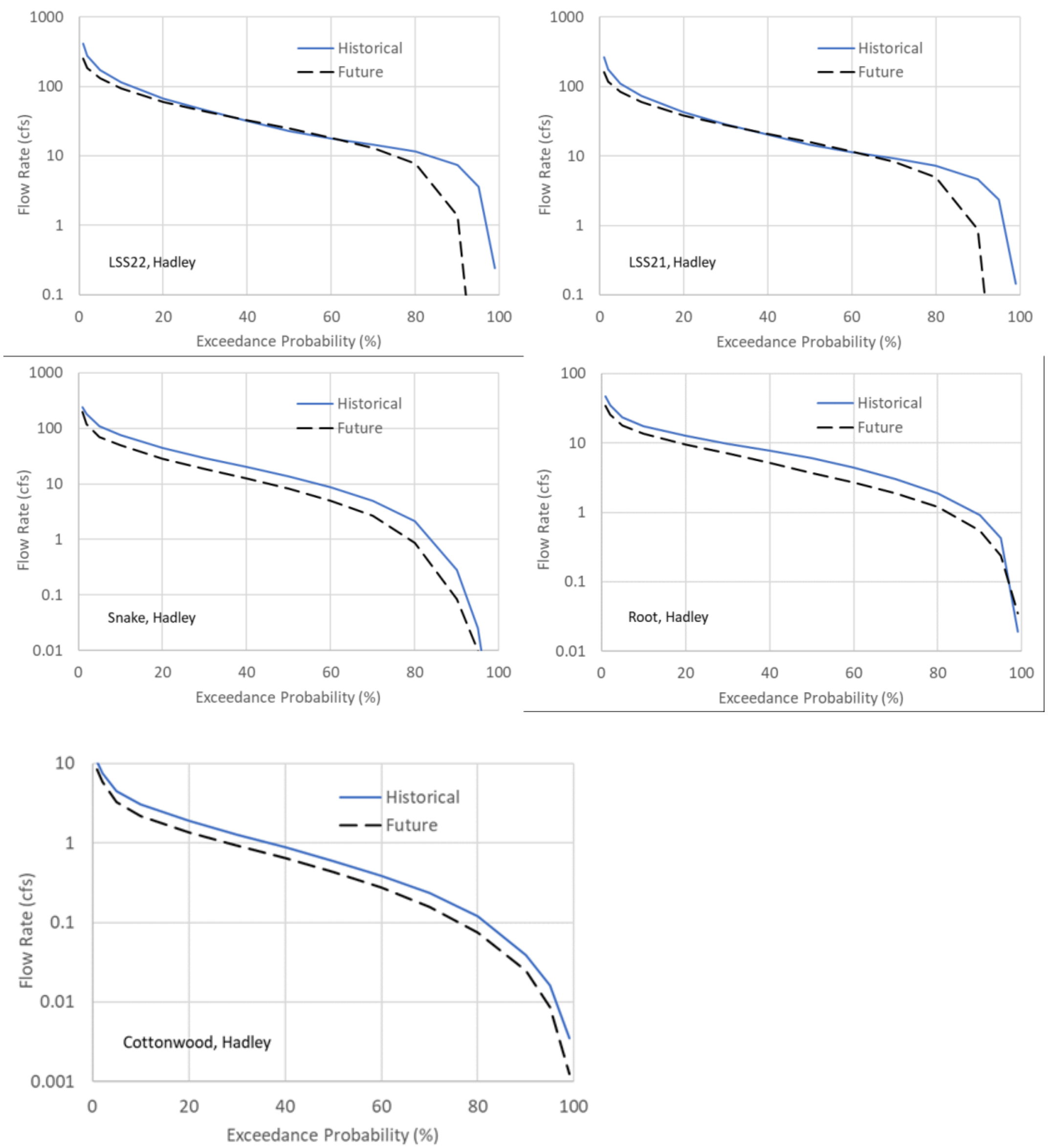


Figure 55. Simulated change in the flow duration curves for the five study culverts in response to the Hadley climate scenario.

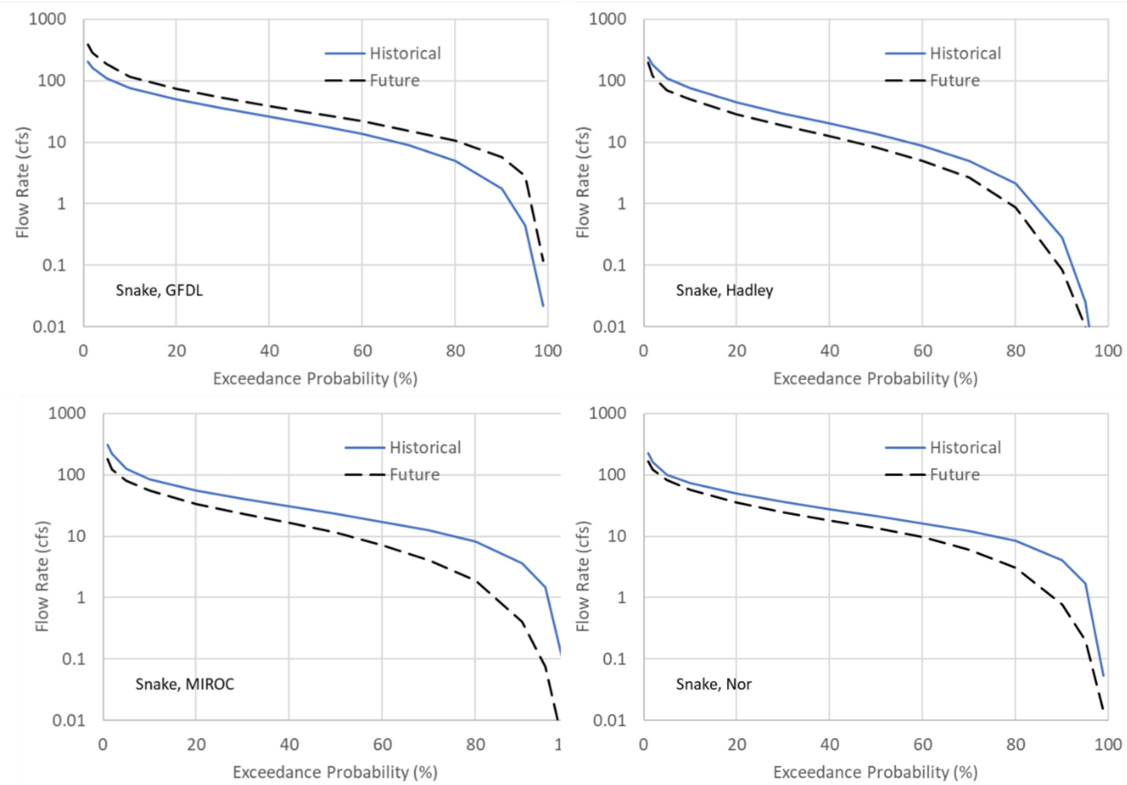


Figure 56. Simulated change in the flow duration curves for the Snake river culvert in response to the four climate scenarios.

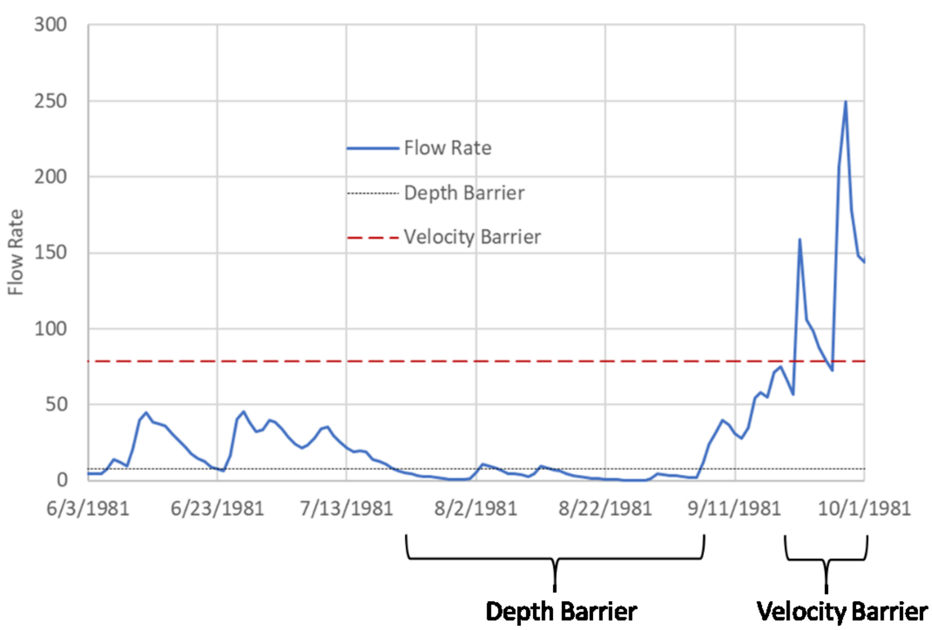


Figure 57. Sample of historical flow simulation in culvert LSS22 (East Beaver River) in comparison to the flow rate thresholds which create a potential velocity barrier (78 cfs) and a potential depth barrier (7.7 cfs).

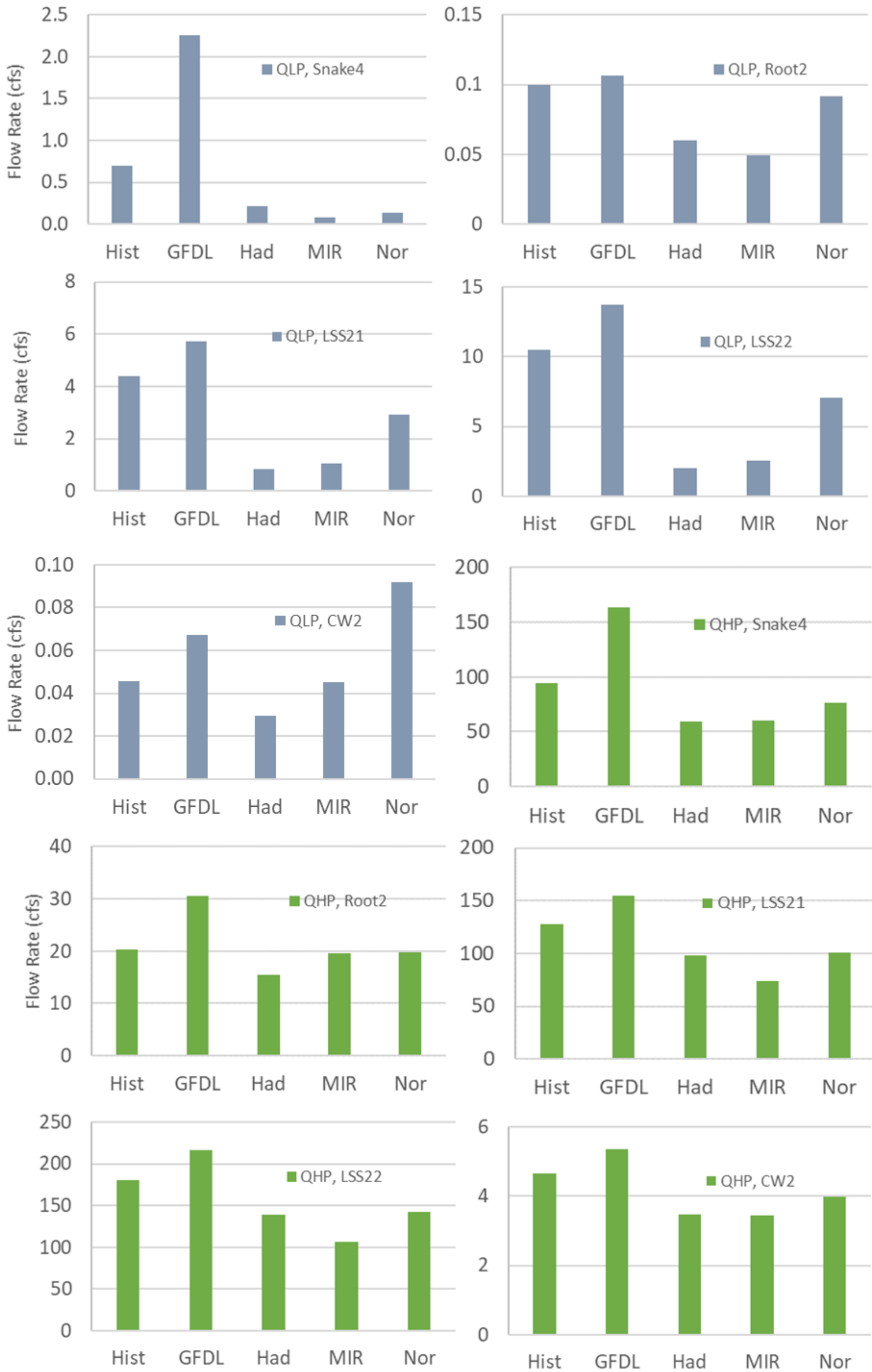


Figure 58. Summary of historical and projected future QLP and QHP flows for each culvert and climate scenario.

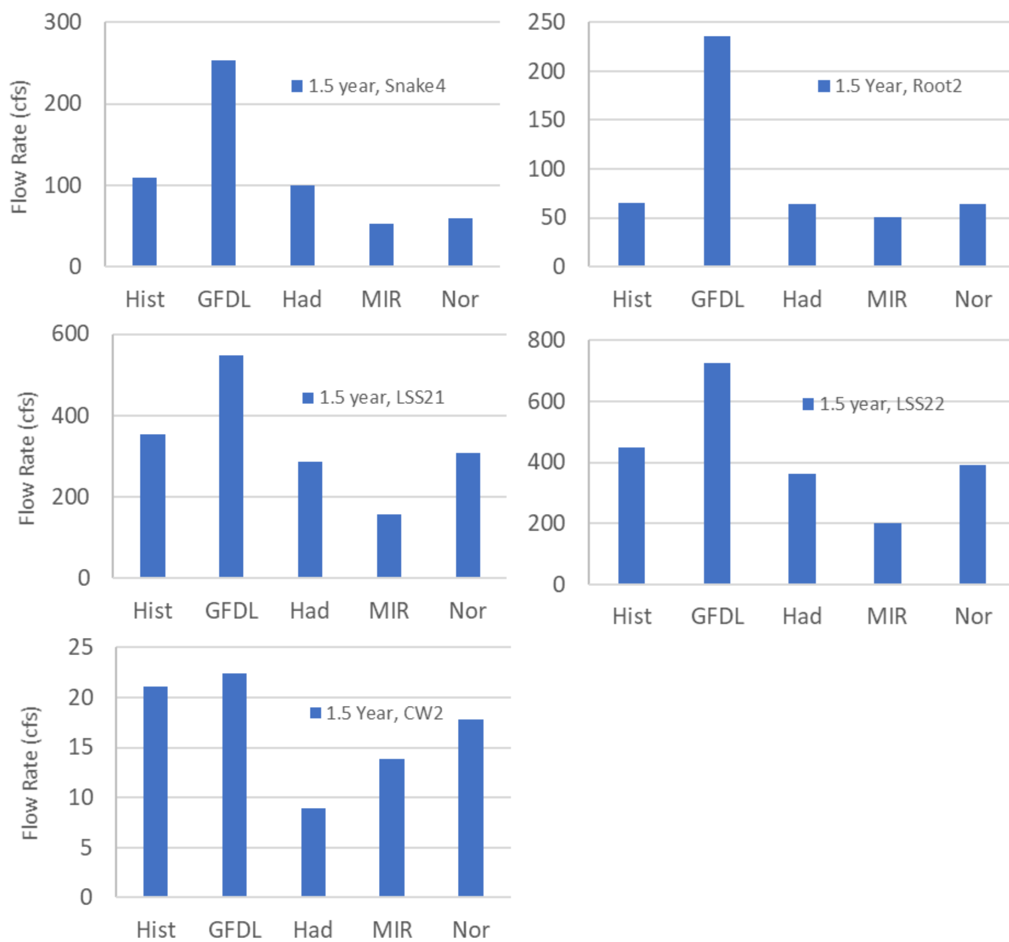


Figure 59. Summary of historical and projected future 1.5 year return period flows for each culvert and climate scenario.

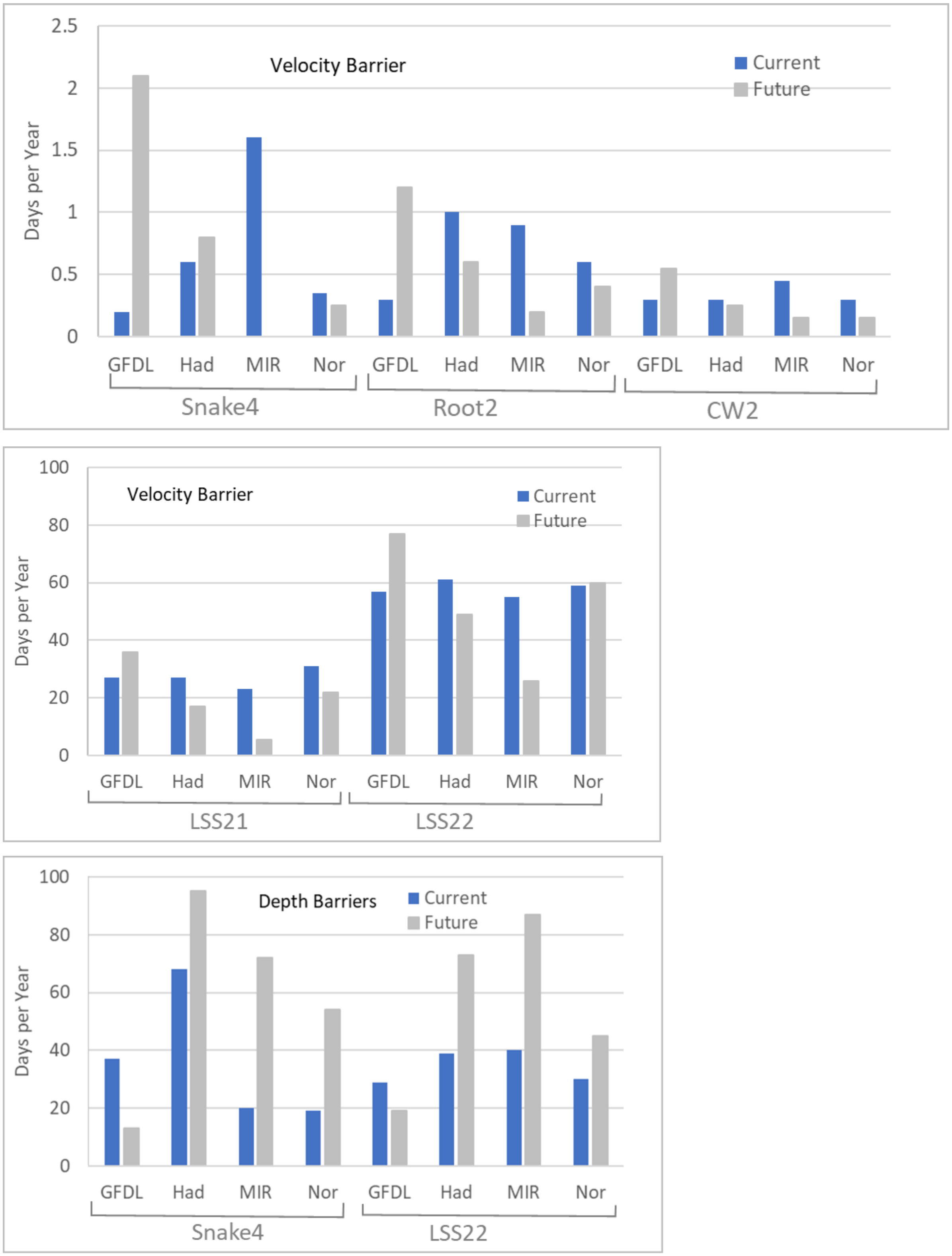


Figure 60. Summary of potential current and future velocity and depth barriers (as days per year) for each culvert and climate scenario. Culverts with no depth barrier numbers (Root2, CW2, LSS21) are backwatered.

6.3 EVENT-BASED ANALYSIS

To address culvert overtopping flows, the HSPF models were additionally used to analyze individual storm events with return periods of 25, 50 and 100 years, for historical and projected future storms. For each study site, 24-hour duration storm depths with return periods of 25 to 100 years were compiled from the Atlas-14 storm database, along with the MSE-3 24 duration distribution (https://www.dnr.state.mn.us/climate/noaa_atlas_14.html). The Atlas-14 24 hour duration storm sizes for the four study sites is given in Table 7. The MSE-3 rainfall distribution used to set the rainfall distribution of the storms over 24 hours is shown in Figure 61, and is similar to the Type-II distribution associated with TP-40.

Table 7. Atlas-14 storm sizes for the three study regions for 25, 50 and 100 year return periods.

Return	Total Precipitation (in)			
(years)	East Beaver	Root	Snake	Cottonwood
25	4.82	5.74	4.82	5.13
50	5.55	6.74	5.55	5.99
100	6.34	7.84	6.33	6.92

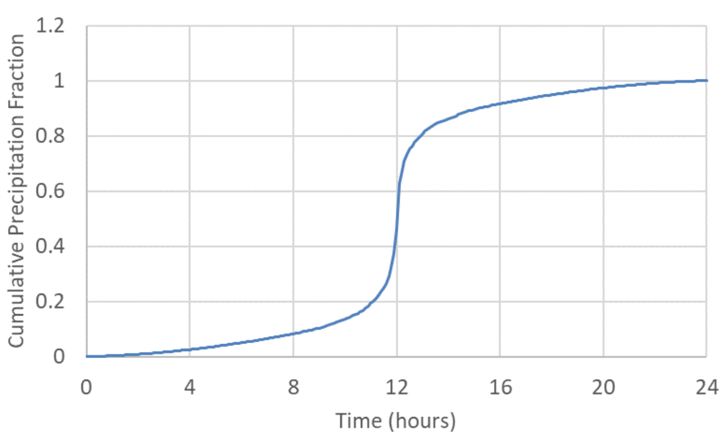


Figure 61. Cumulative rainfall distribution (fraction of total) of the MSE-3 24 hour storm.

To estimate future storm sizes, storm size increments were obtained from the future storm database associated with the EPA CREAT risk analysis tool (https://www.epa.gov/crwu/climate-resilience-evaluation-and-awareness-tool-creat-risk-assessment-application-water). To cover the range of global climate model responses, these estimated future storm sizes were estimated from a suite of climate models (GCMs) in the CMIP3 global climate model data set (US EPA 2012). The results were summarized for a median GCM output, a warm/wet scenario, and a hot-dry scenario. These scenarios are not associated with specific climate models. The CREAT storm increments (% increase in storm size) were obtained for the three study sites (Table 8) using the SWMM-CAT tool, a stand-alone climate analysis tool associated with the EPA-SWMM software package (https://www.epa.gov/water-research/storm-water-management-model-swmm). Note that, for example, the warm/wet future scenario does not necessarily produce the largest storm sizes, since the climate scenarios are based on mean annual precipitation, not storm intensity.

The storm events listed in Table 8 were used as input to the calibrated HSPF models. Since the CREAT database gives storm sizes for 30 years, but not 25 years, a 25 year storm size was interpolated using a polynomial function. The model initial conditions were established as the median stream flow at the model output, based on the continuous simulations. For each storm event, the HSPF model was run and the peak daily flow was recorded. Figure 62 plots the peak flow rates versus storm return period for historical and future scenarios for each culvert, along with the overtopping flow obtained from HY8. Peak flow rates increased the most in the Root River (up to 89%), and least in the Beaver River (up to 28%). Table 9 summarizes the change in return period of overtopping flows, based on the HSPF analysis. For LSS21, the return period of overtopping flow reduces from about 100 years in historical conditions to about 50 years for the warm/wet and hot/dry scenarios. Although the hot/dry scenario has lower mean annual precipitation than the other two scenarios, increasing air temperatures increases the moisture capacity of the atmosphere, which can lead to more intense storm events (Lenderink and Meijgaard 2010). The naming convention is based on mean annual precipitation, not storm intensity; therefore, even the hot/dry scenario can produce more frequent large storm events.

Table 8. EPA CREAT future storm size (2045-2074) increments (% change) for a warm/wet (W/W), median (Med), and Hot/Dry (H/D) scenario, for 5 to 100 year return periods.

Return Period (years)	East Beaver			Root			Snake			Cottonwood		
	WW	Med	HD	WW	Med	HD	WW	Med	HD	WW	Med	HD
5	15.7	7.1	9.3	16.3	7.2	10.2	16.1	7.2	10.2	10.3	7.9	11.2
10	15.4	5.3	10.6	16.2	5.6	10.6	16.3	5.3	11.5	9.1	6.2	11.6
15	15.3	4.4	11.5	16.3	4.8	10.9	16.5	4.5	12.5	8.5	5.2	11.9
25	15.1	3.5	12.9	16.4	3.8	11.4	16.9	3.4	13.8	7.8	4.2	12.3
50	15.0	2.3	14.9	16.5	2.6	12.2	17.5	2.1	15.8	6.9	2.6	13.1
100	14.9	1.2	17.2	16.7	1.5	13.2	18.2	0.9	18.1	6.2	1.2	14.0

Table 9. Summary of the estimated return period for overtopping flow for the study culverts.

	Overtop	Return Period (years)			
Culvert	Flow (cfs)	Historical	Warm/Wet	Median	Hot/Dry
LSS21	2772	99	49	91	50
LSS22	7849	>100	>100	>100	>100
Snake4	1158	38	15	33	18
Root2	3147	>100	>100	>100	>100
CW2	1148	>100	>100	>100	>100

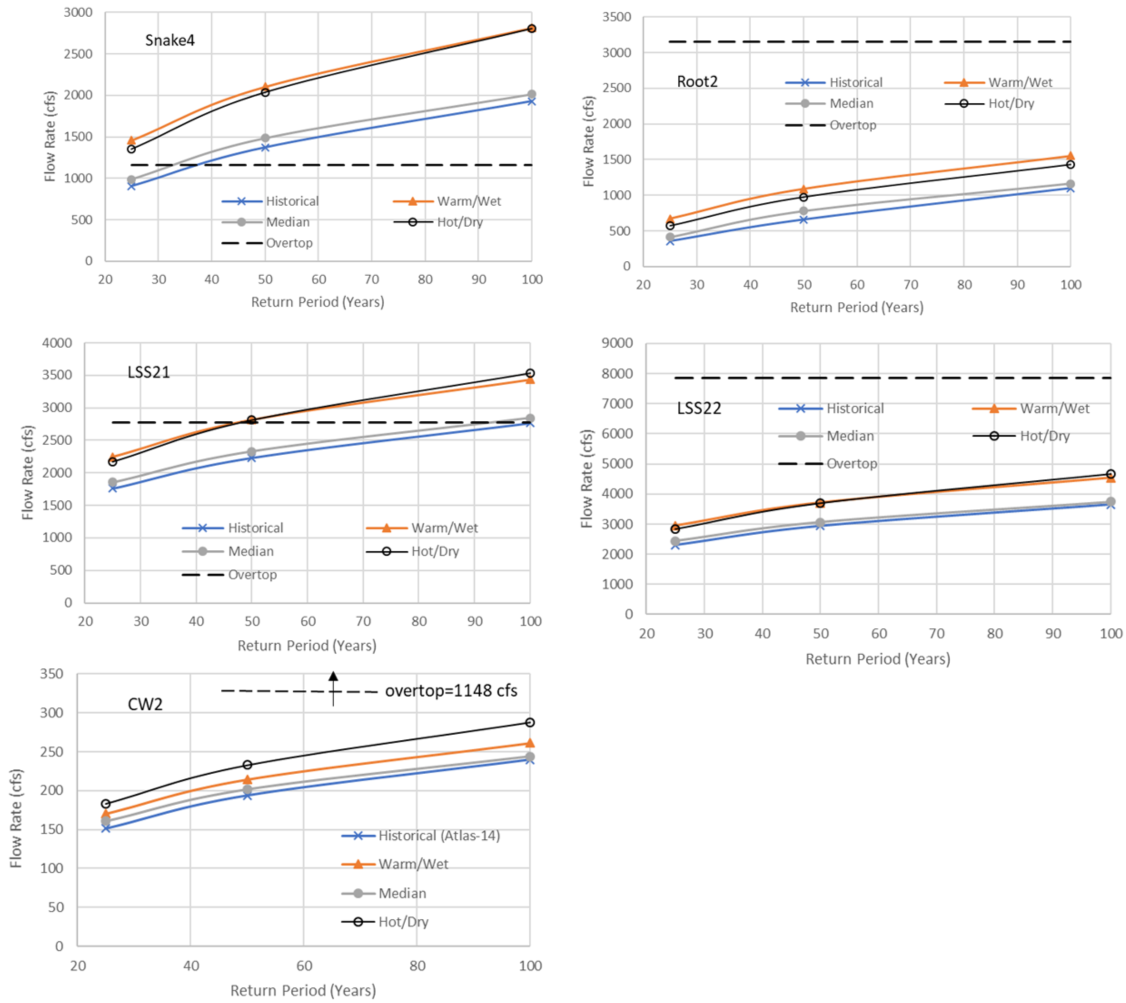


Figure 62. Simulated peak flow rate in each culvert for historical (Atlas-14) and future (warm/wet, median, and hot/dry) storms. The overtopping flow is also shown. Note that the naming convention is based on mean annual temperature and precipitation, not storm intensity.

6.4 DISCUSSION OF FUTURE CLIMATE SCENARIOS

There is substantial uncertainty in the future climate scenarios and the corresponding stream flow simulations. The main sources of uncertainty are the climate projections themselves, which vary substantially between the global climate models (Figure 52) and the uncertainty in the HSPF model calibrations. For the continuous simulations, high flows are sensitive to precipitation projections (storm sizes) and temperature projections, which determine spring snowmelt rates. Simulated low flows are sensitive to projected precipitation patterns, such as drought frequency, and projected changes in evapotranspiration (ET), which influences the availability of baseflow between rainfall events. Projections of future increases in ET were made using empirical models that relate ET to air temperature and humidity under present conditions, but do not take into account how plant water use will respond to increasing CO_2 levels.

The EPA database (CREAT 2.0) that was used to estimate future storm sizes for the overtopping analysis projects increases of storm sizes of up to 18%. A newer EPA database (CREAT 3.1), which was not used because it gives information only for 100 year return period storms, puts bounds on future storm sizes by giving data for a “stormy” scenario and a “not as stormy” scenario. For the Superior Northshore area, these bounds are a 3.2% to 21.1% increase by 2060 in the 100 year return period storm, while for Southeast Minnesota, the range is 6.0 to 25.5% increase. The MnDOT Silver Creek culvert case study (Parsons Brinckerhoff 2014) used a proprietary future storm database (SimCLIM) that projects increases in the 100 year storm event of 4.9 to 21.3 % by 2070. So, the CREAT 2.0 storm database used in this study gave storm sizes slightly lower than other more recent databases, but of similar magnitude.

Another question regarding future storms is the hourly and sub-hourly distribution of rainfall within a 24 period. Some research has suggested that increasing air temperatures, the corresponding increase in the water holding capacity of the atmosphere, and increasing frequency of convective storm systems will lead to storms with higher precipitation intensity at hourly time scales (Lenderink and Meijgaard 2010, Westra et a. 2014). These studies have suggested increases in hourly and sub-hourly rainfall intensities on the order of 10% per degree C of warming, but with substantial variability between regions. A 4 degree C increase in air temperature by the end of the century would correspond to roughly a 40% increase in storm intensity, a potentially larger increase than the projected changes in 24 hour duration rainfall depth used in this study. This research on sub-daily storm intensities was not incorporated into the present study, but provides some context on the limitations of the study.

Given these sources of uncertainty, the strategy for this project was not to claim that we can project future flows in culverts with any level of accuracy, but rather to attempt to put bounds on how much the various key flow parameters could change, and then determine which culvert designs tend to be the most robust to these changes.

CHAPTER 7: CONCLUSIONS: CULVERT PERFORMANCE IN CURRENT AND FUTURE SCENARIOS

From the screening-level (Phase I) results, the following conclusions can be drawn about culverts in Minnesota under current hydrologic scenarios:

1. Both low-flow depth barriers and high-flow velocity barriers present concerns for fish passage in Minnesota across culvert types, and this can have consequences for fish communities. In summer, shallow depths can limit fish movement to areas such as thermal flow refugia and can block both upstream and downstream movement. High velocity can limit upstream movement in critical spawning times, especially for low-endurance swimmers such as Northern Pike.
2. Bankfull width ratios > 2 are a concern for low-flow depth barriers
3. Low bankfull width ratios (< 1) are a concern for high-flow velocity barriers
4. High slope (> 1%) culverts had more low-flow depth barriers and more high-flow velocity barriers.
5. Even for culverts > bankfull width, velocity can be a concern in steeper culverts and roughness elements are important for resting areas.
6. Embedded culverts reduced but did not eliminate barriers, suggesting that other considerations, such as culvert width and slope are also important.

These conclusions support the current guidance for fish passage culvert design in Minnesota in Hernick et al. (2019), with emphasis on the motivation for bankfull-width embedded culverts and the need to address potential low-flow barriers.

There remains significant uncertainty over future hydrologic scenarios. Yet, these scenarios provide a reference and give bounds on future hydrology with which to evaluate culvert resiliency. In general, these conclusions emphasize that culvert designs that maintain stream connectivity (Hernick et al. 2019) are more resilient to effects of changing climate. Conclusions from the future hydrologic scenarios (Phase II) results follow:

1. Future climate scenarios are particularly sensitive to changes in low flows. Maintaining a low-flow channel, or embedded culvert barrel can help protect against a reduction in QLP. Backwatering the culvert with a passible downstream grade control can also help to mitigate this effect.
2. Ensuring culvert widths equal to or greater than the bankfull width in combination with embedded (sediment with resting areas) can help mitigate an increase in QHP.
3. Culverts with bankfull width ratios < 1 are susceptible to decreases in the overtopping return interval.
4. Culverts with shear stresses significantly more or less than the channel are susceptible to scour or deposition. Designing the crossing similar to the channel helps alleviate these issues.

While the results of this study provide additional support for the guidance provided in Hernick et al. (2019), this study also highlights the following limitations and uncertainties in this guidance.

1. Current guidance relies on an accurate estimate of bankfull width, but this parameter is challenging to measure in the field, especially in situations where local hydrology is changing. This study and others (see O'Shaughnessy et al. 2016; Gillespie et al. 2014; Christiansen et al. 2014) indicate that a culvert designed at current bankfull width or slightly greater is more resilient to large flow events, but if bankfull width changes significantly over the life of the culvert, the designed culvert may be undersized (Wilhere et al. 2016).
2. Addressing low flows is likely critical even under warmer/wetter climate scenarios. To address low flows, tools include: offsetting multiple barrel culverts, backwatering culverts with a downstream weir, and/or creating a low-flow channel within an embedded culvert barrel. For all these methods, there exists little quantitative guidance in Hernick et al. (2019) or elsewhere.
3. While not a focus of this study, floodplain culverts are also likely critical to effectively passing large flow events under roadways with minimal infrastructure damage. MNDNR has developed some information on the design of floodplain culverts in Minnesota (https://www.dnr.state.mn.us/eco/streamhab/geomorphology/index.html).

CHAPTER 8: CAVEATS AND STUDY LIMITATIONS

This is a modeling exercise and should not be interpreted as an exact solution for fish passage for any individual culvert. There are significant uncertainties in fish swimming abilities and fish behavior, and many fish species and life stages simply do not have available swimming criteria. There are also uncertainties in the estimated QLP and QHP as these are derived empirically from StreamStats and watershed characteristics can vary greatly. In addition, the selected flow duration for QLP and QHP are a simplified selection of appropriate flows required for fish passage and may not be adequate for all fish species and life-stage movements as different species and life stages need to move at different times of year. HY-8 produces width averaged depth, velocity, and shear stress profiles along a culvert barrel, and thus there are limitations in modeling complex flows, such as low-flow areas along culvert margins, low-flow channels, or resting areas behind boulders that may be areas fish exploit. Also, the hydraulic modeling used in this report was not calibrated against measured flows. Therefore, the selection of roughness values is unverified. Errors in roughness selection may impact the model results. However, taken together, some key trends emerge that support recent guidance on culvert design.

Limitations of using fish swimming performance curves to predict culvert passage tend to lead to a conservative estimate of fish passage (i.e., predicting a full barrier when some fish can pass). Laboratory measurements of swimming performance with captive fish can lead to a conservative estimate of swimming ability (Castro-Santos et al. 2013; Mahlum et al. 2014; Castro-Santos 2006; Peake and Farrell 2006). In addition, there is a large variability in fish swimming performance, even within a single species, that should be considered when evaluating passage. Many studies use fish swimming criteria in combination with hydrologic/hydraulic models of culvert flow (e.g., FishXing). However, the selection of hydrologic scenarios is also critical. For example, selecting flows that are uncommon, could lead to an overestimation of the potential for a culvert to present a barrier to fish passage. The hydraulic model selected to represent culvert hydraulics can also affect the prediction of passage, likely in a conservative manner (over prediction of culvert barriers). The most common culvert hydraulic models are one-dimensional (FishXing, HY-8) and cannot account for low-flow areas near culvert boundaries that fish may use to navigate (Baral 2013). These limitations should be acknowledged in the evaluation of modeling results. Using swimming criteria to evaluate culvert design, is, however, an appropriate way to screen a large number of culverts for potential barriers to fish passage.

This study focused on daily averaged hydrologic data, the hydrologic analysis used daily time step precipitation data from downscaled global climate models, and the HSPF model stream flow outputs were processed at daily time steps. As a result, the study did not consider potential changes in sub-daily storm intensities and did not quantify sub-daily peak flow rates. For fish passage analysis, sub-daily high flows may not be an important limitation, because fish can delay passage for a few hours during peak flows. Sub-daily peak flows may be more important to consider for overtopping analysis, where overtopping for a few hours could be quite damaging.

REFERENCES

Abatzoglou, J. T., & Brown, T. J. (2012). A comparison of statistical downscaling methods suited for wildfire applications. *International Journal of Climatology, 32*(5), 772–780.

Baral, D. (2013). Computational study of fish passage through circular culverts in Northeast Ohio. Youngstown, OH: Youngstown State University.

Cano-Barbacil, C., Radinger, J., Argudo, M., Rubia-Gracia, F., Vila-Gispert, A., & Garcia-Berthou, E. (2020). Key factors explaining critical swimming speed in freshwater fish: A review and statistical analysis for Iberian species. *Sci Rep, 10,* 18947. https://doi.org/10.1038/s41598-020-75974-x

Castro-Santos, T. (2006). Modeling the effect of varying swim speeds on fish passage through velocity barriers. *Transactions of the American Fisheries Society, 135*(5), 1230–1237.

Castro-Santos, T., Sanz-Ronda, F. J., & Ruiz-Legazpi, J. (2013). Breaking the speed Limit — comparative sprinting performance of brook trout (*Salvelinus fontinalis*) and brown trout (*Salmo trutta*). *Canadian Journal of Fisheries and Aquatic Sciences, 70*(2), 280–293.

Christiansen, C., Filer, A., O'Shaughnessy, E., Palmer, M., & Schwartz, T. (2014). *Cost-benefit analysis of stream-simulation culverts.* Madison, WI: Wisconsin Department of Natural Resources.

Chow, V. T. (1959). *Open-channel hydraulics*. New York: McGraw-Hill Book Company.

FSSWG. (2008). *Stream simulation: An ecological approach to road-stream crossings.* U.S. Department of Agriculture Forest Service Stream Simulation Working Group National Technology and Development Program. Retrieved from https://www.fs.fed.us/eng/pubs/pdf/StreamSimulation/hi_res/%20FullDoc.pdf

Gillespie, N., Unthank, A., Campbell, L., Anderson, P., Gubernick, R., Weinhold, M., … & Kirn, R. (2014). Flood effects on road–stream crossing infrastructure: Economic and ecological benefits of stream Simulation Designs. *Fisheries, 39*(2), 62–76.

Hatch, J. (2015). Minnesota fishes: Just how many species are there anyway? *American Currents, 40*, 10–21.

Hernick, M., Lenhart, C., Kozarek, J.,& Neiber, J. (2019) *Minnesota guide for stream connectivity and aquatic organism passage through culverts.* St. Paul, MN: Minnesota Department of Transportation, Research Services & Library

Hillman, A. (2015). *Stream crossing inventory and barrier ranking guidelines*. St. Paul, MN: Minnesota Department of Natural Resources.

Hotchkiss, R. H., & Frei, C. M. (2007). *Design for fish passage at roadway-stream crossings: synthesis report* (No. FHWA-HIF-07-033). Retrieved from https://www.fhwa.dot.gov/engineering/hydraulics/pubs/07033/07033.pdf

Imhoff, J. C., Kittle Jr, J. L., Donigian Jr, A. S., & Johanson, R. C. (1997). *Hydrological simulation program--Fortran: User's manual for version 11*. Athens, GA: US Environmental Protection Agency, National Exposure Research Laboratory.

Kilgore, R. T., Bergendahl, B. S., & Hotchkiss, R. (2010). *Culvert design for aquatic organism passage*. (Hydraulic engineering circular number 26 (HEC-26). FHWA HIF-11-008). Retrieved from https://www.fhwa.dot.gov/engineering/hydraulics/pubs/11008/hif11008.pdf

Lee, T., & Walter, T. (2017). Nonparametric temporal downscaling with event-based population generating algorithm for RCM daily precipitation to hourly: Model development and performance evaluation. *Journal of Hydrology, 547,* 498–516.

Lenderink, G., & Van Meijgaard, E. (2010). Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. *Environmental Research Letters, 5*(2), 025208.

Lorenz, D. L., Sanocki, C. A., & Kocian, M. J. (2010). Techniques for estimating the magnitude and frequency of peak flows on small streams in Minnesota based on data through water year 2005: (U.S. Geological Survey Scientific Investigations Report 2009–5250). Reston, VA: U.S. Geological Survey.

Lorenz, D. J., Nieto-Lugilde, D., Blois, J. L., Fitzpatrick, M. C., & Williams, J. W. (2016). Downscaled and debiased climate simulations for North America from 21,000 years ago to 2100AD. *Scientific Data, 3*(1), 1–19.

Mahlum, S., Cote, D., Wiersma, Y. F., Kehler, D., & Clarke, K. D. (2014). Evaluating the barrier assessment technique derived from FishXing software and the upstream movement of brook trout through road culverts. *Transactions of the American Fisheries Society, 143*(1), 39–48.

Mays, L. W. (2001). *Water resources engineering.* New York: Wiley and Sons.

Motovilov, Y. G., Gottschalk, L., England, K., & Rodhe, A. (1999). Validation of distributed hydrological model against spatial observations. *Agric. Forest Meteorology 98-99*, 257–277.

Parsons Brinckerhoff. (2014). Flash flood vulnerability and adaptation assessment pilot project: District 1 Silver Creek case study. St. Paul, MN: Minnesota Department of Transportation..

O'Shaughnessy E., Landi, M., Januchowski, S., & Diebel, M. (2016). Conservation leverage: Ecological design culverts also return fiscal benefits. *Fisheries, 41*(12), 750–757. https://doi.10.1080/03632415.2016.1246875

Peake, S. J., & Farrell, A. P. (2006). Fatigue is a behavioral response in respirometer- confined smallmouth bass. *Journal of Fish Biology, 68,* 1742–1755.

Rayamajhi, B., Vasconcelos, J. G., Devkota, J. P., Baral, D., & Tritico, H. M. (2012). Should fish passage through culverts be a concern for Midwest engineers and planners? Determining the percentage of culverts that act as barriers to fish passage in NE Ohio. World Environmental and Water Resources Congress 2012: Crossing Boundaries. *Proceedings of the 2012 Congress,* 1624–1634. https://doi.10.1061/9780784412312.162.

Soil Survey Staff. (2015). Soil survey geographic (SSURGO) database, Natural Resources Conservation Service, United States Department of Agriculture. Retrieved from http://sdmdataaccess.nrcs.usda.gov/.

Taylor, J. M., Fisher, W. L., Klein, D., Apse, C., Kendy, E., Schuler, G., … Crabtree, D. T. (2013). *Flow recommendations for the tributaries of the Great Lakes in New York and Pennsylvania.* Rochester, NY: The Nature Conservancy.

U.S. Environmental Protection Agency (EPA). (2012). Climate resilience evaluation and awareness tool version 2 methodology guide, part of the CREAT version 2.0 software. Retrieved from http://water.epa.gov/infrastructure/watersecurity/climate/creat.cfm

Walter, I. A., Allen, R. G., Elliott, R., Jensen, M. E., Itenfisu, D., Mecham, B., Howell, T. A., Snyder, R., Brown, P., Echings, S., Spofford, T., Hattendorf, M., Cuenca, R. H., Wright, J. L., & Martin, D. (2000). ASCE's standardized reference evapotranspiration equation. In Proc. of the Watershed Management 2000 Conference, June. 2000, Fort Collins, CO.

Westra, S., Fowler, H. J., Evans, J. P., Alexander, L. V., Berg, P., Johnson, F., ... & Roberts, N. M. (2014). Future changes to the intensity and frequency of short—duration extreme rainfall. *Reviews of Geophysics, 52*(3), 522–555.

Wilhere, G., Altha, J., Quinn, T., Helbrecht, L., & Tohver, I. (2016). Incorporating climate change into the design of water crossing structures (Final Report). Olympia, WA: Washington Department of Fish and Wildlife.

Ziegeweid, J. R., Lorenz, D. L., Sanocki, C. A., & Czuba, C. R. (2015). Methods for estimating flow-duration curve and low-flow frequency statistics for un-gaged locations on small streams in Minnesota. (US Geological Survey Scientific Investigations Report 2015–5170, 24 pp.). Reston, VA: USGS.

APPENDIX A FISH SWIMMING DATA

Table A1. Distributional list of fish species with valid records in Minnesota (from Hatch 2015) and references for swimming performance criteria for each species. If the swimming performance criteria column is blank, no data have been located.

E = state endangered species ex = extirpated native I = state designated invasive species i = non-native K = native history unclear (not part of state count) L = found only below the St. Croix Dalles m = native species but not native to basin n = native species	r = native species reintroduction S = state special concern species T = state threatened species U = found only above the St. Croix Dalles Red = all valid records prior to 1985 *Italic* = non-reproducing population States and Provinces are denoted by their accepted postal abbreviations.

Common Name	Scientific Name	Red River	Rainy River	L. Superior	Mississippi River HW	St. Croix River	Minnesota River	Des Moines River	Cedar River	Mississippi River SE	Missouri River	Basins Combined	State Conservation Status	Swimming Performance Criteria
Minnesota State Listed Endangered														
Darter, Crystal	*Crystallaria asprella*					L				n		n	E	
Madtom, Slender	*Noturus exilis*								n			n	E	
Shiner, Pallid	*Hybopsis amnis*					n	n			n		n	E	
Skipjack Herring	*Alosa chrysochloris*					L	n			n		n	E	
Minnesota State Listed Invasive														
Alewife	*Alosa pseudoharengus*			i								i	I	Peake 2008; Castro-Santos 2005
Carp, Bighead	*Hypophthalmichthys nobilis*					*i L*				*i*		*i*	I	FishXing; Hoover et al. 2016
Carp, Common	*Cyprinus carpio*	i		i	i	i	i	i	i	i	i	i	I	Heap and Goldspink 1986; FishXing
Carp, Grass	*Ctenopharyngodon idella*				*i*	*i L*		*i*	*i IA*	*i*	*i IA*	*i*	I	Cai et al. 2014
Carp, Silver	*Hypophthalmichthys molitrix*									*i*		*i*	I	Parsons et al. 2016: Hoover et al. 2016
Goby, Freshwater Tubenose	*Proterorhinus semilunaris*			i								i	I	
Goby, Round	*Neogobius melanostomus*			i								i	I	Tierney et al. 2011

Goldfish	*Carassius auratus*				*i*		*i*		i	i		i	I	FishXing
Lamprey, Sea	*Petromyzon marinus*			i								i	I	FishXing; Peake 2008
Ruffe	*Gymnocephalus cernua*			i								i	I	
Smelt, Rainbow	*Osmerus mordax*		i	i	i	i				*i*		i	I	Peake 2008
White Perch	*Morone americana*			i								i	I	Mellas and Haynes 1985; Nelson 1989
Minnesota State Non-native														
Trout, Brown	*Salmo trutta*	i	i	i	i	i	i	i	i	i		i		FishXing; Peake 2008; Aedo et al. 2009
Trout, Rainbow	*Oncorhynchus mykiss*	i	i	i	i	i	i		i IA	i		i		FishXing; Peake 2008
Salmon, Atlantic	*Salmo salar*			i								i		FishXing; Peake 2008
Salmon, Chinook	*Oncorhynchus tshawytscha*			i								i		FishXing
Salmon, Coho	*Oncorhynchus kisutch*			i								i		FishXing
Salmon, Pink	*Oncorhynchus gorbuscha*			i								i		FishXing; Peake 2008
Stickleback, Threespine	*Gasterosteus aculeatus*			i								i		FishXing; Blake 2005; Peake 2008
Minnesota State Listed Special Concern														
Chub, Lake	*Couesius plumbeus*		ON	n								n	S	Peake 2008
Cisco, Nipigon	*Coregonus nipigon*		n									n	S	
Cisco, Shortjaw	*Coregonus zenithicus*		n	n								n	S	
Dace, Redside	*Clinostomus elongatus*									n		n	S	Billman and Pyron 2005; Aedo et al. 2009
Darter, Bluntnose	*Etheostoma chlorosoma*									n		n	S	
Darter, Western Gilt	*Percina evides*					n						n	S	
Darter, Least	*Etheostoma microperca*	n		n	n	U	n		n	n		n	S	
Eel, American	*Anguilla rostrata*			*n*	*n*	*L*	*n*			*n*		*n*	S	Peake 2008
Kiyi	*Coregonus kiyi*			n								n	S	
Lamprey, Northern Brook	*Ichthyomyzon fossor*		n	n						n		n	S	
Lamprey, Southern Brook	*Ichthyomyzon gagei*					n						n	S	

Minnow, Mississippi Silvery	*Hybognathus nuchalis*							IA		n		n	S	
Minnow, Ozark	*Notropis nubilus*								n	n		n	S	
Minnow, Suckermouth	*Phenacobius mirabilis*							IA	n	n	IA	n	S	Ficke 2015
Pirate Perch	*Aphredoderus sayanus*									n		n	S	
Redhorse, Black	*Moxostoma duquesnei*								n	n		n	S	
Shiner, Redfin	*Lythrurus umbratilis*								n	n		n	S	Leavy and Bonner 2009
Shiner, Topeka	*Notropis topeka*							IA			n	n	S	Adams 2000; Ficke 2015
Sturgeon, Lake	*Acipenser fulvescens*	r	n	n	*m*	n	n			n		n	S	Peake et al. 1997
Sucker, Blue	*Cycleptus elongatus*					n	n			n		n	S	
Sunfish, Northern	*Lepomis peltastes*	*i*	n		n	UWI						n	S	
Warmouth	*Lepomis gulosus*		m			LWI				n		n	S	
Whitefish, Pygmy	*Prosopium coulteri*			n								n	S	
Yellow Bass	*Morone mississippiensis*						m			n		n	S	
Minnesota State Listed Threatened														
Buffalo, Black	*Ictiobus niger*					L	n			n	IA, SD	n	T	
Chub, Gravel	*Erimystax x-punctatus*								IA	n		n	T	
Paddlefish	*Polyodon spathula*					L	n			n		n	T	
Shiner, Pugnose	*Notropis anogenus*	n		n	n	n	n	IA		n	IA	n	T	
Topminnow, Plains	*Fundulus sciadicus*										n	n	T	Ficke 2015; Prenosil 2014
Minnesota State No Conservation Status														
Bass, Largemouth	*Micropterus salmoides*	n	n	n	n	n	n	n	n	n	m	n		FishXing
Bass, Rock	*Ambloplites rupestris*	n	n	n	n	n	n	IA	n	n	n	n		
Bass, Smallmouth	*Micropterus dolomieu*	i	i	n	n	n	n		n	n	n	n		Peake and Farrell 2004
Bloater	*Coregonus hoyi*		n	n								n		
Bluegill	*Lepomis macrochirus*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Gardner 2006; Schaefer et al. 1999; Jones et al. 2008; Leavy and Bonner 2009
Bowfin	*Amia calva*	n	m		n	n	n			n		n		
Buffalo, Bigmouth	*Ictiobus cyprinellus*	n			n	L	n	n	n	n	n	n		

Buffalo, Smallmouth	*Ictiobus bubalus*	m				n	n	n		n	n	n		Prenosil 2014
Bullhead, Black	*Ameiurus melas*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Prenosil 2014
Bullhead, Brown	*Ameiurus nebulosus*	n	n	n	n	n	n	n	n	n	n	n		
Bullhead, Yellow	*Ameiurus natalis*	n	n	n	n	n	n	n	n	n	n	n		
Burbot	*Lota lota*	n	n	n	n	n	n			n		n		FishXing; Peake 2008
Carpsucker, Highfin	*Carpiodes velifer*					L	n		IA	n		n		
Carpsucker, River	*Carpiodes carpio*				m	L	n			n	n	n		
Catfish, Channel	*Ictalurus punctatus*	n		n	i	n	n	n	i	n	n	n		
Catfish, Flathead	*Pylodictis olivaris*				m	n	n			n	IA	n		Holcott 1973
Chub, Creek	*Semotilus atromaculatus*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Billman and Pyron 2005; Leavy and Bonner 2009; Ficke et al. 2012
Chub, Hornyhead	*Nocomis biguttatus*	n	n	n	n	n	n	IA	n	n	IA	n		Billman and Pyron 2005
Chub, Shoal	*Macrhybopsis hyostoma*					L	n			n		n		
Chub, Silver	*Macrhybopsis storeriana*	n				L	n			n		n		
Cisco	*Coregonus artedi*	n	n	n	n	m						n		
Crappie, Black	*Pomoxis nigromaculatus*	i	n	n	n	n	n	n	n	n	m	n		
Crappie, White	*Pomoxis annularis*	i			i	n	n	n	n	n	n	n		
Dace, Finescale	*Chrosomus neogaeus*	n	n	n	n	n				n		n		
Dace, Longnose	*Rhinichthys cataractae*	n	n	n	n	n				n		n		Peake 2008; Ficke 2015; Billman and Pyron 2005; Aedo et al. 2009
Dace, Northern Pearl	*Margariscus nachtriebi*	n	n	n	n	n	n		n	n		n		Peake 2008
Dace, Northern Redbelly	*Chrosomus eos*	n	n	n	n	n	n			n		n		Ficke 2015; Mee et al. 2011; Billman and Pyron 2005
Dace, Southern Redbelly	*Chrosomus erythrogaster*							IA	n	n	n	n		
Dace, Western Blacknose	*Rhinichthys obtusus*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015
Darter, Banded	*Etheostoma zonale*						n		n	n		n		
Darter, Blackside	*Percina maculata*	n	n		m	n	n	n	n	n	n	n		

Darter, Fantail	*Etheostoma flabellare*					L	n	n	n	n		n		
Darter, Iowa	*Etheostoma exile*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015
Darter, Johnny	*Etheostoma nigrum*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Gardner 2006
Darter, Mud	*Etheostoma asprigene*					L				n		n		
Darter, Rainbow	*Etheostoma caeruleum*	n				L	n		n	n		n		Webb 1978
Darter, River	*Percina shumardi*	n	n			L	n			n		n		
Darter, Slenderhead	*Percina phoxocephala*					n	n	IA	n	n		n		
Darter, Western Sand	*Ammocrypta clara*					L	n			n		n		
Drum, Freshwater	*Aplodinotus grunniens*	n	n	m	m	n	n	IA	IA	n	m	n		
Gar, Longnose	*Lepisosteus osseus*					L	n			n	IA	n		
Gar, Shortnose	*Lepisosteus platostomus*				n	L	n			n	n	n		
Gizzard Shad	*Dorosoma cepedianum*				*m*	L	n			n	n	n		
Goldeye	*Hiodon alosoides*	n	ON			L	n			n	n	n		Jones et al. 1979
Hog Sucker, Northern	*Hypentelium nigricans*	n			m	n	n	IA	n	n		n		
Killifish, Banded	*Fundulus diaphanus*	n	n		n	n	n		n	n	n	n		Ficke 2015; Peake 2008
Lamprey, American Brook	*Lethenteron appendix*					L	n			n		n		
Lamprey, Chestnut	*Ichthyomyzon castaneus*	n				n				n		n		
Lamprey, Silver	*Ichthyomyzon unicuspis*	n	n	n		n	n			n		n		
Northern Logperch	*Percina caprodes*	n	n	n	n	n	n	IA	IA	n	IA, SD	n		
Madtom, Tadpole	*Noturus gyrinus*	n	n	n	n	n	n	n	n	n	n	n		
Minnow, Bluntnose	*Pimephales notatus*	n	n	n	n	n	n	n	n	n	n	n		Billman and Pyron 2005; Nichols et al. 2018
Minnow, Brassy	*Hybognathus hankinsoni*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Ficke et al. 2011
Minnow, Bullhead	*Pimephales vigilax*				m			IA		n		n		Leavy and Bonner 2009
Minnow, Fathead	*Pimephales promelas*	n	n	n	n	n	n	n	n	n	n	n		Ward et al. 2003; Ficke 2015; Billman and Pyron 2005
Minnow, Pugnose	*Opsopoeodus emiliae*					L				n		n		
Mooneye	*Hiodon tergisus*	n	n			L	n			n		n		

Mudminnow, Central	*Umbra limi*	n	n	n	n	n	n		n	n	n	n		
Muskellunge	*Esox masquinongy*	i	n	n	n	i	i			n	*i*	n		
Northern Pike	*Esox lucius*	n	n	n	n	n	n	n	n	n	n	n		FishXing; Peake 2008
Perch, Yellow	*Perca flavescens*	n	n	n	n	n	n	n	n	n	n	n		
Pumpkinseed	*Lepomis gibbosus*	n	n	n	n	n	n	n	n	n	n	n		FishXing
Quillback	*Carpiodes cyprinus*	n	n		m	n	n	n	n	n	n	n		
Redhorse, Golden	*Moxostoma erythrurum*	n	n		m	n	n	IA	n	n	n	n		
Redhorse, Greater	*Moxostoma valenciennesi*	n	n		n	n	n			n		n		
Redhorse, River	*Moxostoma carinatum*					n	n			n		n		Hatry et al. 2013
Redhorse, Shorthead	*Moxostoma macrolepidotum*	n	n	n	n	n	n		n	n	n	n		Hatry et al. 2013
Redhorse, Sliver	*Moxostoma anisurum*	n	n	n	n	n	n	IA	IA	n		n		Hatry et al. 2013
Sauger	*Stizostedion canadensis*	n	n			L	n			n	IA	n		Dockery et al. 2017
Sculpin, Deepwater	*Myoxocephalus thompsonii*		n	n								n		
Sculpin, Mottled	*Cottus bairdi*	n	n	n	n	U				n		n		Webb 1978; Peake 2008; Aedo et al. 2009
Sculpin, Slimy	*Cottus cognatus*		n	n	n	n				n		n		Peake 2008
Sculpin, Spoonhead	*Cottus ricei*			n								n		
Shiner, Bigmouth	*Notropis dorsalis*	n	n		n	n	n	n	n	n	n	n		
Shiner, Blackchin	*Notropis heterodon*	n	n	n	n	n	n			n		n		
Shiner, Blacknose	*Notropis heterolepis*	n	n	n	n	n	n	IA	IA	n	IA	n		
Shiner, Carmine	*Notropis percobromus*	n					n		n	n	SD	n		
Shiner, Channel	*Notropis wickliffi*				n	L	n			n		n		Webb 1978; Billman and Pyron 2005; Ficke et al. 2011
Shiner, Common	*Luxilus cornutus*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2011
Shiner, Emerald	*Notropis atherinoides*	n	n	n	n	L	n			n	n	n		Leavy and Bonner 2009
Shiner, Golden	*Notemigonus crysoleucas*	n	n	n	n	n	n	n	n	n	n	n		FishXing; Beecham et al. 2007
Shiner, Mimic	*Notropis volucellus*	n	n	n	n	n	n	n	n	n		n		
Shiner, Red	*Cyprinella lutrensis*										n	n		Ward et al. 2003; Leavy and Bonner 2009; Prensosil 2014

Shiner, River	*Notropis blennius*	n	n			L	n	IA	n	n	IA	n		
Shiner, Sand	*Notropis stramineus*	n			n	n	n	n	n	n	n	n		
Shiner, Spotfin	*Cyprinella spiloptera*	n			n	n	n	n	n	n	IA	n		Leavy and Bonner 2009; Hocutt 1973; Nichols et al. 2018
Shiner, Spottail	*Notropis hudsonius*	n	n	n	n	n	n			n	n	n		
Shiner, Weed	*Notropis texanus*	n			n	L	n			n		n		
Silverside, Brook	*Labidesthes sicculus*			m	n	n	n			n		n		
Stickleback, Brook	*Culaea inconstans*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015
Stickleback, Ninespine	*Pungitius pungitius*		n	n	n							n		Peake 2008
Stonecat	*Noturus flavus*	n		n	m	n	n	n	n	n	n	n		FishXing; Ficke 2015
Stoneroller, Central	*Campostoma anomalum*	n			n	n	n	n	n	n	n	n		Ficke 2015; Billman and Pyron 2005; Scott and Magoulick 2008; Leavy and Bonner 2009
Stoneroller, Largescale	*Campostoma oligolepis*	ND				U	n		n	n		n		
Sturgeon, Shovelnose	*Scaphirhynchus platorynchus*					L	n			n		n		FishXing
Sucker, Longnose	*Catostomus catostomus*		n	n								n		FishXing; Peake 2008
Sucker, Spotted	*Minytrema melanops*					L	n			n		n		
Sucker, White	*Catostomus commersoni*	n	n	n	n	n	n	n	n	n	n	n		FishXing; Ficke 2015; Peake 2008; Castro-Santos 2005
Sunfish, Green	*Lepomis cyanellus*	n	n	n	n	n	n	n	n	n	n	n		Ficke 2015; Ward et al. 2003; Scott and Magoulick 2008; Prenosil 2014
Sunfish, Orangespotted	*Lepomis humilis*	n			m		n	n	n	n	n	n		
Trout, Brook	*Salvelinus fontinalis*	i	i	n	i	n	n			n		n		FishXing; Peake 2008
Trout, Lake	*Salvelinus namaycush*		n	n	m	i						n		Peake 2008
Trout-perch	*Percopsis omiscomaycus*	n	n	n	n	n	n			n	n	n		
Walleye	*Stizostedion vitreus*	n	n	n	n	n	n	n	n	n	m	n		FishXing; Castro-Santos 2005

White Bass	*Morone chrysops*	i			*m*	n	n			n	n	n		FishXing
Whitefish, Lake	*Coregonus clupeaformis*	n	n	n	n							n		Peake 2008
Whitefish, Round	*Prosopium cylindraceum*			n								n		Peake 2008
No Significant Population in Minnesota														
Topminnow, Starhead	*Fundulus dispar*									WI		WI		Ficke 2015
Catfish, Blue	*Ictalurus furcatus*					K				K		K		
Shiner, Ghost	*Notropis buchanani*									ex		ex		Leavy and Bonner 2009
Stickleback, Fourspine	*Apeltes quadracus*				i ON								i ON	
Chub, Flathead	*Platygobio gracilis*	m									IA	m	S	Ficke 2015; Ficke et al. 2012

APPENDIX B FIELD DATA COLLECTION SHEET

Surveyor(s): ___________________________ Date: ___/___/______ County: ____________
HUC8: _______________ Culvert ID: _____________ Stream Name: _______________
Road: _______________ Lat/Long: ______________________ # of Barrels: ____
Inlet Configuration: □Headwall □ Projecting □ Mitered □ Wingwall □ Beveled Edge □ Other:_________
Outlet type: □ At stream grade □ Cascade over riprap □ Freefall into pool □ Freefall onto riprap □ Apron
Barrels (left to right, facing downstream)

	Barrel 1	Barrel 2	Barrel 3	Barrel 4
Type	□ Thalweg □ Floodplain □ Offset	□ Thalweg □ Floodplain □ Offset	□ Thalweg □ Floodplain □ Offset	□ Thalweg □ Floodplain □ Offset
Shape	□Circular □ Box □ Elliptical □Pipe-Arch □Open-Bottom arch □ Low-Profile Arch □ High-Profile Arch	□Circular □ Box □ Elliptical □Pipe-Arch □Open-Bottom arch □ Low-Profile Arch □ High-Profile Arch	□Circular □ Box □ Elliptical □Pipe-Arch □Open-Bottom arch □ Low-Profile Arch □ High-Profile Arch	□Circular □ Box □ Elliptical □Pipe-Arch □Open-Bottom arch □ Low-Profile Arch □ High-Profile Arch
Material	□ Concrete □ Aluminum □ Steel □ PVC □ HDPE	□ Concrete □ Aluminum □ Steel □ PVC □ HDPE	□ Concrete □ Aluminum □ Steel □ PVC □ HDPE	□ Concrete □ Aluminum □ Steel □ PVC □ HDPE
Corrugated	☐Y ☐N	☐Y ☐N	☐Y ☐N	☐Y ☐N
Corrugation Spacing (in)				
Skew	□Y □N Angle:______	□Y □N Angle:______	□Y □N Angle:______	□Y □N Angle:______
Barrel Spacing(ft)				
Inlet Description				
Length (ft)				
Span (ft)				
Rise (ft)				
Inlet Invert				
Outlet Invert				
Structure Condition				
Sediment*	☐Y ☐N	☐Y ☐N	☐Y ☐N	☐Y ☐N
Perched	☐Y:____ft ☐N	☐Y:____ft ☐N	☐Y:____ft ☐N	☐Y:____ft ☐N
Flow Level	Low / Med / High	Low / Med / High	Low / Med / High	Low / Med / High
Passage Concerns				

Notes/Comments	

Photos:

Sediment Data*

Sediment Size				
Sediment Distribution	☐ Uniform ☐ Non-Uniform	☐ Uniform ☐ Non-Uniform	☐ Uniform ☐ Non-Uniform	☐ Uniform ☐ Non-Uniform
Sed. Inlet Invert				
Sed. Outlet Invert				

Sediment Distribution Sketches:

Barrel 1

Barrel 2

Barrel 3

Barrel 4

Field Notes:

____

____

____

APPENDIX C CULVERT DATA

Table C1. Culvert Data

	Culvert ID	Northing	Easting	Road Type*	Shape	Inlet Config.	Material	Barrels	Embedded	Offset
Cottonwood	CW1	44.3117	-94.7613	7	box	mitered	concrete	2	Y	N
	CW2	44.1226	-95.2121	5	box	mitered	concrete	1	Y	N
	CW3	44.2831	-95.5284	6	pipe arch	mitered	steel	3	Y	N
	CW4	44.2969	-95.0032	7	pipe arch	projecting	steel	1	N	N
	CWBU1	44.1520	-95.3626	6	box	mitered	concrete	1	Y	N
North Fk. Crow	Crow2	45.1285	-94.3212	3	box	mitered	concrete	1	N	N
	CrowBU1	45.2106	-94.6181	5	box	mitered	concrete	2	Y	N
	CrowBU2	45.1541	-94.3174	3	box	mitered	concrete	2	Y	N
MNHW	MNHW1	45.2982	-96.2076	4	box	30° wingwall	concrete	2	N	N
	MNHWBU2	45.2185	-96.3743	7	open-bottom arch	headwall	steel	1	Y	N
Red Lake R.	RL1	48.0066	-96.1963	7	pipe arch	mitered	concrete	1	N	N
	RL2	47.9812	-96.1273	7	pipe arch	mitered	concrete	1	N	N
	RL5	47.8775	-96.4105	6	Circular	projecting	concrete	3	N	N
	RLBU1	47.6586	-96.5783	7	box	mitered	concrete	2	N	N
	RLBU3	48.0871	-96.0251	7	box	mitered	concrete	1	N	N
Rock River	Rock1	43.5291	-95.7708	7	pipe arch	mitered	concrete	2	Y	N
	Rock3	44.0291	-96.0846	7	pipe arch	mitered	concrete	1	N	N
	Rock4	43.8633	-96.1867	7	pipe arch	mitered	concrete	3	Y	N
	Rock7	43.5115	-96.3124	7	box	mitered	concrete	2	N	N
	RockBU5	43.5582	-95.9998	7	pipe arch	mitered	concrete	2	N	N
	RockBU6	43.8757	-96.2650	4	box	mitered	concrete	1	Y	N
	RockBU7	43.5398	-96.2330	7	box	mitered	concrete	2	Y	N
Root River	Root2	43.5946	-91.9168	7	pipe arch	mitered	concrete	2	N	N
	RS1	43.7866	-91.6373	7	box	mitered	concrete	1	N	N
	RS4	43.7196	-92.3491	7	pipe arch	headwall/30° wingwall	concrete	1	Y	N
	RootBU3	43.7877	-92.1466	7	pipe arch	mitered	steel	1	N	N
	RootBU4	43.7542	-91.6884	7	box	mitered	concrete	2	Y	N

	Culvert ID	Northing	Easting	Road Type*	Shape	Inlet Config.	Material	Barrels	Embedded	Offset
Snake River	Snake1	46.0394	-93.2579	7	Pipe arch	mitered	concrete	2	N	N
	Snake2	45.8970	-93.1609	7	Box	mitered	concrete	2	N	N
	Snake4	45.8464	-93.1452	7	box	mitered	concrete	3	N	N
	Snake9	45.7705	-93.4925	7	Circular	projecting	Steel	1	N	N
	Snake10	45.8899	-93.1264	7	pipe arch	Flared projecting apron	steel	2	N	Y
	SnakeBU2	46.0604	-93.4951	7	Circular	projecting	Steel	2	N	N
	Snake11	45.8176	-93.4670	3	box	30° wingwall	concrete	1	Y	N
Pine R.	Pine1	46.7137	-94.2719	7	Pipe arch	mitered	concrete	3	Y	Y
	Pine2	46.7783	-93.8191	7	Pipe arch	Flared	concrete	2	Y	N
	PineBU3	46.6960	-94.3688	7	Pipe arch	mitered	concrete	2	Y	N
Lake Superior South	LSS4	46.8530	-92.1086	7	pipe arch	projecting	steel	1	N	N
	LSS8	47.1269	-91.5732	7	box	mitered	concrete	1	N	N
	LSS12	46.8746	-92.1022	7	pipe arch	flared end	steel	1	Y	N
	LSS14	47.1270	-91.5879	6	box	mitered	concrete	2	Y	Y
	LSS16	47.2420	-91.4808	6	open-bottom arch	projecting	steel	1	Y	N
	LSS18	46.8760	-92.1110	5	circular,box	projecting	steel,concrete	1	N	N
	LSS21	47.3110	-91.3250	5	box	mitered	concrete	2	Y	Y
	LSS22	47.2951	-91.3190	5	box	mitered	concrete	3	Y	Y
Big Fork R.	BF1	47.7264	-94.1072	5	box	mitered	concrete	2	Y	Y
	BF5	47.8753	-93.7969	4	Pipe arch	mitered	concrete	1	N	N
	BFBU1	47.8522	-93.4441	7	pipe arch	mitered	Coated metal	3	Y	N
	BFBU2	47.7507	-93.6568	4	pipe arch	mitered	concrete	2	N	N
	BFBU4	47.9051	-93.9458	7	box	mitered	concrete	1	Y	N

* 1 Interstate;2 Other Freeways and Expressways; 3 Other Principal Arterial; 4 Minor Arterial; 5 Major Collector; 6 Minor Collector; 7 Local

Table C2. Culvert Dimensions

		Barrel 1			Barrel 2			Barrel 3			
	Culvert ID	Span (ft)	Rise (ft)	Length(ft)	Span (ft)	Rise (ft)	Length(ft)	Span (ft)	Rise (ft)	Length(ft)	Total Span (ft)
Cottonwood	CW1	10	10	112	10	10	111				20.0
	CW2	10	6	87							10.0
	CW3	9.3	6.3	60	9.3	6.3	50	9	5.3	63	27.6
	CW4	11.8	7.6	57							11.8
	CWBU1	12	10	81							12.0
North Fk. Crow	Crow2	10	10	118							10.0
	CrowBU1	8	6	79	8	6	84				16.0
	CrowBU2	8	6	100	8	6	100				16.0
MNHW	MNHW1	10	5	54	10	5	54				20.0
	MNHWBU2	15	6.5	29							15.0
Red Lake R.	RL1	11.5	7.3	72							11.5
	RL2	10.2	6.4	69							10.2
	RL5	9	9	235	9	9	235	8.99	8.99	236	27.0
	RLBU1	14	8	95	14	8	96				28.0
	RLBU3	12	6	66							12.0
Rock River	Rock1	10.2	6.4	64	10.2	6.4	64				20.3
	Rock3	10.2	6.4	54							10.2
	Rock4	11.5	7.3	64	11.5	7.3	63	12.73	7.3	62	35.7
	Rock7	8	4	56	8	4	55				16.0
	RockBU5	8.5	5.2	49	8.5	5.2	51				17.0
	RockBU6	12	6	117							12.0
	RockBU7	12	7	61	12	7	61				24.0
Root River	Root2	14.1	8.9	164	14.1	8.9	164				28.1
	RS1	14	9	254							14.0
	RS4	12.8	8.1	57							12.8

	Culvert ID	Barrel 1 Span (ft)	Barrel 1 Rise (ft)	Barrel 1 Length(ft)	Barrel 2 Span (ft)	Barrel 2 Rise (ft)	Barrel 2 Length(ft)	Barrel 3 Span (ft)	Barrel 3 Rise (ft)	Barrel 3 Length(ft)	Total Span (ft)
	RootBU3	9.8	6.6	48							9.8
	RootBU4	12	7	86	12	7	88				24.0
Snake River	Snake1	11.5	7.3	74	11.5	7.3	74				23.0
	Snake2	12	7	68	12	7	68				24.0
	Snake4	12	6	64	12	6	64	12	6	64	36.0
	Snake9	4	4	38							4.0
	Snake10	4.8	3.2	33	6.6	4.1	36				11.4
	SnakeBU2	4	4	40	4	4	40				8.0
	Snake11	10	4	46							10.0
Pine R.	Pine1	10.2	6.4	54	10.2	6.4	54	10.2	6.4	54	30.6
	Pine2	8.5	5.2	48	8.5	5.2	45				17.0
	PineBU3	9.6	6	89	9.6	6	89				19.2
Lake Superior South	LSS4	5.9	3.9	30							5.9
	LSS8	12	7	85							12.0
	LSS12	6.1	4.6	59							6.1
	LSS14	16	11	119	16	11	119				32.0
	LSS16	20.7	12.1	105							20.7
	LSS18	6	6	68							6.0
	LSS21	12	10	118	12	10	118				24.0
	LSS22	14	11	158	14	11	163	14	11	165	42.0
Big Fork R.	BF1	12	10	65	12	10	65				24.0
	BF5	11.5	7.3	83							11.5
	BFBU1	8.8	6.8	100	10.7	6.9	100	8.8	6.8	99	28.3
	BFBU2	10.2	6.4	117	10.2	6.4	117				20.4
	BFBU4	10	5	57							10.0

Table C3. Culvert Slopes and Sediment Description

	Culvert Bottom Slope (%)			Sediment Surface Slope (%)			Sediment Description
Culvert ID	Barrel 1	Barrel 2	Barrel 3	Barrel 1	Barrel 2	Barrel 3	
CW1	-0.14	0.19			-0.70		Sand/Gravel
CW2	-0.32			0.05			Muck
CW3	0.44	0.91	1.03	0.37	3.00	-0.57	Sandy Muck
CW4	0.05						Gravel
CWBU1	0.17			0.82			Muck/Gravel
Crow2	0.07						no sediment
CrowBU1	-0.11	-0.43		-2.11	0.50		Muck
CrowBU2	0.38	0.38					Gravel
MNHW1	0.12	0.12					Muck
MNHWBU2	0.31			0.31			Gravel/Cobbles
RL1	0.30						Sediment pile at outlet
RL2	0.03						no sediment
RL5	0.11	-0.25	0.04				no sediment
RLBU1	0.04	0.03					no sediment
RLBU3	-0.16						Gravel/Silt
Rock1	0.21	-0.27		1.08	1.16		Muck
Rock3	1.27						Muck
Rock4	-0.88	-0.90	-1.48	-0.38	0.72	0.81	Sand/Muck
Rock7	-0.31	0.19					Muck
RockBU5	0.17	1.11					Muck
RockBU6	0.10						Muck
RockBU7	0.42	0.10		0.33	0.15		Muck/Sand/Silt
Root2	0.74	0.02			0.05		Muck/Sand/Gravel
RS1	1.13						no sediment
RS4	1.13			-0.21			Sand
RootBU3	1.49						Rocks/Sand
RootBU4	0.23	0.81					Sand/Gravel
Snake1	0.35	-0.71			-1.78		Coarse Sand
Snake2	0.12	0.10					no sediment
Snake4	-0.18	-0.55	-0.25			0.31	Sand/Muck
Snake9	-0.36						no sediment
Snake10	0.94	1.39					no sediment
SnakeBU2	0.21	0.67					no sediment
Snake11	0.57						Sand/Clay
Pine1	0.15	0.23	-0.26	-0.75			Sand/Muck
Pine2	-0.27	0.38					Sand/muck
PineBU3	-0.11	0.72					Sand

	Culvert Bottom Slope (%)			Sediment Surface Slope (%)			Sediment Description
Culvert ID	Barrel 1	Barrel 2	Barrel 3	Barrel 1	Barrel 2	Barrel 3	
LSS8	0.25						no sediment
LSS12	-0.17			-2.57			Muck
LSS14	2.00	1.47	2.00	1.47			Gravel/Boulders/Cobble
LSS16	0.16			0.16			Gravel/Boulders
LSS18	0.93						Rocks
LSS21	0.45	0.59					Gravel/Cobble/Silt
LSS22	1.03	0.72	0.79				Boulders
LSS4	2.74						no sediment
BF1	-0.75	-1.60		0.55	-0.94		Muck
BF5	1.06			0.87			Med/Coarse Sand
BFBU1	0.49	0.24	1.12				Gravel/Sand
BFBU2	0.08	0.11					no sediment
BFBU4	-0.16			2.07			Sand/Clay

APPENDIX D DETAILED HYDROLOGIC MODELING RESULTS

Table D1. Summary of 1.5 year return period flow rates for each culvert and climate scenario.

River	Culvert	Climate Scenario	Time Period	1.5 Year Flow (cfs)	% Future Change
Snake River (Mud Creek)	Snake4	Observed	1981-2000	109.9	
		GFDL	1981-2000	192.2	
		Hadley	1981-2000	126.9	
		MIROC	1981-2000	206.7	
		Nor	1981-2000	169.9	
		GFDL	2061-2080	445.2	131
		Hadley	2061-2080	115.6	-8.9
		MIROC	2061-2080	98.6	-52
		Nor	2061-2080	90.9	-46
South Fork Root River	Root2	Observed	1981-2000	65.5	
		GFDL	1981-2000	32.1	
		Hadley	1981-2000	42.5	
		MIROC	1981-2000	60.0	
		Nor	1981-2000	40.5	
		GFDL	2061-2080	115.5	260
		Hadley	2061-2080	41.4	-2.6
		MIROC	2061-2080	46.4	-23
		Nor	2061-2080	39.5	-2.5
East Branch Beaver River	LSS21	Observed	1981-2000	354.7	
		GFDL	1981-2000	325.7	
		Hadley	1981-2000	340.2	
		MIROC	1981-2000	314.6	
		Nor	1981-2000	444.5	
		GFDL	2061-2080	501.7	54
		Hadley	2061-2080	275.1	-19
		MIROC	2061-2080	139.9	-56
		Nor	2061-2080	384.2	-13
	LSS22	Observed	1981-2000	449.6	
		GFDL	1981-2000	492.1	
		Hadley	1981-2000	533.4	
		MIROC	1981-2000	487.5	
		Nor	1981-2000	694.3	
		GFDL	2061-2080	791.0	61
		Hadley	2061-2080	431.3	-19
		MIROC	2061-2080	220.7	-55
		Nor	2061-2080	607.0	-13

Cottonwood River (Dry Creek)	CW2	Observed	1981-2000	21.1	
		GFDL	1981-2000	19.6	
		Hadley	1981-2000	14.0	
		MIROC	1981-2000	22.8	
		Nor	1981-2000	12.9	
		GFDL	2061-2080	20.9	6.4
		Hadley	2061-2080	6.0	-57.5
		MIROC	2061-2080	15.0	-34.1
		Nor	2061-2080	10.9	-15.3

Table D2. Summary of QLP (90th percentile flow duration) and QHP (5th percentile flow duration) for each culvert and climate scenario.

River	Culvert	Climate Scenario	Time Period	QLP (cfs)	QHP (cfs)	QLP % Change	QHP % Change
Snake River (Mud Creek)	Snake4	Observed	1981-2000	0.7	94.1		
		GFDL	1981-2000	1.8	108.2		
		Hadley	1981-2000	0.3	110.1		
		MIROC	1981-2000	3.7	126.9		
		Nor	1981-2000	4.0	101.7		
		GFDL	2061-2080	5.7	188.8	222	74
		Hadley	2061-2080	0.1	69.6	-70.	-37
		MIROC	2061-2080	0.4	81.1	-89	-36
		Nor	2061-2080	0.8	82.9	-81	-19
South Fork Root River	Root2	Observed	1981-2000	0.10	20.4		
		GFDL	1981-2000	2.0	18.9		
		Hadley	1981-2000	0.9	23.6		
		MIROC	1981-2000	2.2	22.5		
		Nor	1981-2000	1.8	20.8		
		GFDL	2061-2080	2.1	28.3	6.8	50
		Hadley	2061-2080	0.5	18.0	-40	-24
		MIROC	2061-2080	1.1	21.7	-51	-3.6
		Nor	2061-2080	1.6	20.1	-8.4	-3.3
East Branch Beaver River	LSS21	Observed	1981-2000	4.4	127.8		
		GFDL	1981-2000	5.8	108.7		
		Hadley	1981-2000	4.6	109.1		
		MIROC	1981-2000	4.6	97.4		
		Nor	1981-2000	5.7	118.7		
		GFDL	2061-2080	7.5	130.9	30	21
		Hadley	2061-2080	0.9	84.0	-81	-23
		MIROC	2061-2080	1.1	56.9	-76	-42
		Nor	2061-2080	3.8	93.9	-34	-21
	LSS22	Observed	1981-2000	10.5	180.8		
		GFDL	1981-2000	9.1	170.0		
		Hadley	1981-2000	7.3	170.4		
		MIROC	1981-2000	7.2	151.7		
		Nor	1981-2000	9.0	185.9		
		GFDL	2061-2080	11.8	204.5	31	20
		Hadley	2061-2080	1.4	131.1	-81	-23
		MIROC	2061-2080	1.8	88.9	-76	-41
		Nor	2061-2080	6.0	146.7	-33	-21

Cottonwood River (Dry Creek)	CW2	Observed	1981-2000	0.05	4.7		
		GFDL	1981-2000	0.08	4.3		
		Hadley	1981-2000	0.04	4.4		
		MIROC	1981-2000	0.06	4.6		
		Nor	1981-2000	0.05	4.0		
		GFDL	2061-2080	0.12	4.9	46.5	15.3
		Hadley	2061-2080	0.02	3.3	-35.7	-25.6
		MIROC	2061-2080	0.05	3.4	-1.6	-26.1
		Nor	2061-2080	0.10	3.4	100.1	-14.8

Table D3. Summary of potential velocity and depth barriers for each culvert and climate scenario. Culverts with no depth barrier numbers are backwatered.

River	Culvert	Climate Scenario	Time Period	Velocity Barrier (Days/year)	Depth Barrier (Days/year)
Snake River (Mud Creek)	Snake4	Observed	1981-2000	1	53
		GFDL	1981-2000	0.2	37
		Hadley	1981-2000	0.6	68
		MIROC	1981-2000	1.6	20
		Nor	1981-2000	0.35	19
		GFDL	2061-2080	2.1	13
		Hadley	2061-2080	0.8	95
		MIROC	2061-2080	0	72
		Nor	2061-2080	0.25	54
South Fork Root River	Root2	Observed	1981-2000	1.6	
		GFDL	1981-2000	0.3	
		Hadley	1981-2000	1	
		MIROC	1981-2000	0.9	
		Nor	1981-2000	0.6	
		GFDL	2061-2080	1.2	
		Hadley	2061-2080	0.6	
		MIROC	2061-2080	0.2	
		Nor	2061-2080	0.4	
East Branch Beaver River	LSS21	Observed	1981-2000	33	
		GFDL	1981-2000	27	
		Hadley	1981-2000	27	
		MIROC	1981-2000	23	
		Nor	1981-2000	31	
		GFDL	2061-2080	36	
		Hadley	2061-2080	17	
		MIROC	2061-2080	5.4	
		Nor	2061-2080	22	
	LSS22	Observed	1981-2000	60	19
		GFDL	1981-2000	57	29
		Hadley	1981-2000	61	39
		MIROC	1981-2000	55	40
		Nor	1981-2000	59	30
		GFDL	2061-2080	77	19
		Hadley	2061-2080	49	73
		MIROC	2061-2080	26	87
		Nor	2061-2080	60	45

Cottonwood River (Dry Creek)	CW2	Observed	1981-2000	0.30	
		GFDL	1981-2000	0.30	
		Hadley	1981-2000	0.30	
		MIROC	1981-2000	0.45	
		Nor	1981-2000	0.30	
		GFDL	2061-2080	0.55	
		Hadley	2061-2080	0.25	
		MIROC	2061-2080	0.15	
		Nor	2061-2080	0.15	

Table D4. Simulated peak daily flow rates and % future change for historical Atlas-14 storms and future adjusted storms based on EPA CREAT database for a warm/wet (W/W), median (Med), and Hot-Dry (H/D) scenario.

	Return Period	Peak Flow (cfs)				
		LSS21	LSS22	Snake4	Root2	CW2
Historical (Atlas-14)	25	1759.5	2301.0	904.8	356.0	151.3
	50	2232.4	2936.7	1370.4	658.5	193.9
	100	2767.3	3653.5	1927.8	1098.3	240.0
Warm/Wet	25	2243.9	2949.9	1459.6	671.7	170.3
	50	2815.7	3711.4	2104.1	1089.2	214.4
	100	3435.4	4536.5	2813.5	1551.3	261.3
Median	25	1858.5	2436.8	987.5	413.5	160.7
	50	2331.2	3066.3	1483.6	777.3	201.6
	100	2839.8	3743.4	2014.3	1161.1	244.1
Hot/Dry	25	2169.3	2850.6	1352.5	569.8	183.1
	50	2810.4	3704.3	2038.6	973.1	232.8
	100	3532.4	4665.7	2809.8	1429.9	288.1

	Return Period	Peak Flow (% Change)				
		LSS21	LSS22	Snake4	Root2	CW2
Warm/Wet	25	27.5	28.2	61.3	88.7	12.6
	50	26.1	26.4	53.5	65.4	10.6
	100	24.1	24.2	45.9	41.2	8.9
Median	25	5.6	5.9	9.1	16.2	6.2
	50	4.4	4.4	8.3	18.0	4.0
	100	2.6	2.5	4.5	5.7	1.7
Hot/Dry	25	23.3	23.9	49.5	60.1	21.0
	50	25.9	26.1	48.8	47.8	20.1
	100	27.6	27.7	45.8	30.2	20.0