Culvert Length and Interior Lighting Impacts to Topeka Shiner Passage

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Culverts can act as barriers to fish passage for a number of reasons including insufficient water depth or excess velocity. In addition, concern is being raised over behavioral barriers where culvert conditions elicit an avoidance response that deters or slows fish movement. Long culverts can block sunlight creating a potential behavioral barrier as fish approach a long, dark culvert. Scant information exists on low light as a potential barrier to fish passage, particularly with warm water species, such as the federally endangered Topeka Shiner. As some older culverts are being replaced with longer total lengths to improve safety by extending the culvert through re-engineered road embankments, information is needed to 1) determine when and if light mitigation strategies are necessary, and 2) to design appropriate light mitigation strategies if necessary. Based on literature review, field monitoring, and laboratory experiments, the effect of light on fish passage for Topeka Shiner and other small prairie stream fish was indiscernible. Therefore, no light mitigation for large box culverts (up to 150 feet in length) can be recommended for similar fish communities. Culverts that are very long or have very small openings may benefit from additional light.

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EXECUTIVE SUMMARY

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This study focuses on the potential for low light levels in long culverts to act as barriers to fish movement. The study was motivated by concerns over the replacement of culvert 59X09, which allows US Highway 75 to cross Poplar Creek in Pipestone County, Minnesota. The crossing was replaced in 2013 as part of a roadway rehabilitation project that included extension of the embankment slopes so that the guardrails could be removed and resulted in lengthening the culvert. The study was specifically designed to determine how much light exists in culvert 59X09, and whether or not those light levels act as a barrier to movements by Topeka Shiners and other associated species. As such, the study determines if the same number of Topeka Shiners and common associates move through culvert 59X09 and other selected culverts as through nearby control reaches of the same streams. In early, mid, and late summer (May/June, July, and August, respectively) 2015, passage through culvert 59X09, culvert 91077 (Elk Creek), and culvert 8884 (Split Rock Creek Tributary) was evaluated using fish mark-recapture techniques. This fieldwork was supplemented with an experimental study to determine if Topeka Shiners and Fathead Minnows, a surrogate species, will travel through shaded and unshaded passageways with equal frequency (or without preference) while holding other variables (depth, velocity, and length) constant.

Light levels experienced by fish swimming in culverts are a not a function of length alone, but also culvert orientation, culvert dimensions, culvert material, the presence of elbows or bends, and the surrounding topography, in addition to water clarity. Because this study focused on box culverts (> 8 ft wide x 8 ft high), light levels within the culvert barrel were much greater than would be expected on similar length small (< 3 ft diameter) pipe culverts. Based on the field and laboratory studies, light could not be isolated as creating a behavioral barrier to fish movement for the fish communities present in southwestern Minnesota including for the federally endangered Topeka Shiner. Therefore, the research team cannot recommend light mitigation efforts to be installed in large box culverts in this area. It should be noted that this recommendation may not apply to culverts that are particularly dark due to elbows or bends, or small culvert opening dimensions. In addition, it should be noted that there was evidence of partial barriers other than light levels in some long box culverts. The results of this study

only apply to low gradient streams in southwestern Minnesota and should not be applied for other fish communities that may be more sensitive to light levels within culverts.

CHAPTER 1: INTRODUCTION

Culverts can act as barriers to fish passage for a number of reasons including insufficient water depth or excess velocity. In addition, long culverts can block sunlight creating a potential behavioral barrier as fish approach a long, dark culvert. Scant information exists on low light as a potential barrier to fish passage, particularly with warm water species, such as the federally endangered Topeka Shiner. As some older culverts are being replaced with longer total lengths to improve safety by extending the culvert through re-engineered road embankments, information is needed to 1) determine when and if light mitigation strategies are necessary and 2) to design appropriate light mitigation strategies if necessary. This report summarizes the research team's recommendations for light mitigation to facilitate fish passage through box culverts.

1.1 OBJECTIVES

The purpose of this research was to quantify the impact of light levels on movement through long box culverts for Topeka Shiner and other warm water fish species. This study focused on critical Topeka Shiner habitat in southwestern Minnesota.

Question 1: How much light is present in longer (>100 ft) box culverts? This objective was met by collecting profiles of light levels along culverts and control reaches and with depth in each study stream.

Question 2: Are Topeka Shiners and other fishes moving through culverts with similar frequency as in control reaches in the same stream? and Does the frequency of movement vary with light levels? These research questions were addressed using a mark-recapture study in three culverts with varying light levels and their associated control reaches.

Question 3: Will Topeka Shiners travel through shaded and unshaded passageways with equal frequency (or without preference)? This research question was addressed in the St. Anthony Falls Laboratory by performing a series of fish movement studies, using both Topeka Shiners and Fathead Minnows, to determine preference for variously shaded or unshaded channels in an experimental flume.

1.2 CULVERTS IN CRITICAL TOPEKA SHINER HABITAT

The Topeka Shiner, *Notropis topeka,* is a federally endangered fish species inhabiting the rapidly declining headwater prairie streams of the central US (Hatch 2001). Once widespread throughout portions of Iowa, Kansas, Minnesota, Nebraska, and South Dakota, the species vanished from 80% of its former sites by the middle of the 1990s, with 50% of the loss occurring after 1973 (Tabor 1998). This decline is attributed to a variety of factors including degradation of stream habitats, stream channelization, construction of small impoundments, and introduction of predator fishes. When roadways intersect streams, culverts can create potential barriers to suitable habitat access by interfering with fish movement (Bouska and Paukert 2010). Understanding the conditions under which culverts act as barriers to the Topeka Shiner could be vital to its survival in Minnesota. In Minnesota, Topeka Shiners are found primarily in the Big Sioux and Rock River systems in the far southwestern corner of the state (Figure 1.1). It should be noted, however, that Topeka Shiners have been found outside of these river systems.

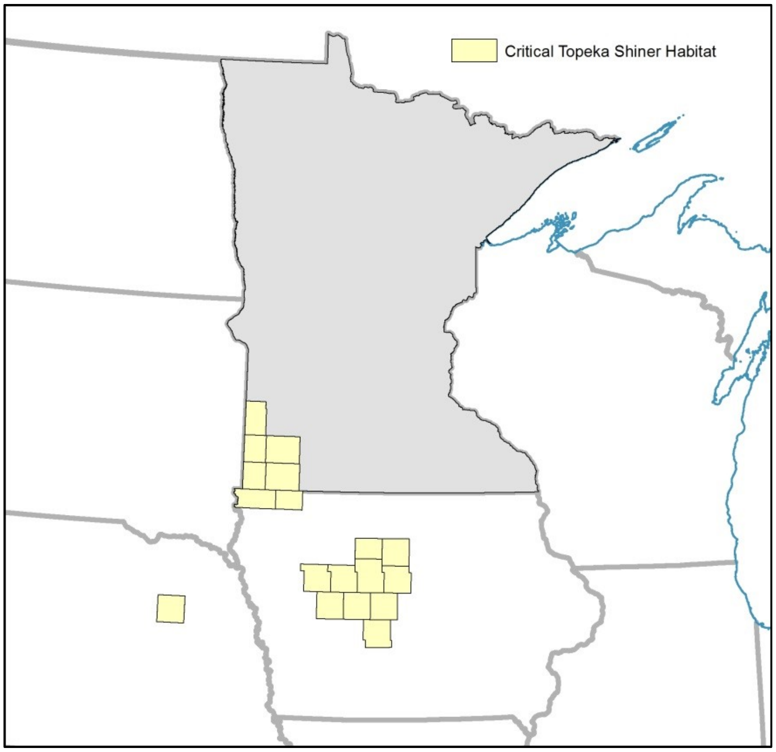

Figure 1.1 Map showing Final Critical Habitat for the Topeka Shiner (*Notropis topeka*) designated July 2004. Note that Topeka Shiners have been found outside of these designated areas (https://www.fws.gov/midwest/endangered/fishes/TopekaShiner/index.html) and are also found in areas of Missouri, Kansas, and South Dakota.

1.2.1 Topeka Shiner Background

The Topeka Shiner is a small cyprinid reaching a maximum of approximately 3 inches (75 mm) in total length (TL), although most males are <2.7 in (68 mm) and most females are <2.4 in (62 mm) TL (Dahle 2001; Figure 1.2). The species is short-lived, with a maximum life expectancy of three years (Dahle 2001, Kerns and Bonneau 2002). Growth is rapid in the first year but highly variable as a result of long spawning seasons and differences in habitat quality. Males grow faster than females throughout their lives but also suffer greater relative mortality, as evidenced by changes in sex ratios after 10 months (Dahle 2001). Topeka Shiners are generalist omnivores that feed opportunistically. While they feed primarily on microcrustaceans and insects, they consistently include other invertebrates, algae, and vascular plant matter. The relative composition of the diet changes seasonally at a given site and varies considerably among sites. Microcrustaceans are slightly more important for juveniles, while insects are slightly more important for adults. The diet of larval Topeka Shiners is unknown (Dahle 2001, Hatch and Besaw 2001, Kerns and Bonneau 2002).

In the Central Plains, the Topeka Shiner inhabits clear headwater stream pools with gravel, rubble, clay hardpan, or bedrock in their southern range (Minckley and Cross 1959, Cross 1967, Pflieger 1997). In comparison, northwestern populations inhabit more turbid streams whose substrates are frequently covered by 2 in or more of silt and detritus (Elsen 1977, Michl and Peters 1993, Hatch 2001). Juveniles and adults occupy backwater and bend pools of the main channels, as well as off-channel oxbows and excavated pools, where they are often—but not always—more abundant (Clark 2000, Dahle 2001, Hatch 2001, Thomson et al. 2005, Ceas and Larson 2010, Bakevich et al. 2013). Topeka Shiners frequently associate with rooted vegetation and tend to avoid current velocities >1.6 ft/s (Kuitunen 2001). This species tolerates high temperatures (87–98˚F), low concentrations of oxygen (2–4 mg/L) (Koehle and Adelman 2007), moderately high levels of nitrite (3.97 mg/L), and very high levels of nitrate (360 mg/L) (Adelman et al. 2009), all of which are characteristic of off-channel habitats.

Figure 1.2 Topeka Shiners caught during Mark-Recapture Study.

Off-channel habitats of headwater streams, as well as reaches within the channels themselves, become disconnected and re-connected periodically as episodic flooding events and droughts occur. The ability to migrate freely into key seasonal microhabitats where adults can reproduce, young can feed, and all life stages can avoid predation is crucial for Topeka Shiners. Despite their short life span, only 52% of females and 20% of males studied in Minnesota reached sexual maturity at age 1 (Dahle 2001). Thus, survival to age-2 is important. The Topeka Shiner is a multiple, synchronous clutch spawner, meaning that only a fraction of immature eggs in a female's ovary ripen at one time (a clutch). The clutch is ovulated and spawned over a short period of time, after which another clutch is ripened, ovulated, and spawned. The number of clutches produced annually by a female is unknown, but clutch size for individuals from populations across the entire range varies from 140–1,700 eggs and is strongly correlated to the size of the female (Dahle 2001, Hatch 2001, Kerns and Bonneau 2002). In Minnesota and elsewhere, spawning takes place primarily in June and July but can begin in mid-May and extend into August (Harlan et al. 1987, Hatch 2001, Kerns and Bonneau 2002, Stark et al. 2002). Spawning begins as water temperatures reach 70–72˚F (Kerns 1983, Katula 1998, Hatch 2001). Topeka Shiners are nest associates of Green Sunfish and Orangespotted Sunfish, although laboratory and aquarium experiments suggest they are not obligate associates (Kerns 1983, Pflieger 1997, Katula 1998, Stark et al. 2002, Witte et al. 2009). Sunfish species use their fins to clear silt and debris from underlying rubble and gravel substrates and spawn their eggs there. They continue to guard the nest after spawning, keeping it clear of silt and well oxygenated while the embryos develop. Access to areas where these sunfish make and maintain nests may be crucial for Topeka Shiner reproduction in Minnesota because Topeka Shiner cannot clear and maintain spawning substrates themselves.

1.2.2 Topeka Shiner Passage through Culverts

Culverts can create barriers to Topeka Shiner and other fish movement along a stream by physically impeding swimming because of insufficient flow depth, high velocity or turbulence, perched outlets, and blockages from debris or sediment (Blank et al. 2011). The few studies that have been conducted for small warm water fish species indicate that certain culvert designs can create barriers to movement for some species and life stages (Warren and Pardew 1998, Cahoon et al. 2007, Briggs and Galarowicz 2013). These studies point toward water velocity, perched outlets, and debris as causal components, especially for smaller fishes. Adams et al. (2000) demonstrated that as velocity increases the amount of time Topeka Shiners can swim is reduced and energetic stress is greatly increased. A lack of streambed material within a culvert can also create a barrier as many smaller fish species use substrate to move through areas of increased velocity (Toepfer et al.1999), and as a form of protection from predators. When culverts block or discourage fish movement, small populations of fish can become isolated causing reduced species abundance and diversity, loss of genetic diversity, and local species extirpation, further endangering long-term survival (Bouska et al. 2010).

There are three studies aimed specifically at evaluating potential culvert barriers for Topeka Shiner movement (Wall and Berry 2004; Bouska and Paukert 2010; Blank et al. 2011). The first, an assessment study by Wall and Berry (2004), developed a screening process for the prioritization of culvert mitigation practices in Topeka Shiner habitat. Corrugated pipe culverts were ranked as high, medium, or low priority for mitigation based on the height of perch, embeddedness, blockage, gradient, and water velocity within the spawning season (mid-May to August). The ranking used to determine high, medium, or low priority for mitigation was a combination of all of these factors. Low passability rankings were assigned for culvert perch > 6 cm (2.4 in), non-embedded culverts, blocked culverts, velocity ≥ 35 cm/s (1.4 ft/s) as determined by Adams et al. (2000) or culvert gradient ≤ 3%. Of the 81 sites with corrugated pipe culverts evaluated in South Dakota, 7 were classified as high priority, 22 were classified as medium priority and 52 were classified as low priority. No actual fish sampling was completed for this study.

Bouska and Paukert (2010), working in Kansas, determined that small cyprinids (minnows) were 1.4 times more likely to move upstream in control reaches of streams than they were to move upstream through roadway crossings and two times more likely to move through box culverts than low-water crossings. In this field study, the proportion of cyprinids moving upstream increased with decreasing crossing slope, length, height of perch, and increasing culvert width. Topeka Shiners made up only 3% of the total catch. Only 5 of 199 marked Topeka Shiners were recaptured and only one moved through a culvert (box). Further evaluation of crossing types (box culvert, corrugated pipe, and natural riffles) was conducted in experimental channels (6 ft long). Both the box culvert and corrugated pipe were covered. The proportion of fish moving upstream did not differ by crossing type for Topeka Shiner, Southern Redbelly Dace, or Green Sunfish. There was, however, a significant difference in movement between crossing types for Red Shiner. Red Shiner demonstrated lower proportional passage through rock riffles compared to the box culvert or corrugated pipe. Water velocity (up to 3.6 ft/s) did not deter upstream movement for any of the fish species tested. The maximum velocity (3.6 ft/s) is significantly higher than the reported sustained (>200 min) swimming velocity for Topeka Shiner of 0.9-1.3 ft/s, and is still greater than the laboratory measured prolonged and burst (0.1-10 min) swimming velocities of 1.31-2.5 ft/s (Adams et al. 2000). However, the channels used to test crossing type in these experiments were much shorter than a culvert (for example, culvert lengths were 28.9-55.6 ft in the field portion of this study). Topeka Shiner swimming endurance is negatively correlated with water velocity (Adams et al. 2000), and longer culverts likely develop a barrier to upstream movement at higher velocities. As there was no significant difference between the proportion of Topeka Shiner moving upstream in experimental box culverts and corrugated pipes, which were covered, and the experimental rock riffles, which were not covered, it can be extrapolated that light was not a behavioral barrier in these short experimental streams. In the field with longer culverts, the effect of light was untested and it is difficult to separate the dual effects of length on swimming ability and length on culvert darkness.

Blank et al. (2011), working in South Dakota, evaluated Topeka Shiner passage through eight culverts and reported that, in general, culverts impede fish passage, but that installing channel-spanning, embedded culverts minimized this impedance. Mark-recapture studies were conducted in culverts and control reaches with the installation of a weir trap at the upstream end of either the culvert or the control. This method was selected because of low mark-recapture efficiencies from netting methods. Because Topeka Shiner numbers were low, surrogate species were used with similar body shapes (Red Shiner, Sand Shiner, and Bigmouth Shiner). Topeka Shiners passed through three culvert sites with different crossing materials (concrete box, corrugate metal pipe, and structural steel). Topeka Shiner passage was documented through culverts with depths of 0.15-1.51 ft (4.6-46 cm), mean velocities of 0.03-2.6 ft/s (0.9-79 cm/s), perch heights up to 0.1 ft (3 cm), slopes of 0.55%-2.12%, and lengths of 53-70 ft. Genetic tests indicated that some culverts (two out of four tested) led to genetic differences above and below the culverts. No light measurements were collected in these culverts and no report was made regarding the effect of light.

From the studies conducted on Topeka Shiner passage through culverts, it is clear that many culverts can act as a permeable barrier (or a partial barrier) to fish movement when compared to control reaches. Topeka Shiner numbers captured in the field, however, are low and it is difficult to draw conclusions from the few fish that were recaptured. Topeka Shiners have been documented to pass through culverts with velocities much higher than their typical habitat, therefore, culverts with moderate velocity (up to 1.3 ft/s; Adams et al. 2000) should be passible in the absence of other barriers (depth, perch, or behavior). No studies have evaluated potential behavioral barriers in long or dark culverts for Topeka Shiners.

1.3 LIGHT AND FISH BEHAVIOR

Concerns over light levels in long (>150 ft) culverts appear in a number of guidelines for fish passage (e.g., National Marine Fisheries Service [NMFS] or the state of California), but there is no consensus on the impact of light on fish passage through culverts (Kilgore 2010). A review of the current literature on light and passage through culverts reveals only one study, conducted on turtles and frogs, which indicates that individual organisms’ behavior may be affected by the passage through dark culverts. This behavioral study investigated aperture size, substrate in the culvert, pipe length, and light permeability (in perforated pipes) (Woltz et al. 2008). Results from this study were species specific: turtles (painted and snapping) preferred moderate aperture size (1.6-2.0 ft), green frogs preferred soil and gravel lined pipes, painted turtles tended to avoid the longest pipes, and frogs (green and leopard) preferred the pipe with the greatest light permeability. The reasons for these preferences are unclear and require further investigation. No studies for fish behavior through dark culverts were found.

While there are no published studies on culverts and behavioral barriers for Topeka Shiners, or even warm water prairie fish in general, there is a growing body of work evaluating behavioral devices that attract or repel migrating fish to preferred routes (Kemp et al. 2012). These investigations often include the effect of light on fish behavior. Research focused on trout and salmon avoidance of velocity gradients (such as at fish bypass entrances) has found that under dark conditions, avoidance behavior of velocity gradients decreases (Vowles et al. 2014; Vowles and Kemp 2012). Fish response to darkness, however, may be a function of life stage or time of day. Johnson et al. (2012) conducted a set of experiments looking at upstream movements of juvenile salmon and found that more small fish moved at night regardless of shading in the upstream and downstream pools. Larger juvenile salmon had similar upstream movements during day and night tests. Light levels can also affect predator/prey interactions, as schooling behavior is lost at low light levels (Einfalt et al. 2012; Kemp and Williams 2009). Abrupt changes in light (such as at culvert entrances or exists) may cause avoidance behavior in lampreys (Moser and Mesa 2009), and these abrupt light changes (shadows under docks) are avoided by migrating juvenile salmon (Ono and Simenstad 2014). Salmon and trout have been shown to avoid cover (tarpaulin) over a turbine intake (Greenberg 2012) and prefer an uncovered channel when given a choice (Kemp et al. 2005). This research, taken together, indicates that fish can respond to a number of stimuli including light with either a positive (attraction) behavior or a negative (avoidance) behavior. To understand the effect of dark culverts on Topeka Shiner and other prairie stream fish movement, we conducted both a mark-recapture study to quantify fish movement through long box culverts and control reaches in southwestern Minnesota. However, this study alone could not control for other potential barriers to fish movement (e.g., velocity, depth, or other habitat variables). Therefore, we conducted a series of fish movement studies with both Topeka Shiners and Fathead Minnows in St. Anthony Falls Laboratory to identify fish preference for shaded or unshaded channels. This report details the results of these studies and summarizes recommendations for light mitigation for long culverts in critical Topeka Shiner habitat.

CHAPTER 2: MARK-RECAPTURE STUDY

Topeka Shiner and other associated fish movement through long box culverts was documented using a mark-recapture study. The probability of movement (POM) through culverts was compared between culverts and similar length control reaches on the same stream.

2.1 STUDY SITES

During summer 2015, the research team conducted a mark-recapture study to evaluate fish passage through three multi-barrel box culverts and three control reaches located on critical Topeka Shiner habitat (Figure 2.1). Culverts were located on Poplar Creek (bridge number 59X09), Elk Creek (bridge number 91077), and a Split Rock Creek Tributary (bridge number 8884). Table 2.1 has a summary of culvert characteristics.

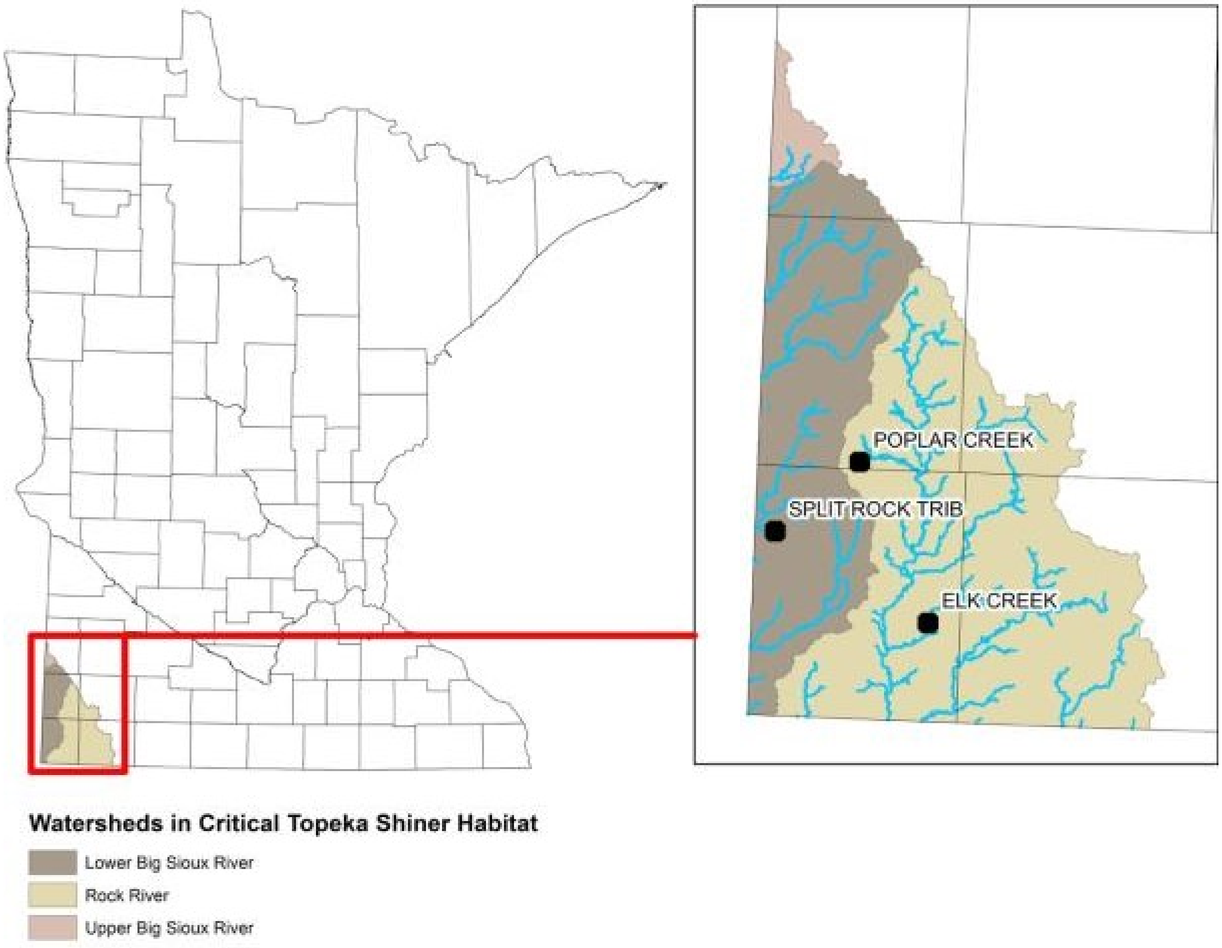

Figure 2.1 Locations of three research sites in Southwestern Minnesota (59X09 on Poplar Creek, Pipestone County; 91077 on Elk Creek, Rock County, and 8884 on Split Rock Tributary in Rock County).

Table 2.1 Stream, location, and description of the culverts (barrels, width, height, length, orientation) at sites sampled in Southwestern Minnesota.

Stream	Road	Lat/Long	Barrels	Barrel Dimension (Width x Height) (ft)	Barrel Length (ft)	Culvert Orientation	Description (looking downstream)
Poplar Creek	US 75	43°51'29"N/ 96°15'25"W	2	16 x 12	120	ENE	Culvert backwatered; two large pools immediately upstream and downstream.
Elk Creek	I-90	43°38'15"N/ 96° 6'52"W	3	10 x 11 (left/right) 10 x 14 (middle)	156	N	Culvert shallow; left barrel little to no flow.
Split Rock Tributary	TH 23	43°45'24"N/ 96°24'51"W	2	8 x 8	200	WNW	Right barrel blocked during low flow; culvert has elbow in middle; large pool downstream.

2.1.1 Culvert 59X09

Culvert 59X09 is located in Pipestone County, 2.5 mi south of Trosky where Poplar Creek flows under US Highway 75. It is comprised of two boxes, each 16 ft wide x 12 ft high x 120 ft long. The culvert is oriented approximately west/southwest to east/northeast (57° heading). Two small tributaries flow into a pool immediately upstream of the culvert (Figure 2.2 left). Flow from the culvert enters a much longer pool that extends approximately 370 ft downstream (Figure 2.2 right). Riprap has been placed around the entire upstream pool, along both banks immediately below the culvert, and within the downstream pool. An older roadbed and remains of a wooden bridge are present approximately 200 ft downstream of the culvert. The control stream reach is a straight stretch of nearly uniform width and depth located 0.25 mi east (downstream) of the culvert (Figure 2.3). The control reach substrate is silt over sand, gravel with a few boulders.

Figure 2.2 Upstream view from culvert 59X09 showing two tributaries feeding into the main pool (left) and downstream view from culvert 59X09, showing the large pool and remains of an old bridge crossing (blue arrows; right).

Figure 2.3 Satellite image (Google Earth) of Poplar Creek with culvert 59X09 and corresponding control area. Imagery taken 05/2015. Image shows pool upstream and downstream of culvert and the two tributaries upstream of the culvert. Blue delineates fish sampling areas, and red lines show the control stream reach. Flow direction is shown by the yellow arrow.

2.1.2 Culvert 91077

Culvert 91077 is located in eastern Rock County, 5 mi east of Luverne, MN where Elk Creek flows under Interstate 90. It is comprised of three boxes (Figure 2.4). The middle box is 14 ft wide x 10 ft tall and the side boxes are 11 ft wide by 10 ft tall. The culvert is 156 ft long and is oriented north to south (heading 179^{o}). The control stream reach is a relatively straight stretch of stream located 0.2 mi north (upstream) of the culvert. The control reach substrate is predominantly silt over gravel and sand (Figure 2.5).

Figure 2.4 Upstream view of culvert 91077 on Elk Creek, Rock County, showing a portion of the small pool (left) and downstream view of culvert 91077, showing vegetated islands and rip-rapped area.

Figure 2.5 Satellite image (Google Earth) of culvert 91077 and corresponding control area (imagery taken 5/2015). Blue delineates fish sampling areas, and red lines show the control stream reach. Flow direction is shown by the yellow arrow.

2.1.3 Culvert 8884

Culvert 8884 is located in northwestern Rock County, 6.5 miles south of Jasper, MN where Split Rock Tributary flows under State Highway 23. It is comprised of two boxes 8 ft wide x 8 ft tall (Figure 2.6). This culvert has an elbow approximately 1/3 of the length downstream bending north (Figure 2.7). The longer barrel (the left barrel, looking downstream) is 206 ft long and the right barrel is 195 ft long. The culvert is oriented approximately southeast/northwest (heading 320^{o}). There is rip-rap along the entire length of the left barrel. There is a small riffle approximately 20 ft upstream of the culvert. Water flows in both boxes during high water levels, but flow is concentrated in the right barrel (looking downstream) during low water levels. The control stream reach is located 0.35 miles east (upstream) of the culvert. There is a second box culvert between the culvert and control (Figure 2.7).

The second culvert (97966) is located 450 ft upstream from the experimental culvert and is 118 ft long. This culvert has two barrels 10 ft wide and 6 ft tall and is oriented approximately west/east (heading 75^{o}). The control stream reach is upstream of this second culvert and is a narrow channel filled with emergent vegetation.

Figure 2.6 Upstream view of culvert 8884 on Split Rock Tributary, Rock County, showing vegetation in left barrel (left) and downstream view of culvert 8884 showing large pool with surrounding vegetation.

Figure 2.7 Satellite image (Google Earth) of culvert 8884 and corresponding control area (imagery taken 8/2012). Image shows a second culvert (orange circle) in between the experimental culvert and control reach. Blue delineates fish sampling areas, and red lines show the control stream reach. Stream direction is shown by the yellow arrow.

2.2 METHODS

This section describes the field and statistical methods used to assess the potential for long box culverts to impede the movements of small prairie stream fishes, especially by reducing ambient light conditions within the culverts. We conducted our fieldwork at three culverts—59X09 on Poplar Creek, 91077 on Elk Creek, and 8884 on Split Rock Creek Tributary—and at three nearby control reaches in each of the streams. The culverts, in the order listed, represented progressively longer and darker environments. At each culvert and control reach we measured water velocity, depth, water transparency, and light levels. Multiple mark and recapture studies were used to document fish movement through each reach. Table 2.2 summarizes the sampling dates and data collection at each culvert and control site.

Table 2.2 Summary of measurements collected at each culvert or control site.

Date	Fish	Light	Light Extinction	Depth	Velocity	Transparency
Culvert 59X09						
5/20-5/21/15	Mark	X	NR	X	ADV	NR
5/27/15	Recap/Mark	X	NR	Right	NR	NR
7/6/15	NR	NR	NR	X	Tracer	NR
7/20/15	Recap/Mark	X	X	X	ADV	X
7/27/15	Recap/Mark	X	X	X	ADV	X
8/17/15	Recap	Ambient	X	NR	NR	X
Control 59X09						
5/21/15	Mark	NR	NR	NR	NR	NR
5/28/15	Recap/Mark	X	NR	NR	NR	X
7/21/15	Recap/Mark	X	X	X	ADV	X
7/28/15	Recap/Mark	X	X	X	ADV	X
8/25/15	Recap	X	X	X	ADV	X
Culvert 91077						
5/22/15	Mark	X	NR	X	ADV	NR
5/29-5/30/15	Recap/Mark	X	NR	NR	NR	X
7/6-7/7/15	Recap/Mark	X	NR	X	Tracer	X
7/13/15	Recap/Mark	X	X	X	Tracer	X
8/12/15	Recap	X	X	X	ADV	X
Control 91077						
5/23/15	Mark	X	NR	NR	NR	NR
5/30/15	Recap/Mark	X	NR	NR	NR	X
7/7-7/8/15	Recap/Mark	X	NR	NR	Tracer	NR
7/14/15	Recap/Mark	X	X	X	ADV	X
8/13/15	Recap	X	X	X	ADV	X
Culvert 8884						
6/9-6/10/15	Mark	X	NR	X	NR	X
6/15/15	Recap/Mark	X	NR	NR	Tracer	X
7/6/15			NR		Tracer	NR
7/8-7/9/15	Recap/Mark	X	NR	X	Tracer	X
7/15/15	Recap/Mark	X	X	X	ADV	X
8/10-8/11/15	Recap	X	X	X	ADV	X
Control 8884						
6/10/15	Mark	X	NR	NR	NR	X
6/16/15	Recap/Mark	X	NR	X	Tracer	X
7/9/15	Recap/Mark	X	NR	NR	Tracer	X
7/16/15	Recap/Mark	X	X	X	ADV	X
8/11/15	Recap	X	X	X	ADV	X

ADV = acoustic Doppler velocimeter ; NR = Not Recorded

2.2.1 Physical Measurements

All physical habitat measurements were collected in the culvert and control reach at the same relative locations. The length of each control reach corresponded to the shaded length of its paired culvert (A-E in Figure 8). A and E were located where the top edge of the culvert overhangs the stream. All measurements in the culvert were collected at the middle of the culvert barrel width.

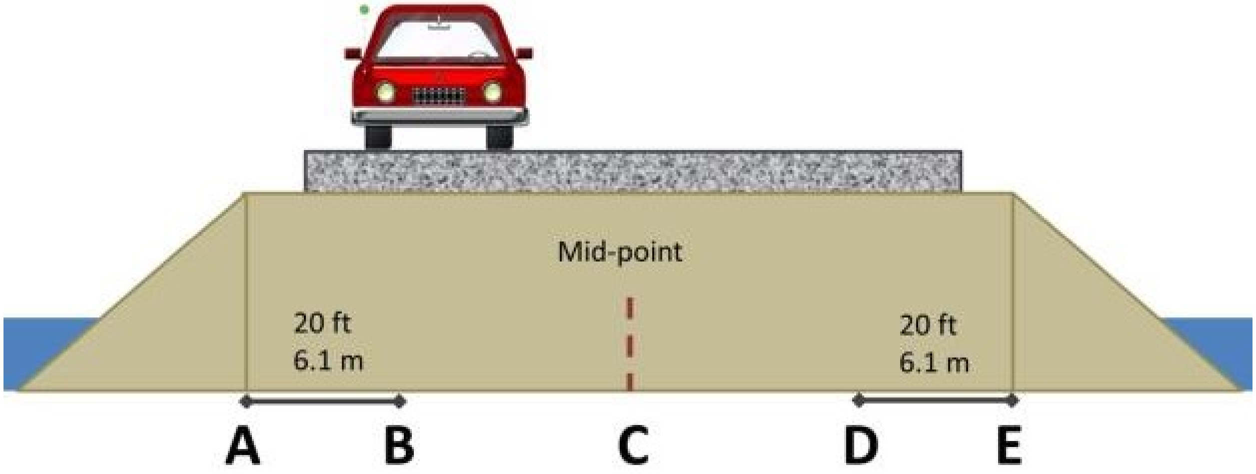

Figure 2.8 Sketch of culvert physical measurement sampling points. Flow is from point A to point E.

2.2.1.1 Velocity and depth

Stream velocity was measured when feasible using a Sontek Flowtracker acoustic Doppler velocimeter (ADV). Velocity and depth measurements were collected in the middle of each culvert barrel at points A and E. In control reaches, velocity cross sections were collected at representative A and E points. Because of the variability in cross section shape, multiple points were collected to calculate mean velocity and depth at each cross section. If water depth or velocity was too high to safely record velocity measurements, ADV measurements were not collected. To estimate water velocity if water depth was too shallow, or if the ADV was infeasible, multiple neutrally-buoyant orange peels were released at the start of each box or control and timed until they reached the end of the culvert or control.

2.2.1.2 Light and water transparency

Light measurements were collected at three distinct periods—morning, midday, and late afternoon—using a handheld digital photometer (Extech Model EA30). Light readings were taken in ambient daylight and at points A, B, C, D, and E just above the water surface at mid-width within the culvert and at control sites. Light attenuation with depth was also recorded with light level loggers (HOBO Pendant Temperature/Light Data Logger, Onset Computer Corporation) at both the culvert and control reaches in July and August to illustrate the effect of water depth and water transparency on light levels.

Water transparency was measured using a 1 ¾ inch Secchi transparency tube 3-5 times during each visit to the culvert and control reaches.

2.2.2 Fish Mark and Recapture

Fish were collected for the mark-recapture study during 5 separate visits at culverts and controls in May-August (Table 2.2). Fish sampling methods were dictated by site conditions depending on water depth and accessibility. A combination of fish capture methods using a mini-Missouri trawl (used for deep pools in Poplar Creek; Herzog et al. 2009), and a bag seine (used for shallow stream sides and the mouth of tributaries), were used to sample the stream upstream and downstream of each culvert and control Figure 2.9). Drop nets were used to block the entrance and exit of culverts and control reaches to prevent fish passage caused by human disturbance. All collection gear and drop nets had 0.125-in mesh netting.

Figure 2.9 Deployment of the mini-Missouri trawl in the in a deep pool, and bag seine in a shallower stream reach.

After installing drop nets, areas upstream and downstream of the culvert were sampled independently. Each site was sampled for about 12-13 hours with half of the day spent upstream of the culvert or control and the other half spent downstream. An area was deemed sufficiently sampled once catch-per-unit-effort declined or day length prevented further sampling. Only fishes 1.2-5.9 inches total length (TL) were used in the marking process. Fishes to be marked were first anaesthetized using buffered tricaine methanesulfonate (MS-222) (80 ppm) before handling and tagging. If a fish showed any negative effects to capture or anesthesia, it was revived in a separate aerated cooler and deemed unfit for marking or analysis. Each fish was measured (total length, TL) and marked by injecting visible implant elastomer (VIE; Northwest Marine Technology) between the skin and musculature with a 29-gauge hypodermic needle (Figure 2.10).

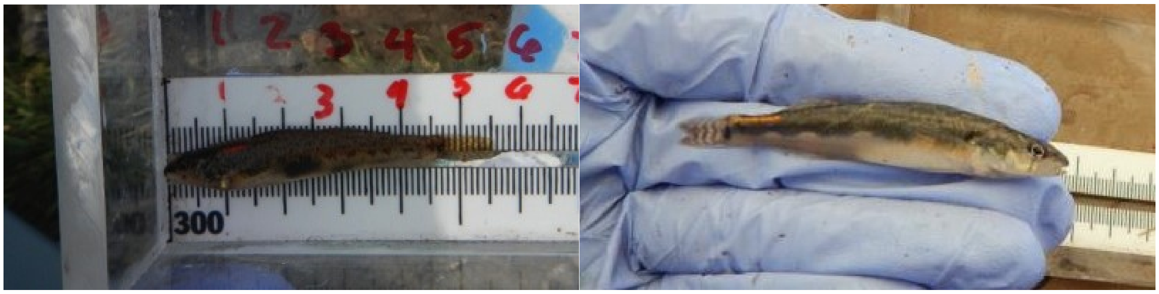

Figure 2.10 Examples of VIE (visible implant elastomer) tags.

The location of a mark on the fish was determined by the date and site of capture. The color of the mark was determined by a combination of the capture date and the release location (Figure 2.11). Fish collected at a culvert were marked on the left side of the body, and fish collected at a control were marked on the right side of the body. Specimens of each species were marked in lots of 10 (one color and one release location) before changing to another color corresponding to the opposite release location. For example, ten Fathead Minnows caught upstream were tagged blue and released upstream and the next set of ten Fathead Minnows caught upstream were tagged orange and released downstream. Then the pattern was repeated. A previously marked fish was recorded and given a second mark of a color consistent with the recapture and release location. This color schemed allowed tracking of fish movement to determine if a fish moved across a culvert or control reach and in which direction it moved. Recapture rates were calculated as number of fish of a given taxon recaptured divided by the total number of fish of the same taxon marked and released.

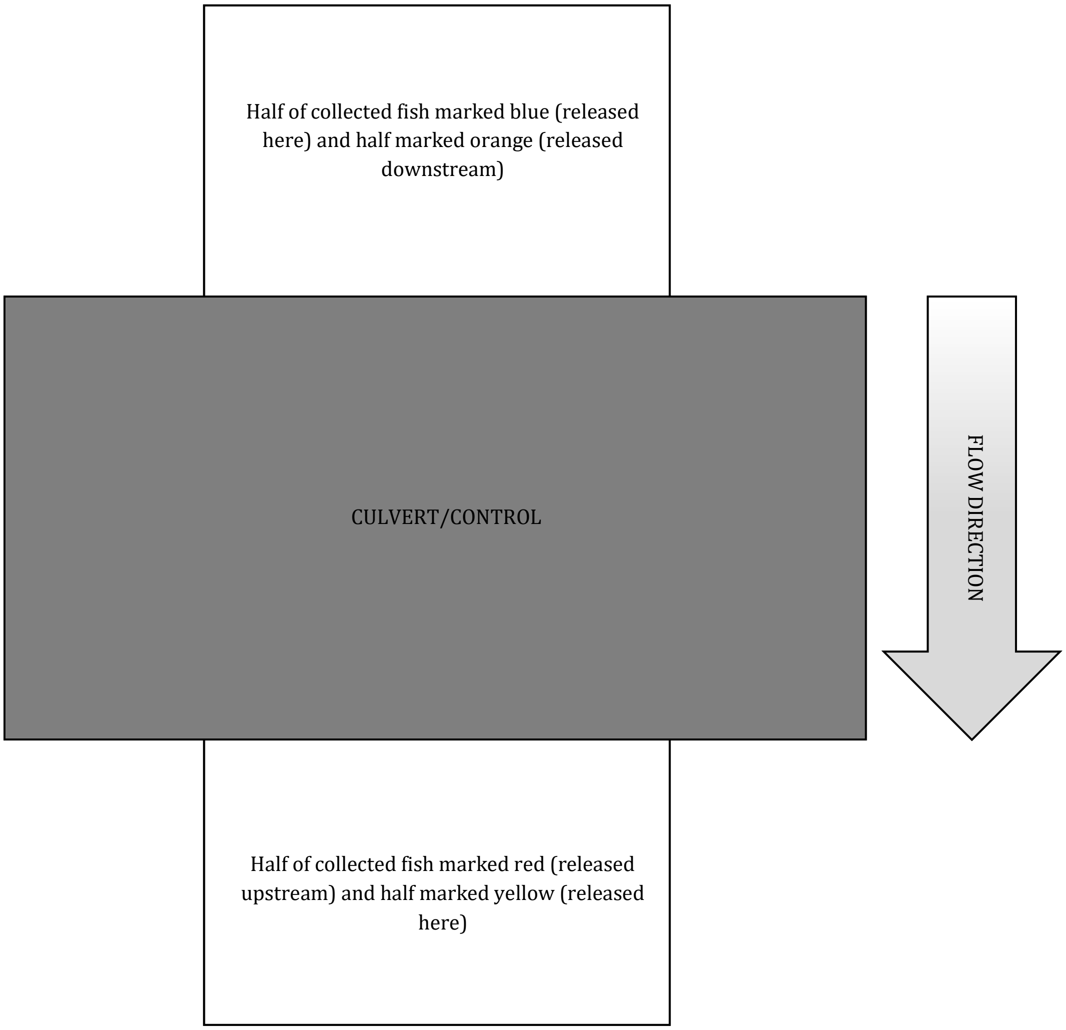

Figure 2.11 Diagram of the fish mark-recapture design with the corresponding collection sites, mark colors, and release sites. Marking scheme was similar for culvert and control sites, except that culvert fish were marked on the left side as opposed to the right for control fishes.

2.2.3 Statistical Analyses

A chi-square test for all recaptured fish indicated that the POM at culverts and controls was different (P-value < 0.01). As a result, a generalized linear model with a logit transformation was fitted to test for two- and three-factor interactions among the predictors: experiment area (culvert or control), stream (Poplar, Elk, Split Rock), and most recent tag color (movement direction) using the Wilkinson-Rogers notation (Wilkinson and Rogers 1973).

For the full community of marked and recaptured fishes, using a type II analyses of deviance (ANOVA), all predictors were significant except the three-factor interaction. A new model was fitted to exclude the three-factor interaction using the Wilkinson-Rogers notation (Wilkinson and Rogers 1973) with significance based on α = 0.05 or greater (Fox and Weisberg 2011). Thus, the model became logit(x) = β_0 + Experimental.Area:Stream + Stream:Most.Recent.Tag.Color + Experimental.Area:Most.Recent.Tag.Color where β_0 = constant, Experimental.Area = culvert or control, Stream = Elk, Poplar, or Split Rock, Most.Recent.Tag.Color = movement-yes or no and upstream or downstream if yes. The probability of movement (POM) through each reach was estimated using logistic regression by averaging across the other experimental predictors, including stream, study site, tag color, and direction of movement. All statistical analyses for fish movement were completed using R Version 3.2.2. All POMs were calculated using the R Package Effect Displays (Fox 2003). All P-values were computed using Least-Squares Means in the R Package lsmeans (Lenth 2016).

Similar type II analyses of deviance (ANOVA) were conducted to determine if POM differed between culverts and controls when using data from a single family and from four different species with large sample sizes. Table 2.3 shows the significant predictors and interactions for each model for the total fish community and individual species tested.

Table 2.3 Summary of significant effects and interactions for the generalized linear model for each community of fish (Total, all cyprinids, and by individual species). Experimental Area = Culvert or Control, Stream = Poplar, Elk, or Split Rock Tributary, Most Recent Tag Color = direction of movement. X indicates a significant effect at α = 0.05.

Fish Community	Experiment Area (EXP)	Stream	Most Recent Tag Color (MRTC)	Exp*Stream	Exp*MRTC	Stream*MRTC
Total	X	X	X	X	X	X
Cyprinid	X		X	X	X	x
Bluntnose Minnow			X			X
Fathead Minnow	X		X	X	X	
Johnny Darter	X		X	X		
Sand Shiner	X		X			X

2.3 VELOCITY, DEPTH, AND LIGHT IN CULVERTS

Physical habitat measurements were collected at each culvert and control location in conjunction with fish mark and recapture. Physical measurements included light intensity at the midpoint of each culvert barrel and in unobstructed daylight, and water depth, transparency, and velocities within the culvert barrels.

Water depth and velocity measurements were collected at every visit at all of the culverts and control unless high water levels prevented safe measurements (Table 2.2). Flow was generally very deep and slow in both barrels in culvert 59X09. Flow was very shallow and relatively fast in the middle and left barrel in culvert 91077. The right barrel (looking downstream) of 91077 had fine sediment deposition and vegetative debris that slowed flow and blocked the movement of flow tracers. Flow was deeper at culvert 8884 than culvert 91077 and relatively slow. The left barrel of 8884 had high vegetation growth and riprap at the entrance that often prevented flow during low water levels. The range of velocity and depth measurements collected at each culvert and control is shown in Figure 2.12 (culvert) and Figure 2.13 (control).

The light at the midpoint within every culvert was always less than unobstructed daylight (Figure 2.14). Unobstructed daylight levels across all control and culvert sites ranged from 2,100 lux to 115,700 lux. Light readings collected at the Poplar Creek culvert midpoint had an average reduction at midday of 66.7% (log scale), ranging from 10 lux to 73 lux. Light readings were similar between barrels. Light level readings collected within the Elk Creek culvert had an average reduction at midday of 77.0% (log scale), ranging from 2 lux to 24.6 lux. Light level readings were similar among barrels. In general, mean light levels at the Elk Creek culvert midpoint were less than the mean levels at the Poplar Creek culvert midpoint. Light level readings collected within the Split Rock Tributary culvert had an average reduction at midday of 99.2% (log scale), ranging from 0.1 lux to 2.1 lux. Light levels at the Split Rock Tributary culvert midpoint were always less than those measured at Poplar and Elk Creek culvert's midpoints. Altogether, light levels at the Poplar and Elk Creek culvert midpoints fell between light levels typical for twilight and deep twilight conditions, whereas levels at Split Rock Tributary culvert fell between deep twilight and full moon conditions (Figure 2.14).

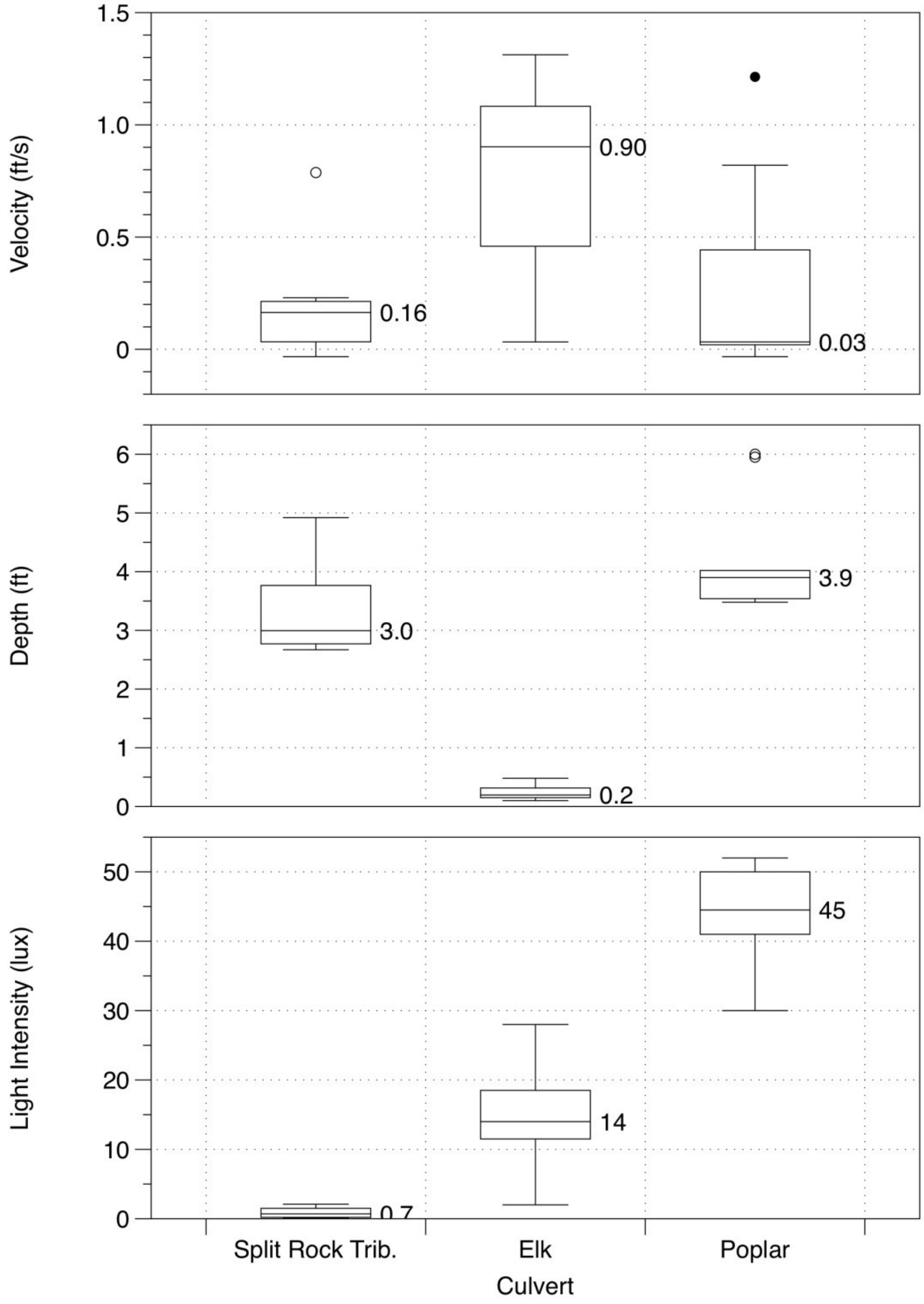

Figure 2.12 Velocity, depth, and light intensity for each culvert. Light intensity was measured at the midpoint of each culvert at midday. The graphs depict the interquartile range (box), mean values, range with exclusion of outliers (whiskers), and any outliers (dots). Numbers next to each box represent the median value.

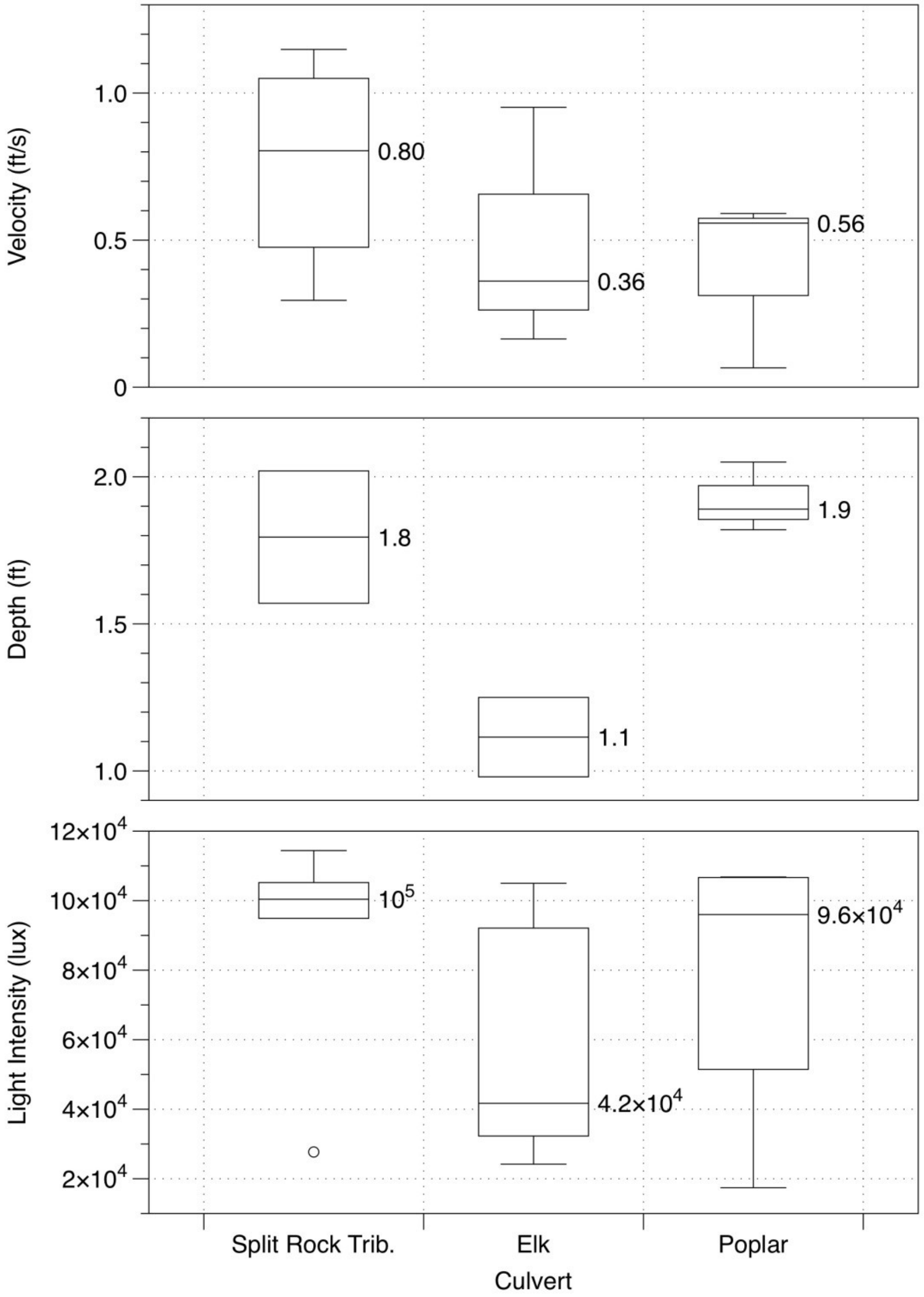

Figure 2.13 Velocity, depth, and light intensity for each control reach. The graphs depict the interquartile range (box), mean values, range with exclusion of outliers (whiskers), and any outliers (dots). Numbers next to each box represent the median value.

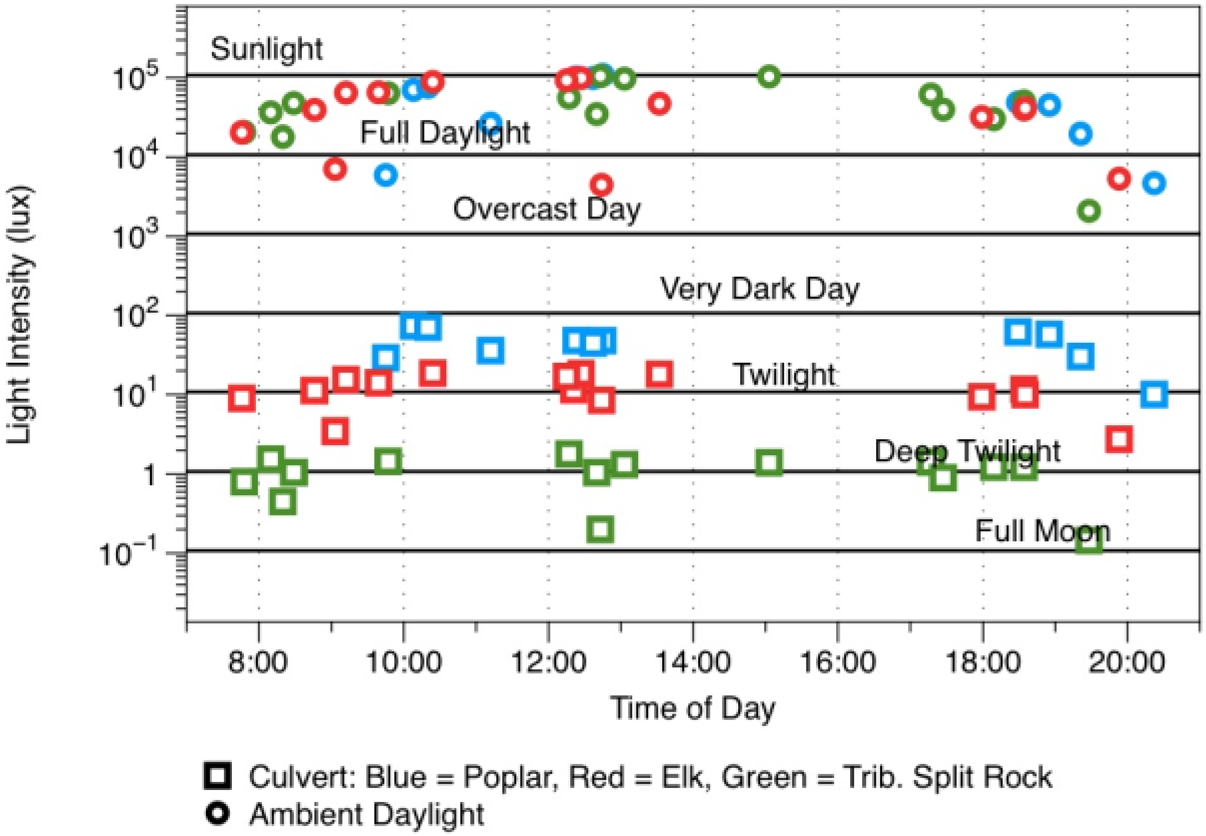

Figure 2.14 Light intensities recorded in unobstructed daylight and mid-culvert at culvert 59X09 (Poplar), 91077 (Elk), and 8884 (Split Rock Tributary) compared typical light intensities (taken from The Engineering Toolbox 2016).

Although the handheld light level instrument and the waterproof light logger pendants record different light distributions (see HOBO Pendant Light Data Logger UA-002-08 User's Manual), the waterproof pendant light loggers are useful for examining relative light levels at various points within the stream. Plots illustrating relative light levels over a single day at each paired culvert/control site (at point C) are shown in Appendix B. During night hours, the light levels were too low for the pendant to record. Key observations from these plots include: 1) Some light reached the bottom of the control stream reach at all three sites, but only culvert 91077 had recordable light levels at the bottom of the culvert barrel (in very shallow flow); 2) Culvert 91077 and 59X09 had recordable light levels at the water surface within the culvert, but culvert 8884 did not; and 3) Depth, water transparency, and initial light levels (in culvert or out) affect the available light levels for fish in the stream. Additional plots of light extinction at various sampling dates, and the longitudinal light distribution at the water surface in 91077 are included in Appendix B.

The amount of light able to reach the bottom of the culvert or stream was a function of depth and water transparency. Water transparency measured with a transparency tube at each site was lower in May, but increased as the summer progressed, returning to relatively low transparency at most sites in August (Figure 2.15).

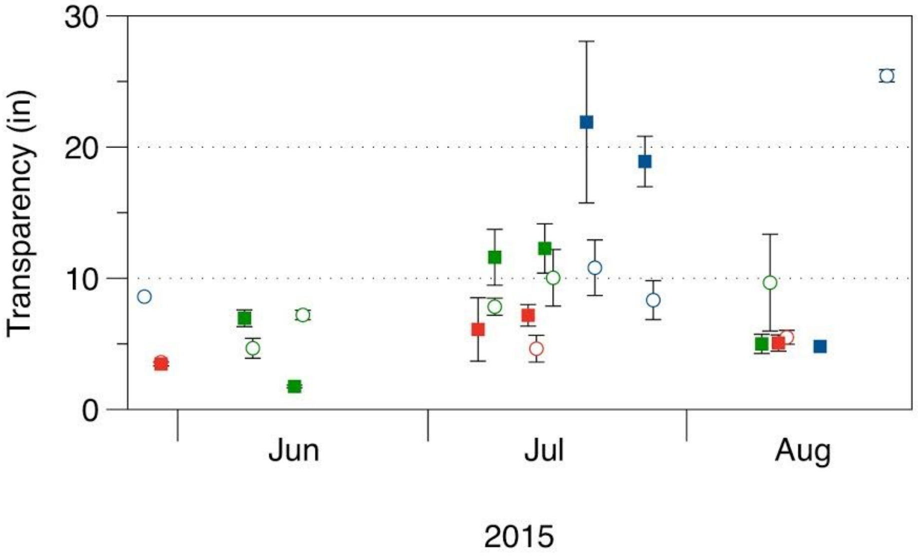

Figure 2.15 Transparency measured within each stream or control reach. Blue=Poplar, Red=Elk, Green=Split Rock Creek Tributary. Open symbols are control sites and closed symbols are culvert sites.

2.4 FISH MOVEMENT

Mark-recapture studies were completed to track fish movement through each culvert and its corresponding control according to the schedule in Table 2.2. Results summarized here include relative abundance of each fish species marked on each date, and a summary of fish movement through each culvert and control reach. A complete fish mark-recapture data set is included in Appendix A.

2.4.1 Fish Mark-Recapture

The research team marked 18,963 fish (456 Topeka Shiner) in all three study streams from May through August 2015. Across all three streams, three species contributed 66.4% of the total fish marked: Fathead Minnow (36.9%), Sand Shiner (19.6%), and Bluntnose Minnow (9.9%) (Figure 2.16). Topeka Shiner accounted for 2.4% of the total fish marked. The research team recaptured 1,874 fish (9.9%). Recapture rates were highest at the Split Rock Tributary control (18.2%) and culvert (13.1%), followed by Elk Creek control (11.8%), Elk Creek culvert (8.9%), Poplar Creek control (6.7%), and Poplar Creek culvert (3.6%). Four species contributed 79.5% of the total recaptured fishes: Fathead Minnow (27.9%), Sand Shiner (23%), Johnny Darter (16.1%), and Bigmouth Shiner (12.5%). Forty-six (2.5%) Topeka Shiner were recaptured. Recapture rates are summarized in Table 2.4.

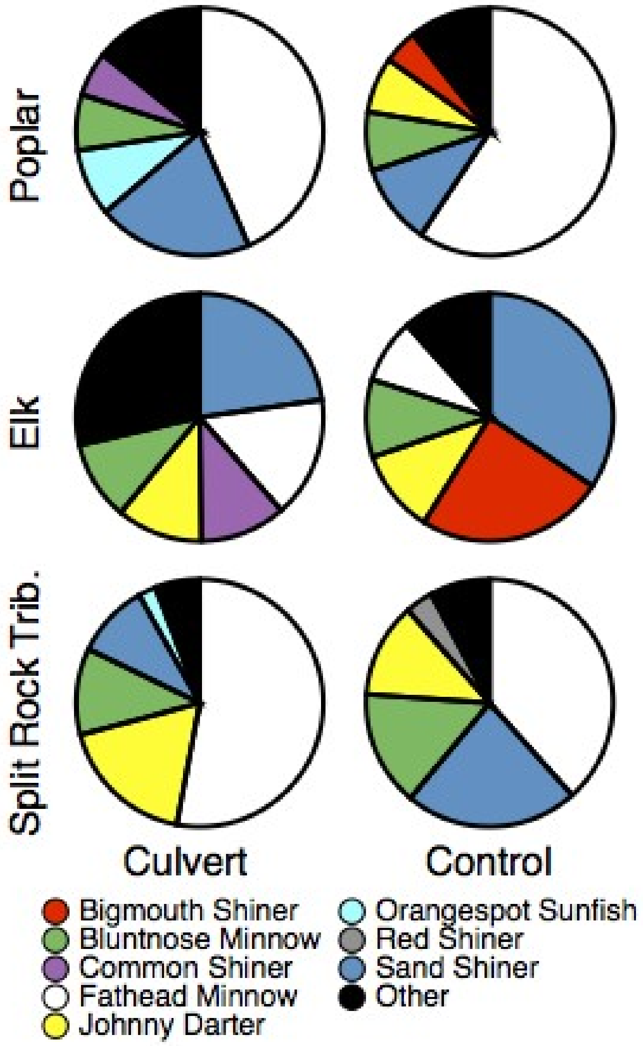

Figure 2.16 Five most abundant species marked at each culvert and control. All other species included in the "other" category.

Table 2.4 Summary of recapture rates and Probability of Movement (POM) by site, direction, family, and species. (Tot = total fish community, Sp = # of species, and Freq = three most frequently collected species. BMS = Bigmouth Shiner, BNM = Bluntnose Minnow, CRC = Creek Chub, CSH = Common Shiner, FHM = Fathead Minnow, JND = Johnny Darter, OSS = Orangespotted Sunfish, SDS = Sand Shiner, and TKS = Topeka Shiner.)

	Marked				**Recaptured**				**Moved**			**Recapture Rate**		**Probability of Movement**									
Site	Tot	Sp	Freq	TKS	Tot	Sp	Freq	TKS	Tot	Freq	TKS	Tot	TKS	Tot	U/U	D/D	U/D	D/U	Cyp	FHM	BNM	JND	SDS
Poplar 59X09	3,738	16	FHM SDS OSS	165	133	9	SDS OSS FHM	13	57	SDS FHM OSS	8	3.60%	8%	40.6	13.6	17	77.8	54.8	42.6	44.7	42.7	NC	35.7
Poplar Control	3,612	17	FHM SDS BNM	69	243	12	FHM BNM JND	8	119	FHM JND OSS	6	6.70%	12%	44.8	36	17.9	68.1	58.3	43.1	38.2	50.2	NC	41.4
Elk 91077	2,868	14	SDS FHM CSH	69	254	10	SDS BMS JND	7	105	SDS BMS CRC	1	8.90%	10%	34.4	5.7	25.9	73.3	41.2	37	NC	26.2	23.8	42.1
Elk Control	3,149	13	SDS BMS JND	7	373	8	BMS SDS JND	0	182	SDS BMS CRC	0	11.80%	0%	48.9	25.1	36.4	72	55.3	48.9	NC	47.9	51.9	50.6
SRT 8884	2,999	13	FHM JND BNM	65	394	9	FHM SDS BNM	7	83	FHM JND SDS	4	13.10%	11%	18.6	40.7	13.2	42.1	22.6	23	18.6	14.9	8.3	23.5
SRT Control	2,597	12	FHM SDS BNM	58	477	10	FHM SDS JND	11	225	FHM SDS JND	6	18.40%	19%	48	5.4	35.5	60.1	53.3	48	48.7	39.9	43.5	48.2

NC: not calculated due to low recapture numbers. Fathead Minnow (Elk): N = 25, Johnny Darter (Poplar): N = 19

2.4.2 Overall Fish Movement

Recaptured fish moved through all culvert and control reaches in both directions; therefore, no reach, culvert or control, was a complete barrier to fish movement (Figure 2.17). The type II analysis of deviance (ANOVA) showed that all factors (Experiment Area, Stream, Most Recent Tag Color, and the two-way interactions) were significant for the POM for the general community of fish (Table 2.3). The POMs at culverts decreased from 40.6% to 18.6%, as the culvert length and darkness increased from Poplar Creek to the Split Rock Creek Tributary. POMs were not different between culverts and controls at Poplar Creek (P-value = 0.34) but were significantly different at Elk Creek (P-value < 0.01) and at Split Rock Tributary (P-value < 0.01). The POMs of all recaptured fishes at each of the three control stream reaches were similar and not significantly different from one another—Poplar Creek 44.8%, Split Rock Tributary 48.0%, and Elk Creek 48.9% (P-value Poplar Creek-Elk Creek = 0.76, P-value Poplar Creek-Split Rock Tributary = 0.69, P-value Elk Creek-Split Rock Tributary = 0.99).

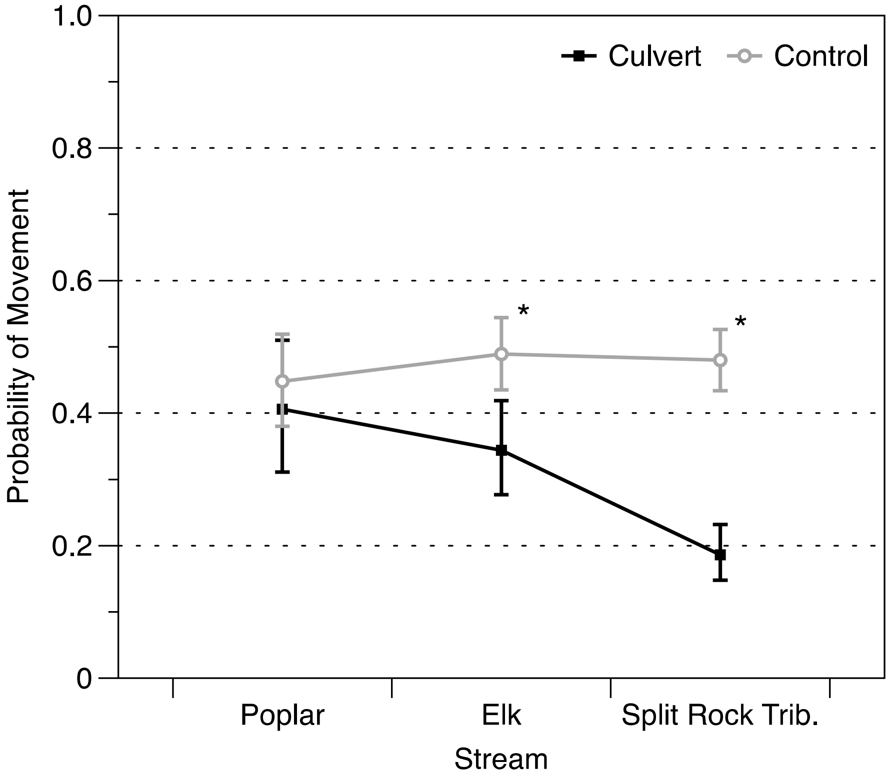

Figure 2.17 Probability of movement of all recaptured fish (both directions) at each culvert and control site (± 2 SE), arranged in order of increasing length of the culverts. *Significant difference between POM in culvert and control ($\alpha < 0.05$).

2.4.3 Direction of Movement

Colors of marks and location of recapture determined the net direction of movement by all recaptured fish. The same type II analysis of deviance (ANOVA) was used to evaluate differences between POMs by the direction of fish movement. Fish moved both upstream and downstream through both culverts and controls, but POM in certain directions at the controls were significantly higher than at the culverts (P-value caught upstream/released upstream < 0.01, P-value caught downstream/released downstream = 0.01, P-value caught downstream/released upstream < 0.01). Overall, fish were more likely to move when released in the area opposite from which they were captured (Figure 2.18), and fish were most likely to move when they were captured upstream and released downstream (thus, movement was in the upstream direction) (POM 60.8% for culverts, 65.9% for controls). Regardless of the release area, across all streams and reaches, more fish moved upstream (451) than downstream (322).

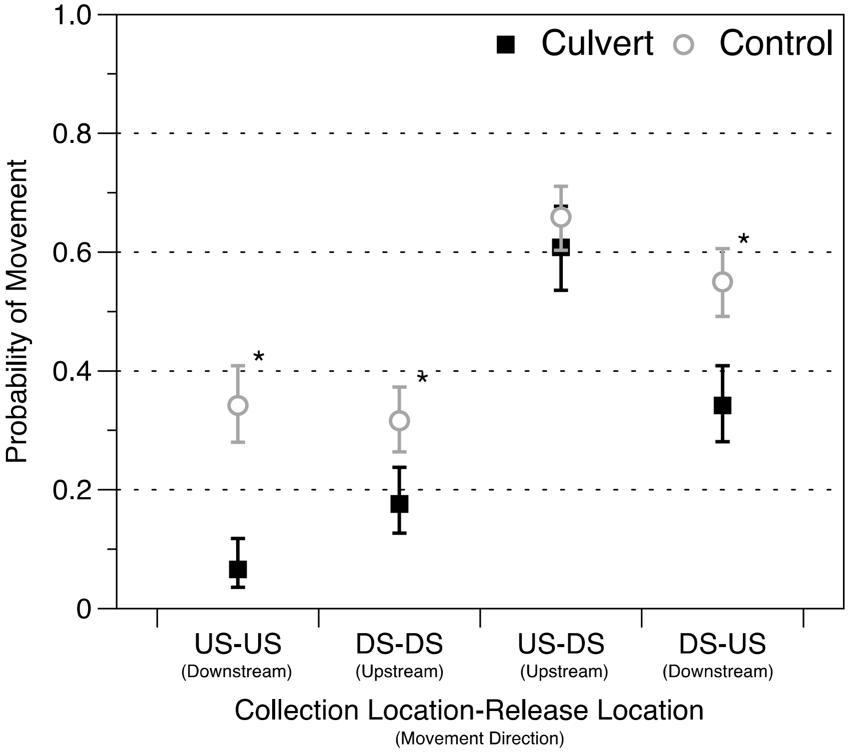

Figure 2.18 Probability of movement of all recaptured fish based on direction across all culverts and control (± 2 SE). DS = downstream, US = upstream. *Significant difference between POM in culvert and control ($\alpha < 0.05$).

2.4.4 Movement by Family and Species

At least one Topeka Shiner moved through each culvert, Poplar Creek control, and Split Rock Tributary control. Because of the low capture and recapture rates of Topeka Shiner, movement influenced by culverts is uncertain; so Topeka Shiner analysis was combined under the family Cyprinidae. The family Cyprinidae comprised 85.2% (nineteen species including Topeka Shiner) of the overall marked fish and

80.0% (nine species including Topeka Shiner) of the overall recaptured fishes (Percidae-16.2%, Centrarchidae-3.8%, and Fundulidae- < 0.1%) and was the only family analyzed. Although Percidae accounted for a large proportion of the catch, analysis was only conducted at the species level because all but two of the individuals recaptured were Johnny Darter.

2.4.4.1 Cyprinid Fish Movement

The POM by Cyprinidae followed a similar pattern to the entire fish community (Figure 2.19). The type II analysis of deviance (ANOVA) showed that most factors (Experiment Area, Most Recent Tag Color, and the two-way interactions) were significant for the POM of Cyprinidae ($\alpha < 0.05$; Table 2.3). Treating the significant factors as before, the POMs at Poplar Creek culvert and at its respective control reach were not significantly different (Poplar P-value = 0.77); however, the POMs by Cyprinidae were significantly different between the culverts at Elk Creek and Split Rock Tributary and their control reaches (Elk P-value = 0.01; Split Rock Tributary P-value < 0.01). Movement was lowest (23.0%) at the Split Rock Tributary culvert. The control POMs at Split Rock Tributary (48.0%) and Elk Creek (48.9%) were identical to the POMs for the general fish community. The POM at Poplar Creek control was only slightly lower than the general fish community at 43.1%, and was comparable to the other two sites. Hence, none of the controls was significantly different from any another (P-value Poplar Creek-Elk Creek = 0.61, P-value Poplar Creek-Split Rock Tributary = 0.48, P-value Elk Creek-Split Rock Tributary = 0.98).

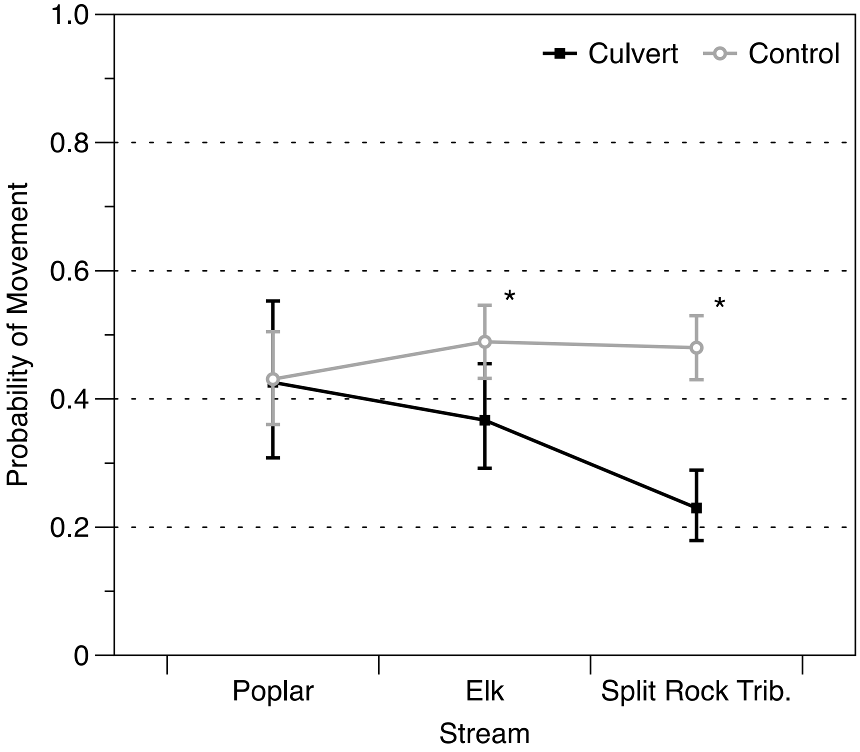

Figure 2.19 Probability of movement by all recaptured Cyprinidae at each culvert and control site (± 2 SE). *Significant difference between POM in culvert and control ($\alpha < 0.05$).

2.4.4.2 Fish Movement by Most Abundant Species

The POM was calculated independently for the four most abundant recaptured species: Bluntnose Minnow, Fathead Minnow, Sand Shiner, and Johnny Darter. Sites where species had sample sizes less than 30 were excluded from analyses. Bluntnose Minnow and Sand Shiner were evaluated at all sites, whereas Fathead Minnow was not analyzed at Elk Creek and Johnny Darter was not analyzed at Poplar Creek.

The type II analyses of deviance (ANOVA) revealed that Experiment Area (culvert vs. control) was a significant predictor for all species, except Bluntnose Minnow ($\alpha = 0.05$) (Table 2.3). Most Recent Tag Color (directional movement) was also a significant predictor for all species, along with various factor interactions for some species. Stream was not a significant predicator for any species, but the interaction between Stream and Experiment Area was significant for Fathead Minnow and Johnny Darter.

Except at sites where the number of recaptured fish was small, the pattern of increasing difference between control POM and culvert POM as culvert length and darkness increased (seen in the whole community and cyprinid family analyses) was repeated for each species tested (Figure 2.20). There were no significant differences between control and culvert POMs Bluntnose Minnow in any stream. However, the remaining three species had significantly lower POMs at the Split Rock Tributary culvert compared to the control (P-value Fathead Minnow < 0.01, P-value Johnny Darter < 0.01, P-value Sand Shiner < 0.01). Johnny Darter, a benthic species, also had a significantly lower POM at the Elk Creek culvert (P-value $= 0.02$), which was quite shallow much of the time (Figure 2.12).

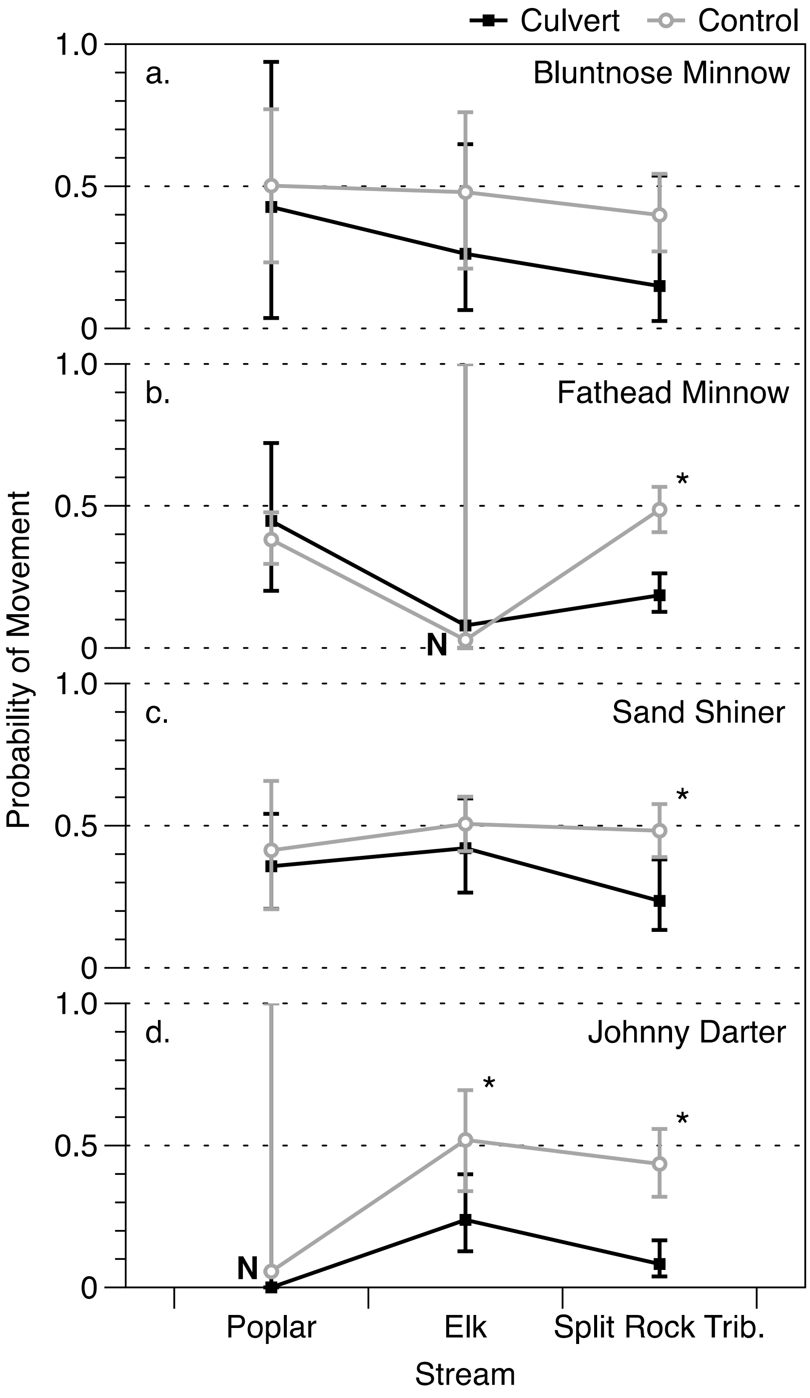

Figure 2.20 Probability of movement by most abundant species at each culvert and control site (± 2 SE). Low recapture sizes (Fathead Minnow: N = 25, Johnny Darter: N = 19). *Significant difference between POM in culvert and control ($\alpha < 0.05$).

2.5 SUMMARY AND CONCLUSIONS

2.5.1 Fish Movement

The likelihood of total fish movement was slightly less than 50% in control reaches. The POM in control reaches ranged 44%-48.9%, similar to Bouska and Paukert (2010), who reported fish movement rates of 41%-45% in South Dakota. POMs in control reaches were similar when based on cyprinids only or on each of the four most abundant species in this study. The mark-recapture study provided no evidence that the shortest culvert, the culvert that motivated this study (Poplar Creek), created a barrier to fish movement. The culvert at Elk Creek was a partial barrier to cyprinids and to Johnny Darters. Some fish passed, but the POM through the culvert (37% for Cyprinids) was significantly less than the control. The longest culvert at Split Rock Tributary, created a partial barrier for all fish groups tested, with the exception of Bluntnose Minnow.

Typically, studies only focus on one direction of movement through a culvert (Warren and Pardew 1998; Bouska and Paukert 2010; Blank et al. 2011). This study design measured both upstream and downstream movement. Overall, the total recaptured fish community demonstrated greater upstream movement than downstream movement at all culvert and control sites. Other studies have noted this upstream movement phenomenon. Gerking (1953) found similar movement in Smallmouth Bass, Spotted Bass, Golden Redhorse, and Hogsuckers. Similarly, Benton et al. (2008) observed higher upstream movement rates than downstream in clear-span bridges, box culverts, and tube culverts in small Georgia streams. Goforth and Foltz (1998) demonstrated a seasonal trend with Yellowfin Shiner (*Notropis lutipinnis*), where upstream movements were higher in late spring and summer and downstream movements were higher in fall and winter. Although two culverts appeared to inhibit fish movement, the culverts in this study did not appear to bias movement in a downstream direction, thus upstream off channel or spawning habitat is still accessible.

2.5.1.1 Topeka Shiner Movement through Culverts

Because of their low numbers, it is not possible to determine explicitly if Topeka Shiner movement was influenced by the presence of culverts. At least one Topeka Shiner moved through all three culverts, as well as the control reaches at Poplar Creek and Split Rock Tributary. This means that none of these sites was a complete barrier to the species. Unfortunately, very few Topeka Shiner were caught at the Elk Creek control reach, and none was recaptured to analyze movement patterns. Results from analysis of Cyprinidae (minnow family), and Bluntnose Minnow, Sand Shiner, and Fathead Minnow movement indicate that movement patterns of these groups of fish are similar to the entire fish population and indicate that these patterns may represent the movement of Topeka Shiner in absence of other information. Despite low recapture numbers (46 total), at least one Topeka Shiner passed through each of the sampled culverts. Movement of Topeka Shiner occurred in both directions at Poplar Creek culvert and control and Split Rock Tributary culvert and control. Topeka Shiner belong to the family Cyprinidae, which includes Bluntnose Minnow, Fathead Minnow, and Sand Shiner. The latter two species in particular are ecologically similar to Topeka Shiner.

In Minnesota streams, adult Topeka Shiners and Fathead Minnows are classified as “medium pool” (depth 23.6–58.7 in., velocity <0.98 ft/s) inhabitants, and adult Sand Shiners are “shallow pool” (depth <23.6 in., velocity <0.98 ft/s) inhabitants (Aadland and Kuitunen 2006). = Nuptial (spawning) Sand Shiners are more associated with “slow riffles” (depth <23.6 in., velocity 0.98–1.94 ft/s), nuptial Fathead Minnows with “shallow pools” (see above), and nuptial Topeka Shiners remain associated with “medium pools. All three of these species are optimally associated with low-velocity habitats. In addition, all three species are tolerant of high temperatures and low dissolved oxygen conditions (Kowalski et al. 1978; Smale and Rabeni 1995; Koehle and Adelman 2007). Given that the family Cyprinidae, Fathead Minnow, and Sand Shiner analyses yielded similar patterns of POM, we believe that the Topeka Shiner pattern likely would have been similar had numbers permitted analysis.

2.5.2 Study Limitations

There are several important limitations that should be noted for our mark-recapture study. There were substantially different recapture numbers and rates in the three different streams (Table 2.4). We attribute much of these differences to two interacting factors—difficulty in sampling similar portions of the water volume at each site (sampling efficacy), and differences in habitat variety. While we likely sampled as much as or more water at culvert 59X09 (Poplar Creek) as any other site, because of the size and depth of the pools immediately upstream and downstream of the culvert, the percentage of pool volume sampled was small relative to the other sites (see Figure 2.3). These large pools remained deep (> 5 ft) throughout the study period. The pools above and below culvert 91077 (Elk Creek) were at times deep, but we were able to sample most of their water volume on most occasions, as well as a length of channel above and below the culvert (see Figure 2.5). Small pool size and narrow channels in Split Rock Tributary led to our highest percentage of water volume sampled and our highest numbers and rates of recapture.

Control reaches in Split Rock Tributary and Elk Creek yielded much higher recapture numbers and rates than the Poplar Creek control reach. We attribute that result to differences in habitat variety. The upstream and downstream sampling zones in the Poplar Creek control reach showed by far the least amount of habitat variation of the three sites (channelized, uniform reach; see Figure 2.3). Lower habitat variety may have led to higher emigration rates from the sample reach, which may have contributed to lower recapture rates. Emigration has been identified as a potential cause of low recapture rates and, hence, of underestimating percentage movement of individuals in a population or community (Gowan et al. 1994; Lonzarich et al. 2000). However, we do not believe that undetected emigration or the known variation in our site-specific recapture rates had much impact on our POM analyses. It is true that if a fish moved beyond the limits of any study zone, its movement would not have been detected, but its absence did not differentially affect POM, which was based solely on recapture numbers not on total marked fishes. Certainly, if marked fish were less likely to be recaptured, as we have indicated may have been the case at Poplar Creek culvert (59X09), recapture rates would go down, but POM would only be impacted if we were less likely to recapture moving versus not-moving fish or vice versa. There is no reason to assume such, and POM at culvert 59X09 was statistically similar to its control reach, which in turn was the same or nearly the same as the other two control reaches in all analyses. Thus, we believe that differences in sampling efficacy and habitat variability, while evident in recapture efficiency, had negligible effect on POM and its analyses.

Our choice of a one-week recapture interval also may have influenced recapture rates. Briggs and Galarowicz (2013) experienced higher recapture rates in the fall than in the spring when sampling at two-week intervals, and suggested that fish moved less during the fall. Our preliminary sampling in the fall of 2014 with a recapture interval of 24 hours provided no documentation of fish movement at Poplar Creek culvert, but movement was detected when a one-week recapture interval was used at the Poplar Creek and Elk Creek culverts. Thus the study design for the 2015 field season was changed to a one-week recapture interval. However, fish activity increases with warmer water temperatures, and some minnow species, including Topeka Shiner, migrate to spawning areas. As already noted, marked fishes leaving the sampling zones during the one-week recapture interval would have lowered recapture rates. Our one-week recapture rates were lower in the summer than in the fall perhaps for this reason. Use of a shorter summer recapture interval may have increased our recapture rates, but its effect on POM is hard to predict because a shorter interval for movement could just as easily add to non-movers as it could to movers. So, we do not know if our recapture interval affected the magnitude of our POM results, but it seems unlikely that it would have affected the differences that we detected among POMs at the various sites.

Lastly, undetected marks and predation of moving fishes would have affected recapture and possibly POM. The blue fluorescent dye was difficult to see in darker pigmented fishes even with the Visible Implant light provided by Northwest Marine Technology. This problem may have reduced the apparent recapture rates of Green Sunfish and Creek Chub but, again, was unlikely to have affected POM. We also collected three large Northern pike within the Poplar Creek culvert in 2014. If predators congregated in the culvert, marked fish that attempted to pass through the culvert may have suffered a higher predation rate relative to non-moving fish, which would have lowered the POM. This possibility was considered a minor influence, because POM was similar between the Poplar Creek culvert and control. All of the above limitations are common in mark-recapture studies, and our recapture rates were within the range of other mark-recapture studies associated with fish passage through culverts (Vander Pluym et al. 2008; Briggs and Galarowicz, 2013).

A potentially more impactful limitation stems from the periodic blockage of the left barrel at culvert 8884 (Split Rock Tributary) during low flows. It is possible that POMs for this culvert may have been higher had the left barrel remained accessible throughout the study. Such a possibility introduces some uncertainty on how much of the reduction in POM might be attributed to the length/darkness components of this culvert. Due to the enormous resources required to adequately mark-recapture at 6 sites (culverts plus control), additional sites which may have helped to rule out other potential limitations to fish movement were not feasible in this research study. Therefore, the field study results should be interpreted in conjunction with the laboratory study described in Chapter 3.

2.5.3 Light Levels Experienced within Culverts

The goal of this study was to investigate the influence of light levels in long culverts on Topeka Shiner movement. Light within each culvert barrel, while correlated to length, is not just a function of length. Culvert orientation, culvert dimensions, culvert material, the presence of elbows or bends, and the surrounding topography and vegetation, all influence the amount of light that can reach within the barrel. This study focused on relatively large concrete box culverts, and light levels in small pipes, for example, are expected to be much less. Noontime light levels in the middle of the culvert generally fell within a range of light intensities representative of a very dark day, twilight, or even deep twilight. Light levels measured at the water surface were above the threshold light intensity of 0.1 lux for effective visual location of prey at culvert 59X09 and 91077 (Hyatt 1979). Light levels at culvert 8884 were near this threshold limit at the water surface; however, light levels are expected to decrease with water depth. The rate at which this happens depends in part on the water transparency. In culvert 91077 where water depths were low, most of the light at the water surface is expected to reach the culvert bottom. In culvert 59X09, where depths exceeded three feet, light levels are expected to be noticeably different at the culvert bottom. Light extinction rates can vary considerably in natural waters from 0.06 ft^{-1} for very clear lakes (e.g., Lake Tahoe) to 1.2 ft^{-1} for highly stained lake water with high turbidity to 3.0 ft^{-1} for river inflows under high fine sediment load (Wetzel 2001). Light extinction coefficients in Poplar Creek ranged from 0.8 to 2.2 ft^{-1} (see Table 4.2). These extinction values indicate that at one foot depth in Poplar Creek, light levels are approximately 12% to 44% of the light values at the surface. Depending on where in the water column fish swim, their experience of light could be very different. Regardless, to develop guidance for the installation of light mitigation strategies in culverts, full culvert dimensions, as well as predicted water depths, need to be incorporated. Length alone will not accurately predict light levels and may result in the over installation of light mitigation in large culverts, or under installation of light mitigation in small diameter culverts.

2.5.4 Factors Influencing Fish Movement through Culverts

Some fish (including Topeka Shiner) were found to pass through all culverts. While none of the culverts acted as a complete barrier (blocking all fish movement), the culverts at Elk Creek and Split Rock Tributary appeared to be partial barriers, with the most dramatic effect at Split Rock Tributary, the longest and darkest culvert. There was no evidence that the culvert on Poplar Creek was a barrier to fish movement as there was no significant difference in POM between the culvert and the corresponding control reach. Of the physical variables measured, only light intensity (measured at the middle of the culvert length at midday) was significantly correlated to POM (r = 0.84; P-value <0.0001). However, light was also inversely correlated to culvert length (r = -0.94; P-value <0.0001) and thus culvert length is inversely correlated to POM (r = -0.93; P-value < 0.0001). Velocity and depth were not correlated to POM (P-values = -0.2657 and 0.4863, respectively). It should be noted that while depth and velocity do not follow the same trends as fish movement amongst culverts in this study, they can be confounding factors limiting fish movement, as both velocity and depth can affect fish behavior and swimming ability. For example, culvert 91077 generally had shallower, faster flows than the other culverts and the corresponding control reach (see Figure 2.12) that may have limited fish movement. In addition to perched outlets, depth and velocity characteristics within culverts are commonly cited factors that limit fish movement (e.g. Warren and Pardew, 1998; Wall and Berry, 2004; Briggs and Galarowicz 2013; USFS 2008). In this study, which focused only on low slope large box culverts, depth and velocity were not expected to be limiting. Other research suggested, that when properly designed, box culverts create minimal barriers to prairie stream fish movement when compared to other crossing types (Bouska and Paukert, 2009, Warren and Pardew 1998). More narrow structures (pipe culverts) increase velocity and reduce fish movement (Briggs and Galarowicz 2013), and could possibly reduce light levels further.

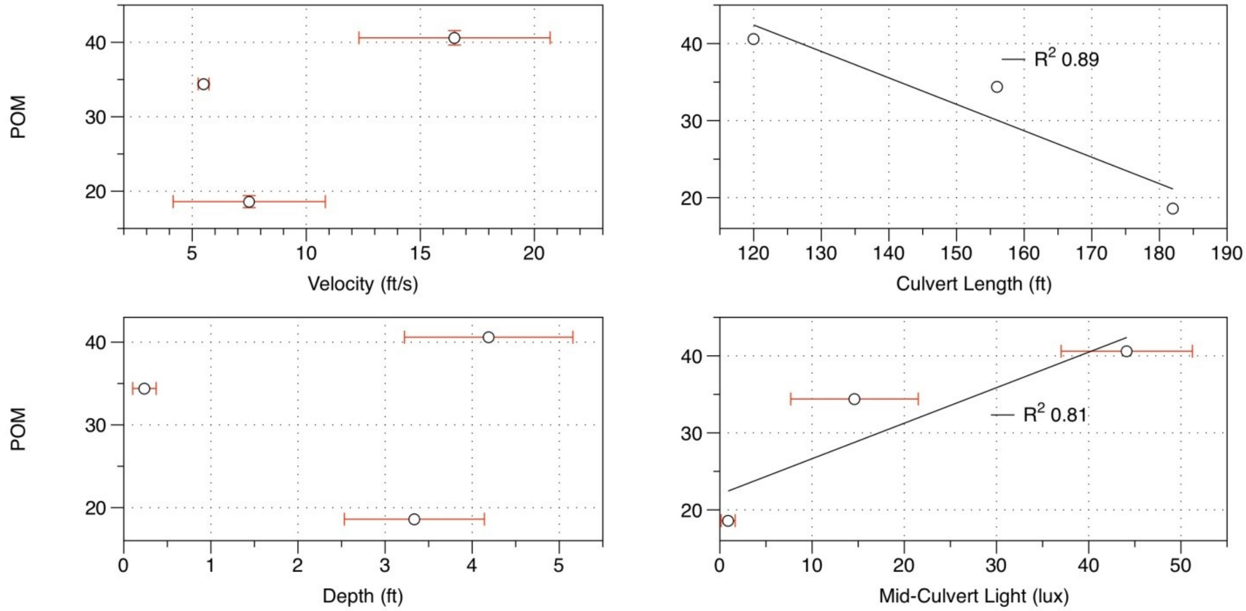

Figure 2.21 Relationships between Probability of Movement (POM) and the measured velocity, depth, light at the midpoint of the culvert (midday), and culvert length. Only light and culvert length were significantly correlated to POM (α = 0.05).

The results of the fish mark-recapture study are suggestive that light levels in a culvert barrel may be an issue for fish passage, but with this limited field study other confounding variables cannot be fully excluded. Crossing length has been identified in other studies as a factor associated with reduced fish movement (Bouska and Paukert, 2009; Briggs and Galarowicz, 2013), but the reasons for this reduction are unclear. It is possible that certain species may view the long dark tunnel as unsafe to traverse, or they may be unaware that there is habitat beyond the structure due to limited perceptual range, or the lack of cover within the culvert may cause avoidance in small fish species. To control for potential confounding variables (length, velocity, and depth), laboratory experiments described in Chapter 3 were used to investigate fish preference for movement through shaded and unshaded passageways.

CHAPTER 3: LIGHT AND FISH PASSAGE EXPERIMENTS

Flume experiments were utilized to quantify fish preferences for shaded or unshaded passageways while holding other variables that could limit fish movement (length, depth, velocity) constant. Due to the large effort required to calculate POM through culverts in the field, conducting fish mark-recapture through more than three culverts was unfeasible in the project timeframe; therefore, despite efforts to select culverts with similar habitat, confounding variables (other than light) could not be eliminated. The flume experiments detailed in this chapter provided insight into Topeka Shiner and Fathead Minnow preference for movement through shaded or unshaded passageways.

3.1 METHODS

A series of flume experiments were conducted from June 7 to June 29, 2016 at the University of Minnesota's St. Anthony Falls Laboratory (SAFL) to examine the impact of light levels on fish movement. These experiments were used to quantify the movement of fish through shaded and unshaded passageways. In each experiment, fish were offered two passageways of similar or different light levels and allowed to swim freely for one hour. Two fish species were used in experiments: Fathead Minnow (*Pimephales promelas*) from Rice Creek near New Brighton, MN, and Topeka Shiner (*Notropis topeka*) from a nonessential, experimental population propagated at the Neosho National Fish Hatchery in Missouri (Federal Fish and Wildlife permit TE60133B-0).

3.1.1 Experimental Setup

The research flume was 5 ft wide by 25 ft long and was supplied with water from the Mississippi River (Figure 3.1). The flume test section (20 ft) was divided into two separate passageways. For each experiment, each passageway was assigned a shade treatment using no shade (0%), shade cloth (70% and 80%), or a light impermeable foam cover (100%). The experiments consisted of three shade-level tests (70%, 80%, and 100%) and two types of control tests to determine left/right passageway bias (0% shade or 100% shade in both passageways). Three trials were conducted for each shade-level test, and four trials were conducted for each control test. In the shade-level tests, shading randomly assigned to one of the passageways was achieved by covering the test section approximately one ft above the water level. The unassigned passageway remained uncovered, except in the 100/100 control test; both passageways remained uncovered in the 0/0 test.

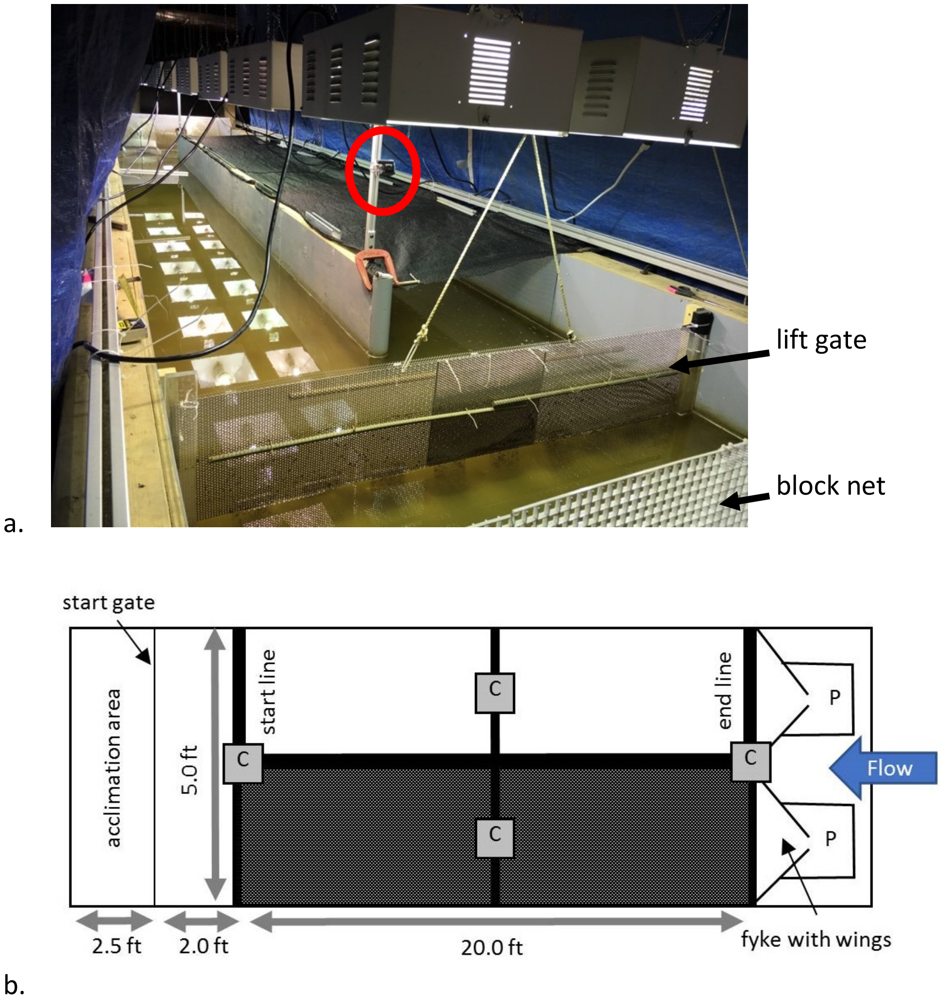

Figure 3.1 Experimental setup to evaluate behavioral choices between shaded and unshaded passageways, St. Anthony Falls Laboratory: (a) actual experimental setup with metal halide lights, lift gate, block net, 80% shade cloth and 6 in water depth, downstream camera in red circle, (b). design schematic, C=camera, P=capture pen. Shade side was randomized for each trial.

The fish acclimated downstream of a lift gate. A block gate was placed at the most downstream point in the flume to prevent fish from leaving the experimental area. A slotted gate attempted to dissuade schooling effects and was placed just upstream of the lift gate (Figure 3.1). Beyond the gate, fish were allowed to freely swim about and into either passageway. The flume was divided into two passageways that ended in separate winged slit fykes that led to capture pens. All ambient light was blocked from the experimental area and light levels were controlled using metal halide (400 W Type M59, published color temperature 4000K) lights. Lights were hung approximately 1.6 ft above the entire length of the flume to maximize the light levels (lux) but high enough to prevent overheating the water.

Water depth, velocity, and turbidity were measured at the beginning and end of each day’s experimental runs. Water depth and velocity were adjusted when necessary (6 in and 2 in/s). Velocity was measured using an acoustic Doppler velocimeter (ADV; Sontek Flowtracker). Turbidity was monitored using a turbidimeter (HACH Model 2100N) and remained low ranging from 7.2 to 17.4 ntu over the course of all experiments. Water temperature ranged from 68° F to 79° F.

Longitudinal profiles of light levels were measured at the water surface for each experimental setup using a handheld digital photometer (Extech Model EA30). Longitudinal profiles of each passageway under varying shade levels were conducted prior to and after experiments commenced.

Captive-raised Topeka Shiners and wild-caught Fathead Minnows were used to test the effect of varying shade levels on fish movement. Fish of similar size (1.2-2.8 in total length) were held in four 40 gallon flow-through aquaria supplied with Mississippi River water and held on a natural photo period in accordance with a protocol approved by the Institutional Animal Care and Use Committee (IACUC). Fish were fed a mixture of brine shrimp and freshwater fish flakes once a day. During experiment days, fish were only fed after the last experiment was completed. To begin an experiment, a group of ten fish of one species was placed in the acclimation area at the downstream end of the flume for ten minutes to adjust to testing conditions. After ten minutes the lift gate was pulled and fish were given one hour to swim freely. After one hour, the number of fish in each capture pen was counted, and the positions of all fish not in the pens were noted. Each fish was used in only one trial.

For each trial, fish movement was recorded using multiple video devices. For areas with sufficient lighting, GoPro video cameras were used. For low light areas, underwater ice fishing cameras outfitted with infrared LEDs were used (Aqua-Vu). A single centered GoPro camera was suspended at the downstream entrance and at the upstream exit of the passageways (Figure 3.1). Cameras were also placed at the midpoint of each passageway (10 ft upstream from start line). GoPro cameras were suspended under the 0%, 70%, and 80% shade cloth above the water surface, while two Aqua-Vu cameras were used underwater in the passageway covered with 100% shade cloth. Camera placement with the Aqua-Vu cameras was randomized for sides during the 100/100 condition trials since only two cameras were available and both were necessary for maximum exposure.

3.1.2 Statistical Analysis

To determine if light influenced upstream fish movement data analysis focused on the follow questions.

1. How did shading affect fish that crossed the start line in any passageway?
2. How did shading affect fish that crossed the end line in any passageway?
3. Was there a time difference to cross each of these lines under the various shade conditions?

Recorded video revealed that fish moved in and out of the capture pens and up and down the passageways; therefore counts of fish within the capture pen after one hour were not a reflection of the true choices fish made. Fish also crossed the starting and ending lines numerous times (sometimes hovering right at the lines, crossing several times in a matter of seconds), so the total number of crossings was not an accurate counting method either. Consequently, fish movement was assessed by the maximum aggregate number fish (MAN), which is the largest number of fish present at one time above the start or the end line of a passageway. For example, if two fish swam upstream over the end line, one swam back downstream, four swam upstream over the end line later, and three swam back downstream, then the end line MAN would be five. MANs for crossing the start and end lines were used for statistical analysis to test for preference of shaded or unshaded passageways. To assess any delay in crossing into or out of shaded areas, the time of the first fish crossing at the start line and at the end line were assessed.

Before looking for differences between shaded and unshaded passageway choices, MANs for the two different control experiments (0 and 100) was analyzed to asses if there was a passageway side bias (R Version 3.2.2). A right-side bias was detected and was accounted for in further analyses as a factor in the regression equation (Shade.Side factor shown below).

The probability of selecting a shaded passageway under each shade condition was evaluated using MAN crossings. The MAN crossings per shade level condition were assessed using logistic regression (Bates 2015) with the predictors: shade level (70, 80, 100), shade side (left or right), condition (shaded or unshaded) and species (Topeka Shiner or Fathead Minnow) (Fox and Weisberg 2011). The MAN was assessed separately at the start and end line for each species. The general model using Wilkinson-Rogers notation (Wilkinson and Rogers, 1973) was $\text{logit}(x) = \beta_0 + \text{Shade.Level} + \text{Shade.Side} + \text{Condition}$, where β_0 is the constant.

The first fish time of crossing for each trial was evaluated between unshaded and shaded passageways with a mixed-effects model using lme4. The same model was used to evaluate the fish first to cross the end line in each passageway (Bates et al. 2015). If no fish crossed a start or end line for any shade level, 3600 seconds (maximum length of time during any experiment) was assigned to that particular group. Shade level times (70, 80, and 100) at a particular crossing line were lumped into a single group due to low sample numbers and were compared to their unshaded counterparts. The general model, using Wilkinson-Rogers notation, for this analysis was $Y = (1/\text{Time}) + \text{Experiment} + \text{Shade.Side} + \text{Species} + \text{Condition} + (1|\text{run})$. Because time (seconds) varied across three orders of magnitude, the inverse of time (= speed) was used in the regression model. P-values were computed using Least-Squares Means: The R Package lsmeans (Lenth 2016).

3.2 LIGHT LEVELS

Light levels during the unobstructed control experiment (0/0) averaged 12,592 lux within the middle of the passageway (Figure 3.2). Light levels with 70% shade cloth averaged 3,083 lux within the middle of the covered passageway. This resulted in a 14.9% reduction in light at the darkest point (log scale). Light levels with 80% shade cloth averaged 1,967 lux within the middle of the covered passageway. This resulted in a 19.7% reduction in light at the darkest point (log scale). Light levels with 100% cover averaged 2.3 lux within the middle of the covered passageway. This resulted in a 91.2% reduction in light at the darkest point (log scale), which was similar to the reduction experienced at the longest and darkest culvert (Split Rock Tributary-99.2%) in the field study.

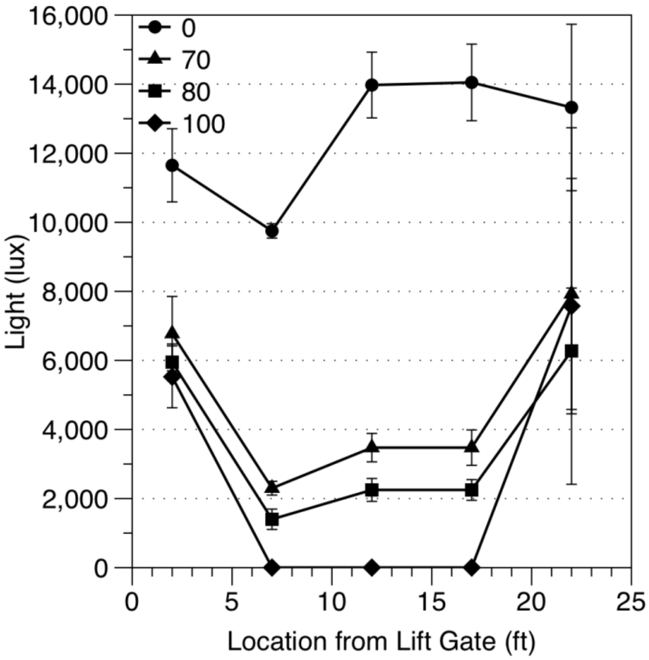

Figure 3.2 Average light levels (± SE) recorded within the flume under the four shade conditions. Readings were taken just under the shade overhang at both entrance and exit of each passageway. Shade started 2 ft from release gate and continued for 20 ft upstream.

3.3 FISH MOVEMENT

3.3.1 Maximum Aggregate Number

We analyzed the probability of selecting the shaded passageway using MAN of the end line for both species. Only the MANs for Topeka Shiner were analyzed at the start line because the downstream camera failed to log the entire-hour-long trial for five out of nine Fathead Minnow trials.

None of the shaded passageways created a full behavioral barrier to fish movement in these experiments. Both species of fish completed the passageway ascent under each shade condition. The probabilities of selecting and completing the shaded passageway for Topeka Shiner were highest under the 70 shade cloth (86.7%) and decreased with more shade (80=75.0% and 100=45.9%), but there were no significant differences among any combination of the conditions (P-value 100-70=0.1038, P-value 100-80=0.5349, and P-value 80-70=0.8390) (Figure 3.3). The null hypothesis of no difference between shaded and unshaded corresponds to the probability of 0.5 of selecting the shaded or unshaded side (dashed line in Figure 3.3). The probability for selecting the shaded side was only significantly different for the 70 shade cloth experiment for Topeka Shiner (P-value < 0.05). The probabilities for Fathead Minnow displayed a different trend. The probabilities of selecting and completing the shaded passageway for Fathead Minnow were lowest under the 70 shade cloth (45.7%) and increased with more shade (80=52.6% and 100=71.6%), but were not statistically significant among the conditions (P-value 100-70=0.3768, P-value 100-80=0.6153, and P-value 80-70=0.9474) (Figure 3.3). Also, because the probabilities' confidence intervals encompass 50% for each of the three conditions, none of the probabilities for selecting the shaded side is significantly different from the unshaded probabilities.

Both species entered the shaded passageway under each shade condition; however, only Topeka Shiner could be analyzed for the probability of crossing the shaded start line. The probabilities of Topeka Shiner selecting the shaded side were similar among all three shade conditions (70=53.8%, 80=45.4%, and 100=49.3%) (Figure 3.3) and were not statistically different (P-value 100-70=0.9017, P-value 100-80=0.9492, and P-value 80-70=0.7401). The probabilities' confidence intervals encompass 50% for each of the three conditions, so the probability of selecting the shaded side was indistinguishable from selecting the unshaded side.

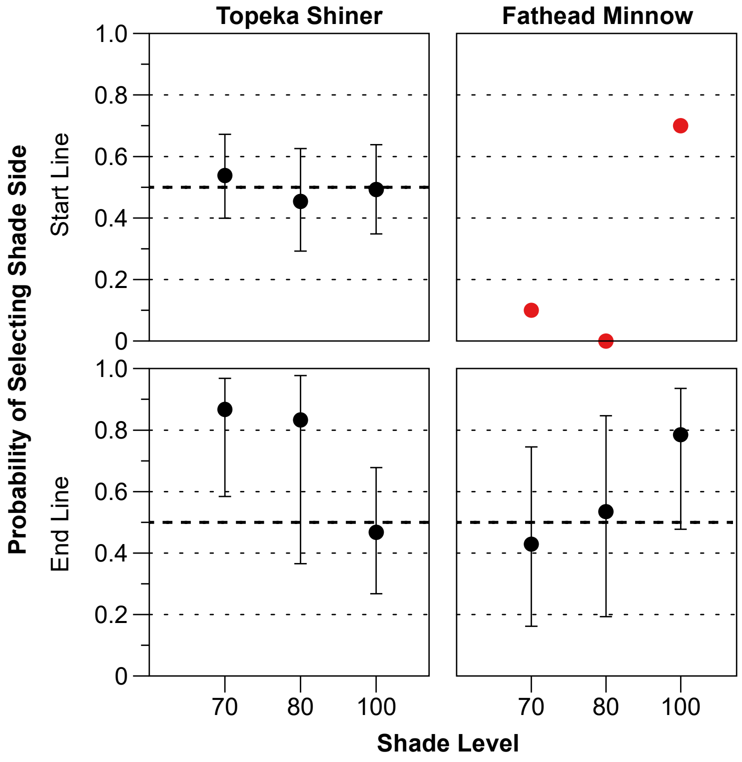

Figure 3.3 Probability of Topeka Shiner (left) and Fathead Minnow (right) selecting the shaded passageway by crossing the start line of the passageway (top) (± 2 SE) and crossing the end line of the passageway (bottom) (± 2 SE) for the three shade levels. Dotted line signifies 50% probability = no significantly different probabilities, except for Topeka Shiner at shade level 70. Cameras failed to log the entire hour on multiple trials at the start line for Fathead Minnow; therefore, the red circles illustrate only four trials where cameras did not fail (one 70 shade, one 80 shade, and two 100 shade).

3.3.2 Time to First Crossing

The speeds (inverse of time) of first crossing at the start line for Topeka Shiner were slower on the unshaded sides in comparison to the shaded sides but were not significantly different (Figure 3.4) (P-value=0.5922). The speeds of first crossing at the start line for Fathead Minnow were very similar between the unshaded and shaded sides and not significantly different (P-value=0.9632).

The speeds of first crossing at the end line for Topeka Shiner were again slower on the unshaded sides in comparison to the shaded sides but were not significantly different (Figure 3.4) (P-value=0.1300). The speeds of first crossing for Fathead Minnow at the end line were faster on the unshaded sides in comparison to the shaded sides but again were not significantly different (Figure 4) (P-value=0.1536).

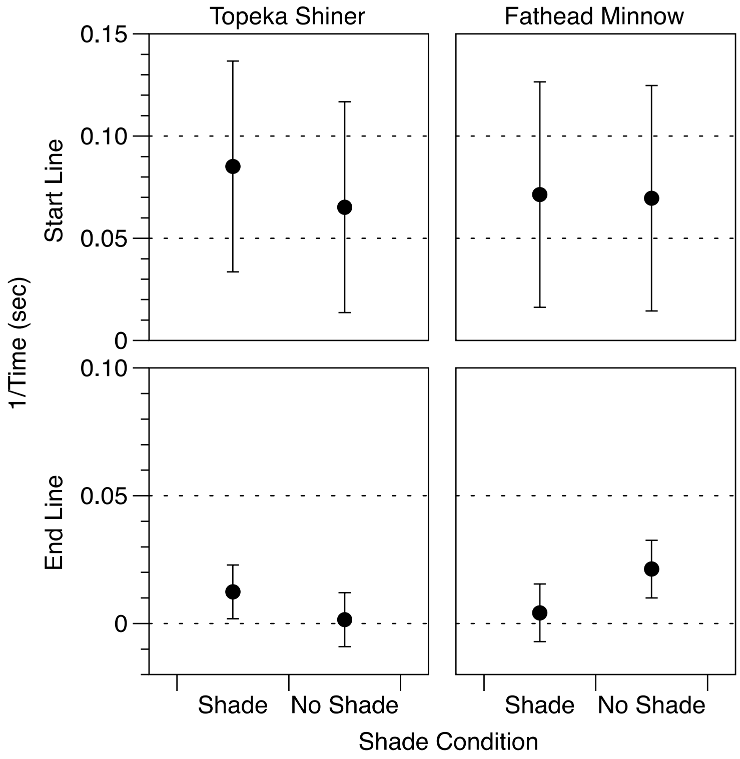

Figure 3.4 Speed of Topeka Shiner (left) and Fathead Minnow (right) crossing the start line of each passageway (top) (± 2 SE) and crossing the end line of each passageway (bottom) (± 2 SE) under the two shade conditions.

3.4 FISH PASSAGE

In these experiments, we created shaded passageways with light levels similar to conditions within culverts located in designated critical habitat of the Topeka Shiner measured in our field studies. Light levels experienced under the shaded passageway compared to natural light levels experienced at deep twilight (The Engineering Toolbox 2016). The ambient light levels, however, were not as bright as the average levels experienced during the field study, but were still within the range experienced at each field site. As a result, light reductions were relatively small in the lab in comparison to the field. The findings indicate reduced light levels did not dissuade either fish species from ascending a passageway, based on the conditions used in this laboratory setting. In fact, Topeka Shiner showed a slight preference for the 70 shade condition (P-value< 0.05). While Topeka Shiner showed no statistical preference for or avoidance of the other shade levels, the probability of selecting the shaded passageway decreased with increasing shade level. The opposite trend was demonstrated with Fathead Minnow, but none of the probability comparisons was significant. The results from the time of first crossing also demonstrated no behavioral delays for fish passage based on light levels. Neither Topeka Shiner nor Fathead Minnow showed any significant time difference when choosing to cross the start line at the unshaded versus the shaded passageway. The same outcome was obtained when choosing to cross the end line.

3.5 SUMMARY AND CONCLUSIONS

3.5.1 Fish Movement through Shaded and Unshaded Passageways

The objective of this study was to assess the behavioral swimming responses of two small warm-water stream species through experimental fish passageways under different shading conditions. The goal was to determine if shading could adversely affect fish movement when other variables were controlled. Under the conditions of our experiment, we were unable to demonstrate that shading could deter fish from ascending a passageway. In these experiments, shading levels did not dissuade either fish species from ascending a passageway. In fact, Topeka Shiner indicated a slight preference for the 70 shade condition. Although there was no statistical preference for or avoidance of the other shade levels by Topeka Shiner, the probability of selecting a shaded passageway decreased with increasing shade level. The opposite trend was demonstrated with Fathead Minnow, but these probabilities were not significant. There also were no demonstrable behavioral delays when comparing passage time between shaded and unshaded passageways.

3.5.2 Limitations

In this laboratory study, Fathead Minnows showed no preferential difference in selecting shaded or unshaded passageways. Topeka Shiners showed a slight difference in selection at the 70 shade condition, but only at the end line, and all other shade conditions were insignificant. Neither species showed any behavioral delays in the time of selection. This outcome casts doubt on reduced lighting being the sole factor associated with reduced movement in the progressively longer and darker culverts. Future research should expand upon this project with other potential culvert barriers (length of passage and substrate) and other species of fish while exploring if there is a synergistic relationship with light levels. When interpreting these laboratory results, the following limitations should be noted:

- This study only examined the effect of light levels on two small minnow species similar in size that demonstrate comparable feeding and swimming behaviors. So, the results may not apply to other small stream fish species or even to other size ranges within the species we tested.
- We did not tag fish in this study because tagging could have added a stressor that may have influenced their behavior. Thus, we were unable to track the movements of each individual fish. Consequently, we cannot determine if a fish that crossed a given passage's start line also

crossed its end line, or a single fish ascended both passageways, or if a single fish ascended the same passageway multiple times. From video analysis of one trial, we detected a group of nine fish that swam up one passageway, a group of nine fish that later passed back down the same passageway, and finally a group of nine fish that swam up the other passageway. Because the fish were not marked, we cannot assume that the group of nine consisted of the same fish throughout all videos. Thus, results had to be assessed via MAN and not by individual fish.

- Both Topeka Shiner and Fathead Minnow demonstrated schooling during the acclimation period and after the start gate was raised. Thus, ascents on either side of the flume likely did not represent ten individual decisions. This is a behavior that fish demonstrate in the wild, so was deemed acceptable in this experiment. Experiments consisting of one fish may have allowed for individual analysis (more individual times to first crossings), however, experiments allowing one fish within the flume at a time were not feasible under our constraints (time flume was available), nor would they reflect the behavior of either species *in situ*. Topeka Shiners and many other species of minnows (Cyprinidae) are known to swim in conspecific schools of various sizes (Hubbs and Cooper 1936; Becker 1983; Pflieger 1997; Kerns and Bonneau 2002). Topeka Shiners, at least at times, would approach culverts in schools in natural settings.
- Each trial lasted an hour unless all ten fish were found upstream earlier. Ambient noise was avoided by preventing any foot traffic near the flume. Trials were conducted from 12:00 p.m. until 7 p.m. due to lab activity restrictions and to simulate daytime movement. As a result, the study was limited in the number of trials that could be conducted daily and the overall number of trials. More trials would have allowed for more time to first crossing results. Additionally, more trials may have demonstrated a higher significance for MAN for certain categories, especially Topeka Shiner under the 70 shade condition. Because of the large variability in fish behavior in these experiments, it is possible that more trials would have produced a significant effect of shading on overall fish movement; however, it is clear that shading was not a complete behavioral barrier as fish moved through the darkest channels. A longer test culvert or a passageway without visible lighting at the other end (similar to the Split Rock Tributary culvert) may have produced different behaviors.

CHAPTER 4: SUMMARY AND RECOMMENDATIONS

Combining results of light measurements and fish passage in the field and laboratory provides insight into the need (or lack thereof) for light mitigation strategies within culverts to minimize behavioral passage barriers for Topeka Shiner and their associates.

4.1 SUMMARY FIELD AND EXPERIMENTAL RESULTS: LIGHT IN CULVERTS

Light within each culvert barrel, while correlated to length, is not just a function of length. Culvert orientation, culvert dimensions, culvert material, the presence of elbows or bends, and the surrounding topography all influence the amount of light that can reach within the barrel. This study focused on relatively large concrete box culverts, and light levels in small pipes, for example, are expected to be much less. Noontime light levels in the middle of the culvert generally fell within a range of light intensities representative of a very dark day, twilight, or even deep twilight (Figure 1). Light levels measured at the water surface were above the threshold light intensity of 0.1 lux for effective visual location of prey at culvert 59X09 (Poplar Creek) and 91077 (Elk Creek; Hyatt 1979). Light levels at culvert 8884 (Trib. Split Rock) were near this threshold limit at the water surface; however, light levels are expected to decrease with water depth. The rate at which this happens depends in part on the water transparency. In culvert 91077 where water depths were low, most of the light at the water surface was expected to reach the culvert bottom. In culvert 59X09, where depths exceeded three feet, light levels were expected to be noticeably different at the culvert bottom. Depending on where in the water column fish swim, their experience with light could be very different. Regardless, to develop guidance for the installation of light mitigation strategies in culverts, full culvert dimensions, as well as predicted water depths, need to be incorporated. Length alone will not accurately predict light levels and may result in the over installation of light mitigation in large culverts or under installation of light mitigation in small-diameter culverts.

4.1.1 Light Distribution with Culvert Barrels

To investigate the effect of culvert dimension on light levels within a culvert barrel, the daylight factor (DF) was calculated at each point within the culvert barrel where light levels were measured with a handheld light meter (Extech Model EA30). The DF is defined as the ratio between the local illumance (in lux) to the illumance outside of the structure. For each culvert, light measurements were collected at the water surface along the middle of the culvert and above the culvert at midday. Measurements were collected just under the culvert overhang, at 20 ft in from each end of the culvert, and at the midpoint. For the experimental culvert, light measurements were collected at the overhang, 5 ft from each barrel, and at the midpoint of the shaded region. The average midday DF for each location was then plotted against the length from the culvert end (Figure 4.1). This relationship generally follows an exponential function of the form:

$$DF = C\, e^{k\, L}$$

where C represents the daylight factor at the culvert entrance (intial daylight factor), k is an exponential light extinction rate specific to each culvert, and L is the distance from the end of the culvert. The light extinction rate, k, is related to the inverse of the open height (Figure 4.2). Open height is the difference between the culvert height and the water depth. This relationship is driven by the very small opening of the experimental culvert. If the experimental culvert is excluded, k is still related to the inverse of the opening height. This indicates that the light extinction rate along the culvert is primarily related to the opening size, while C is likely a factor of the location of the culvert (topographic shading), reflectivity of the water, etc. Note that culvert 91077, which had the smallest C, was oriented in a N/S direction and was located under I-90 (Table 4.1).

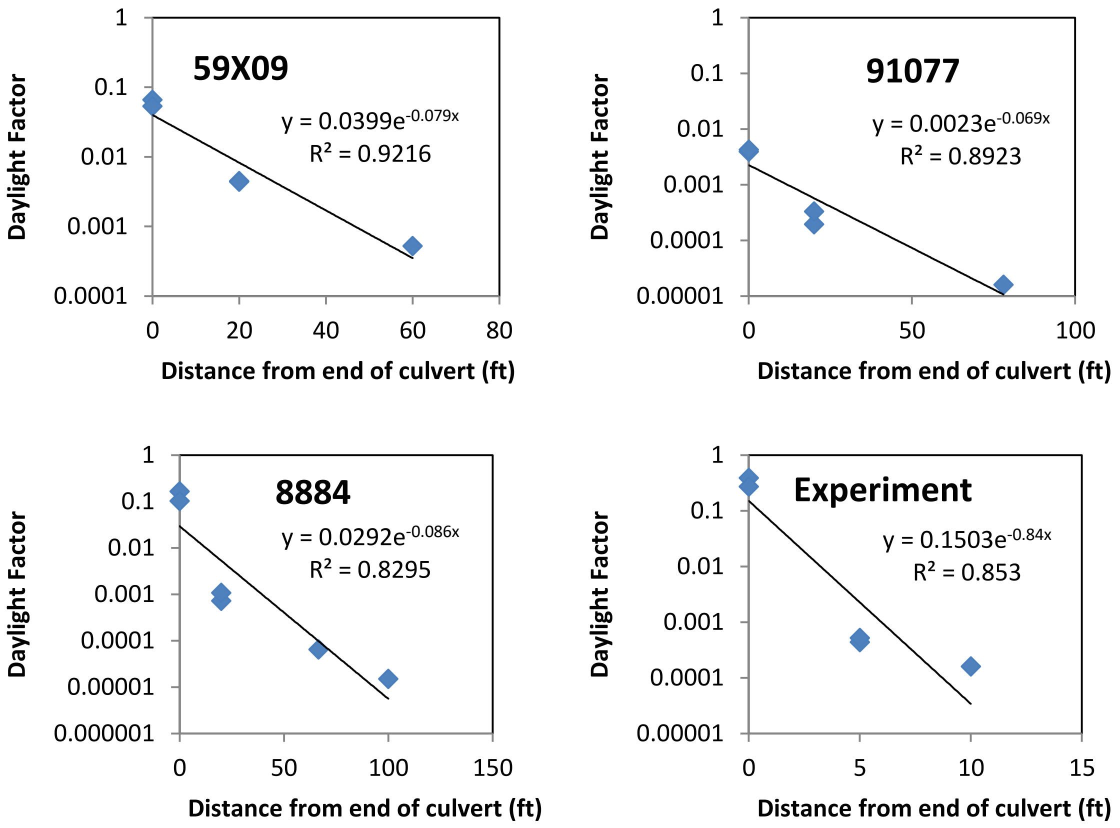

Figure 4.1 Relationship between daylight factor (DF) and distance from the end of each culvert (L).

Table 4.1 Light extinction rate (k) along the culvert, and initial daylight factor (C) for each culvert.

Culvert	k	C	Open Height (ft)	Orientation
59X09	-0.079	0.040	7.8	ENE
91077	-0.069	0.002	9.5	N
8884	-0.086	0.029	4.7	WNW
Experiment	-0.840	0.1503	1.5	

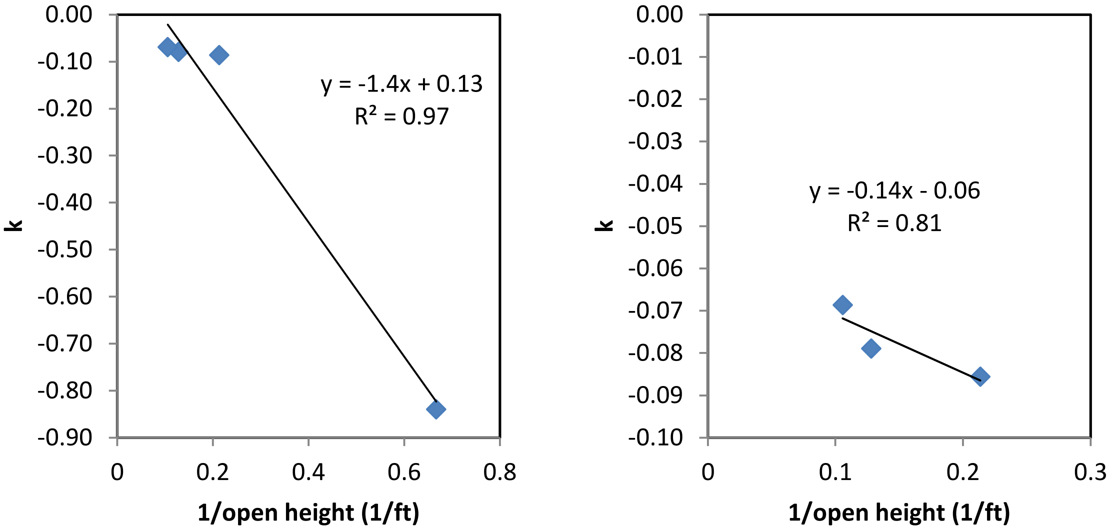

Figure 4.2 Relationships of light extinction (k) to the inverse of the culvert opening height. left: including experimental culvert; right: excluding experimental culvert.

The above relationships represent the relative light levels (DF) at the water surface. Light levels also decay with water depth:

$$I_z = I_o e^{-\eta z}$$

where I_z is the light intensity at depth z; I_o is the light intensity at the water surface; and η is the light extinction coefficient. Note that this is an approximation and that light extinction depends on light wavelenth. Light extinction rates can vary considerably in natural waters from 0.06 ft^{-1} for very clear lakes (e.g., Lake Tahoe) to 1.2 ft^{-1} for highly stained lake water with high turbidity to 3.0 ft^{-1} for river inflows under high fine sediment load (Wetzel 2001). Light extinction coefficients were calculated using vertical light level profiles collected with light loggers (Onset UA-002-08). These loggers measure a slightly different wavelength profile than the handheld logger, which measures visible light, but they are capable of submergence and thus provide an approximation of light extinction coefficients. Figure 4.3 shows an example of light extinction profiles with depth collected in Poplar Creek. The light extinction coefficients in Poplar Creek ranged from 0.8 to 2.2 ft^{-1} (Table 4.2). These extinction values indicate that at one-foot depth in Poplar Creek, light levels were approximately 12% to 44% of the light values at the surface (Table 4.2). In general, light extinction coefficients trend inversely with transparency, but it is not a significant relationship indicating that other factors such as water chemistry may play a role.

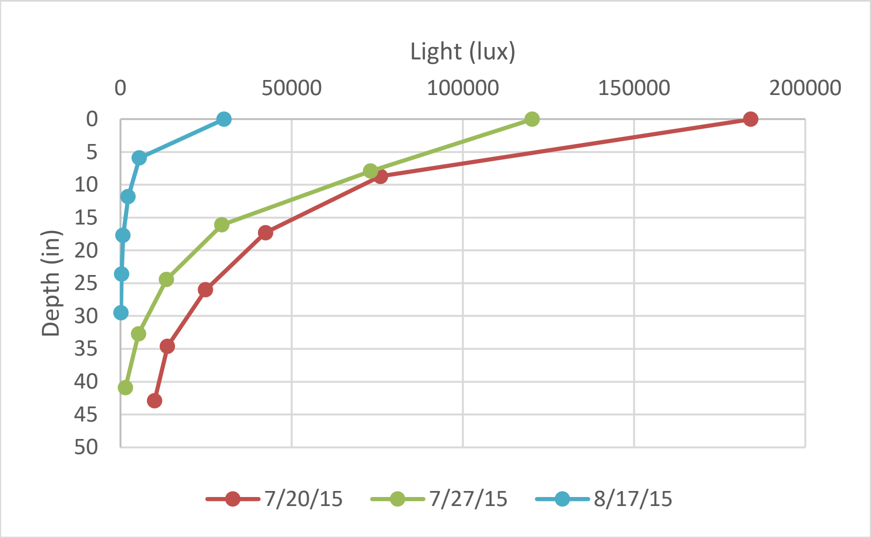

Figure 4.3 Example light extinctions measured on three dates with logger pendants near culvert 59X09.

Table 4.2 Transparency, light extinction coefficients (η), the percentage of surface light calculated to reach 1 ft depth (% I_o), and the depth at which light reaches 10% of the surface light measured at culvert and control field sites.

Date	Stream	Site	Reach	Transparency (ft)	η (ft^{-1})	% I_o (at 1 ft)	10% surface light depth
8/11/2015	Split Rock Trib.	8884	control	0.7	2.7	7%	0.85
7/16/2015		8884	control	0.8	4.5	1%	0.51
7/15/2015		8884	culvert	1.1	2.5	8%	0.91
8/10/2015		8884	culvert	0.4	4.6	1%	0.50
8/13/2015	Elk	91077	control	0.3	2.6	7%	0.88
7/14/2015		91077	control	0.3	7.2	0%	0.32
8/12/2015		91077	culvert	0.4	3.0	5%	0.77
7/13/2015		91077	culvert	0.4	3.5	3%	0.65
8/25/2015	Poplar	59X09	control	2.1	0.9	41%	2.55
7/28/2015		59X09	control	0.7	1.7	18%	1.36
7/21/2015		59X09	control	0.8	1.9	14%	1.19
7/20/2015		59X09	culvert	2.1	0.8	44%	2.77
7/27/2015		59X09	culvert	1.5	1.3	28%	1.81
8/17/2016		59X09	culvert	0.4	2.2	12%	1.07

Combined, these relationships can provide an estimate of light profiles through a culvert and light profiles with water depth. Generally, the extinction of the DF along a culvert barrel is related to the culvert opening (culvert height – water depth), but to use these relationships to model light in culverts, many more measurements need to be collected to refine and validate across a range of culvert geometries. Similarly, light extinction with depth provides an estimate of how much of the light at the water surface may reach different depths, but these relationships are dependent on water conditions (transparency and water chemistry) as well as water surface conditions, and light angle. These variables can change daily or seasonally depending on weather hydrologic conditions, or water chemistry.

4.2 SUMMARY FIELD AND EXPERIMENTAL RESULTS: FISH MOVEMENT

Combining the results from the field (Chapter 2) and fish passage experiments (Chapter 3), light levels in large box culverts cannot be identified as a potential barrier to the fish communities present in southwestern Minnesota. An extensive fish passage study in three streams (Poplar Creek, Elk Creek, and Split Rock Creek Tributary) found no difference in the probability of fish movement in Poplar Creek between the culvert and a control reach. In Elk Creek, there was a small, but significant difference in the probability of movement between the culvert and the control, and the largest difference was seen in the longest/darkest culvert on Split Rock Tributary (Figure 2.17); however, fish, including Topeka Shiners, were able to pass through all three culverts. These results indicate that culverts on Elk Creek and Split Rock Tributary create partial barriers to fish movement that trend with both length and light. As longer culverts are darker, it is impossible with the field study alone to attribute differences in the probability of fish movement to light. The length of artificial habitat (concrete box culvert) with little cover and no habitat diversity compared to the stream also may inhibit fish movement.

To test fish preference for light levels independently, controlled laboratory studies were conducted with two species (Topeka Shiner and Fathead Minnow). In these experiments, we were unable to identify a preference of either species for unshaded or shaded passages (Figure 3.3). These experiments, which allowed fish to select either a shaded or unshaded channel, showed no avoidance of shaded channel regardless of shading level.

Taken together, there was discernable evidence that light levels within box culverts are a primary factor inhibiting fish movement through culverts. While the field study indicated that longer, darker culverts had a greater difference in the probability of fish movement between culverts and control reaches, the controlled laboratory experiments illustrated no avoidance of shaded areas. There are other factors including culvert length that could explain the difference in probability of movment within the longer darker culverts, but light cannot be identified as the sole limiting factor.

4.3 RECOMMENDATIONS FOR LIGHT MITIGATION IN CRITICAL TOPEKA SHINER HABITAT

Light levels experienced by fish swimming in culverts are a not a function of length alone, but also of culvert orientation, culvert dimensions, culvert material, the presence of elbows or bends, and the surrounding topography and vegetation, in addition to water clarity. Because this study was focused on box culverts (> 8 ft x 8 ft), light levels within the culvert barrel were much greater than would be expected on similar length small (< 3 ft) pipe culverts. Based on the field and laboratory studies, light could not be identified as a barrier to fish movement for the fish communities present in southwestern Minnesota including for the federally endangered Topeka Shiner. Therefore, the research team cannot recommend light mitigation efforts to be installed in large box culverts in this area. It should be noted that this recommendation may not apply to culverts that are particularly dark due to elbows or bends, or small culvert opening dimensions. In addition it should be noted that there may be partial barriers other than light levels in some long box culverts. The results of this study only apply to low gradient streams in southwestern Minnesota and should not be applied for other fish communities that may be more sensitive to light levels within culverts.

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APPENDIX A

SUMMARY FISH MARK-RECAPTURE DATA

A.1 Species list with biotic code for fish caught in May through August 2015 at all sites.

Bigmouth Shiner	BMS
Blackside Darter	BSD
Bluntnose Minnow	BNM
Brassy Minnow	BRM
Common Carp	CAP
Common Shiner	CSH
Creek Chub	CRC
Fathead Minnow	FHM
Green Sunfish	GSF
Iowa Darter	IOD
Johnny Darter	JND
Largemouth Bass	LMB
Northern Pike	NOP
Orangespot Sunfish	OSS
Plains Topminnow	PTM
Red Shiner	RDS
Sand Shiner	SDS
Topeka Shiner	TKS
Western Blacknose Dace	BND
Yellow Perch	YEP

A.2 Number, length, and date of fish marked at Poplar Creek culvert May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Poplar Creek culvert-Marked							
	5/20-5/21/15		5/27/15		7/20/15		7/27/15	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	25	56 (11)	6	50 (10)	18	56 (7)	20	59 (4)
BSD							1	72 (-)
BNM	14	41 (10)	54	42 (16)	83	58 (9)	109	55 (9)
BRM			3	72 (2)				
CSH	92	49 (9)	12	49 (10)	28	70 (11)	76	76 (11)
CRC			2	76 (4)	3	31 (2)	6	58 (30)
FHM	776	43 (8)	99	46 (12)	367	46 (7)	313	46 (8)
GSF	20	47 (22)	35	40 (6)	54	55 (16)	43	56 (18)
IOD	3	51 (7)	20	49 (7)	3	52 (6)	4	49 (7)
JND	44	45 (6)	63	46 (6)	19	48 (10)	12	44 (11)
NOP			1	47 (-)				
OSS	64	39 (9)	33	53 (18)	119	45 (9)	98	45 (7)
PTM			69	41 (6)	8	50 (6)	1	49 (-)
RDS	5	42 (4)	1	37 (-)	8	51 (5)	15	51 (5)
SDS	56	47 (11)	111	39 (6)	313	43 (7)	244	43 (5)
TKS	**50**	**47 (9)**	**45**	**47 (7)**	**25**	**53 (5)**	**45**	**52 (12)**
Totals	**1149**	**-**	**554**	**-**	**1048**	**-**	**987**	**-**

A.3 Number, length, and direction of movement for recaptured fish at Poplar Creek culvert May through August 2015. TL = mean total length in mm, SD = standard deviation.

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BNM	8	1	61 (0)	7	59 (6)	0	
CSH	4	0		2	55 (7)	2	82 (12)
FHM	19	2	47 (1)	8	44 (9)	9	52 (5)
GSF	11	2	47 (7)	5	64 (27)	4	57 (7)
IOD	1	0		0		1	55 (0)
JND	2	0		2	46 (1)	0	
OSS	29	6	55 (10)	19	52 (11)	4	46 (3)
PTM	1	0		1	50 (0)	0	
SDS	45	4	46 (5)	27	43 (3)	14	43 (4)
TKS	13	4	47 (3)	5	47 (2)	4	52 (9)

Table A.4 Number, length, and date of fish marked at Poplar Creek control May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Poplar Creek control-Marked							
	5/21/2015		**5/28/2015**		**7/21/2015**		**7/28/2015**	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	19	53 (11)	48	57 (10)	67	59 (7)	30	59 (4)
BSD					3	53 (18)		
BNM	55	49 (17)	83	45 (14)	91	48 (8)	48	50 (10)
BRM			7	77 (6)	16	78 (4)	9	75 (5)
CSH	11	78 (19)	26	84 (27)	10	84 (17)	26	82 (30)
CRC	12	94 (29)	11	89 (21)	10	101 (34)	4	121 (30)
FHM	239	43 (10)	762	46 (12)	329	47 (9)	813	47 (7)
GSF	8	43 (9)	16	50 (15)	1	84 (-)	2	86 (1)
IOD	3	50 (7)						
JND	77	49 (6)	61	50 (6)	75	48 (7)	49	44 (8)
LMB					1	35 (-)		
OSS	25	44 (10)	11	38 (7)	45	49 (12)	19	44 (6)
PTM					1	48 (-)		
RDS	2	39 (6)	3	42 (10)	15	44 (9)	10	46 (3)
SDS	42	45 (10)	109	46 (9)	161	48 (10)	70	41 (6)
TKS	**31**	**43 (9)**	**22**	**46 (4)**	**13**	**56 (10)**	**3**	**52 (4)**
BND			2	54 (6)	6	69 (6)		
Totals	**524**	**-**	**1161**	**-**	**844**	**-**	**1083**	**-**

Table A.5 **Number, length, and direction of movement for recaptured fish at Poplar Creek control May through August 2015. TL = mean total length in mm, SD = standard deviation.**

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BMS	18	5	58 (3)	9	56 (4)	4	61 (6)
BSD	1	0		0		1	73 (0)
BNM	20	4	53 (6)	10	55 (8)	6	50 (5)
CSH	3	0		2	77 (9)	1	90 (0)
CRC	3	0		1	108 (0)	2	93 (4)
FHM	132	31	51 (6)	77	49 (7)	24	51 (7)
GSF	2	1	101 (0)	0		1	85 (0)
JND	17	2	50 (1)	4	49 (4)	11	50 (5)
OSS	20	6	59 (6)	9	55 (7)	5	49 (6)
RDS	1	0		0		1	48 (0)
SDS	18	3	50 (10)	10	43 (3)	5	43 (4)
TKS	8	5	47 (2)	2	47 (0)	1	48 (0)

Table A.6 Number, length, and date of fish marked at Elk Creek culvert May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Elk Creek culvert-Marked							
	5/22/2015		**5/29-5/30/2015**		**7/6/2015**		**7/13/2015**	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	47	59 (9)	22	57 (11)	104	63 (6)	98	59 (5)
BNM	119	47 (17)	64	48 (16)	52	60 (14)	61	53 (12)
BRM	18	78 (7)	7	70 (4)	2	92 (2)	4	58 (24)
CSH	78	56 (18)	162	52 (15)	60	64 (23)	24	69 (21)
CRC	67	100 (28)	34	98 (26)	75	96 (22)	71	97 (30
FHM	161	61 (10)	124	64 (8)	144	37 (11)	23	46 (16)
GSF	1	40 (-)	2	69 (37)	3	58 (6)	1	64 (-)
JND	78	55 (7)	56	55 (6)	53	51 (9)	136	52 (10)
OSS	6	43 (22)	3	70 (29)	3	47 (4)	3	59 (12)
RDS	23	47 (13)	23	50 (12)	29	49 (11)	23	51 (9)
SDS	93	55 (12)	182	47 (13)	157	56 (10)	220	53 (10)
TKS	**19**	**41 (8)**	**8**	**57 (13)**	**21**	**49 (3)**	**21**	**52 (5)**
BND	8	64 (26)	8	51 (16)	8	65 (14)	58	56 (9)
YEP							1	90 (-)
Totals	**718**	**-**	**695**	**-**	**711**	**-**	**744**	**-**

Table A.7 **Number, length, and direction of movement for recaptured fish at Elk Creek culvert May through August 2015. TL = mean total length in mm, SD = standard deviation.**

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BMS	52	7	59 (7)	25	64 (5)	20	61 (9)
BNM	15	1	56 (0)	9	57 (17)	5	54 (13)
CSH	3	0		3	78 (28)	0	
CRC	39	12	107 (19)	20	101 (17)	7	104 (27)
FHM	16	0		11	64 (8)	5	56 (11)
JND	49	4	58 (9)	36	60 (6)	9	56 (5)
RDS	8	2	69 (10)	4	49 (4)	2	52 (7)
SDS	63	10	56 (10)	34	55 (10)	19	58 (6)
TKS	7	1	59 (0)	6	53 (7)	0	
BND	2	1	44 (0)	1	50 (0)	0	

Table A.8 Number, length, and date of fish marked at Elk Creek control May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Elk Creek control-Marked							
	5/23/2015		**5/30/2015**		**7/7-7/8/2015**		**7/14/2015**	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	217	58 (9)	200	58 (9)	133	59 (7)	223	59 (7)
BNM	79	46 (14)	72	45 (9)	97	51 (9)	71	54 (8)
BRM	2	71 (4)			1	77 (-)	9	47 (14)
CSH	35	59 (23)	23	50 (12)	33	61 (21)	23	58 (14)
CRC	40	93 (27)	19	99 (26)	26	95 (16)	30	92 (28)
FHM	49	62 (10)	78	61 (9)	38	46 (16)	99	44 (12)
IOD			1	56 (-)				
JND	123	54 (6)	55	54 (5)	70	52 (9)	95	50 (9)
OSS			1	35 (-)				
RDS	32	43 (10)	25	46 (10)	30	47 (12)	16	44 (8)
SDS	241	51 (12)	306	52 (12)	238	52 (10)	297	52 (10)
TKS	**2**	**42 (2)**	**3**	**40 (1)**	**2**	**45 (3)**		
BND	2	63 (22)	3	45 (1)	8	56 (8)	2	52 (6)
Totals	**822**	**-**	**786**	**-**	**676**	**-**	**865**	**-**

Table A.9 **Number, length, and direction of movement for recaptured fish at Elk Creek control May through August 2015. TL = mean total length in mm, SD = standard deviation.**

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BMS	140	21	58 (8)	79	60 (6)	40	60 (6)
BNM	21	5	52 (10)	14	60 (9)	2	52 (22)
CSH	2	1	53 (0)	0		1	67 (0)
CRC	26	12	103 (17)	8	112 (17)	6	111 (22)
FHM	9	1	70 (0)	8	61 (10)	0	
JND	35	7	58 (11)	18	56 (5)	10	58 (6)
RDS	6	0		1	39 (0)	5	48 (4)
SDS	134	29	57 (8)	63	56 (9)	42	54 (9)

Table A.10 Number, length, and date of fish marked at Split Rock Tributary culvert May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Split Rock Tributary culvert-Marked							
	6/9 - 6/10/2015		**6/15/2015**		**7/8/2015**		**7/15/2015**	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	1	57 (-)	1	56 (-)				
BNM	49	44 (11)	44	48 (17)	102	47 (11)	144	45 (10)
CAP	1	119(-)						
CSH							14	95 (21)
CRC	6	107 (22)	4	111 (22)	4	115 (14)	10	124 (26)
FHM	463	45 (8)	243	47 (8)	397	45 (6)	486	46 (7)
GSF	11	56 (25)	7	54 (13)	9	61 (13)	1	83 (-)
IOD	1	48 (-)	2	56 (1)	2	46 (3)	2	54 (8)
JND	131	47 (5)	117	48 (4)	89	50 (5)	199	48 (8)
OSS	18	48 (15)	27	43 (7)	9	47 (7)	16	57 (16)
RDS	1	37 (-)	4	39 (13)	9	40 (9)	20	43 (9)
SDS	42	36 (4)	40	37 (6)	71	39 (7)	137	38 (5)
TKS	**10**	**46 (3)**	**7**	**48 (6)**	**15**	**50 (5)**	**33**	**54 (4)**
Totals	**734**	**-**	**496**	**-**	**707**	**-**	**1062**	**-**

Table A.11 Number, length, and direction of movement for recaptured fish at Split Rock Tributary culvert May through August 2015. TL = mean total length in mm, SD = standard deviation.

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BNM	19	1	51 (0)	15	46 (9)	3	51 (12)
CRC	6	1	130 (0)	1	150 (0)	4	127 (20)
FHM	181	16	46 (5)	142	47 (7)	23	52 (7)
GSF	1	0		0		1	80 (0)
JND	120	2	53 (7)	106	50 (4)	12	50 (4)
OSS	5	0		5	47 (10)	0	
RDS	2	1	45 (0)	0		1	50 (0)
SDS	53	8	39 (4)	39	38 (3)	6	43 (5)
TKS	7	2	56 (0)	3	53 (1)	2	51 (4)

Table A.12 Number, length, and date of fish marked at Split Rock Tributary control May through August 2015. TL = mean total length in cm, SD = standard deviation.

	Split Rock Tributary control-Marked							
	6/10/2015		6/16/2015		7/9/2015		7/16/2015	
Species	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**	**#**	**TL (SD)**
BMS	8	52 (5)	27	54 (4)	28	55 (4)	8	58 (6)
BNM	62	46 (15)	133	45 (12)	90	43 (9)	106	45 (9)
CSH			1	96 (-)				
CRC	5	113 (23)	2	156 (9)	9	112 (19)	13	125 (18)
FHM	84	43 (8)	255	47 (9)	243	47 (8)	414	49 (7)
GSF	3	71 (26)	4	46 (7)	8	56 (21)	9	49 (4)
IOD			3	51 (3)	2	53 (1)	1	53 (-)
JND	69	48 (4)	89	50 (5)	68	50 (6)	95	50 (6)
OSS	6	45 (8)	7	41 (4)	1	55 (-)	1	62 (-)
RDS	14	38 (3)	38	40 (9)	36	41 (7)	7	44 (11)
SDS	101	35 (4)	131	37 (5)	183	38 (6)	175	38 (5)
TKS	**17**	**47 (4)**	**31**	**46 (5)**	**6**	**49 (3)**	**4**	**49 (1)**
Totals	**369**	**-**	**721**	**-**	**674**	**-**	**833**	**-**

Table A.13 Number, length, and direction of movement for recaptured fish at Split Rock Tributary control May through August 2015. TL = mean total length in mm, SD = standard deviation.

Species	# Recaptured	Downstream		No Movement		Upstream	
		# Moved	TL (SD)	#	TL (SD)	# Moved	TL (SD)
BMS	25	10	58 (4)	12	57 (6)	3	57 (3)
BNM	52	8	49 (11)	30	49 (9)	14	52 (10)
CRC	8	1	101 (0)	5	137 (20)	2	129 (18)
FHM	166	37	49 (6)	88	48 (7)	41	49 (8)
GSF	2	0		0		2	58 (14)
JND	78	11	54 (3)	42	51 (4)	25	50 (3)
OSS	1	1	53 (0)	0		0	
RDS	16	0		8	41 (6)	8	38 (5)
SDS	118	28	38 (5)	62	39 (5)	28	38 (6)
TKS	11	3	50 (4)	5	50 (4)	3	48 (1)

APPENDIX B

ADDITIONAL LIGHT MEASUREMENTS

Table B.1 Light levels (lux) and time recorded in the Poplar Creek culvert May through August 2015. R = right barrel, L = left barrel.

Poplar Creek culvert									
Date	Start Time	End Time	Barrel	Point A (lux)	Point B (lux)	Point C (lux)	Point D (lux)	Point E (lux)	Full Sun (lux)
5/20/15	10:40	11:20	R	8900	345	42	420	6700	20000
5/20/15	10:40	11:20	L	8700	480	30	125	220	32700
5/20/15	20:10	20:25	R	1700	62	10	81	800	6500
5/20/15	20:10	20:25	L	600	84	10	84	992	2900
5/27/15	9:52	10:10	R	2150	315	72	820	5200	67000
5/27/15	9:52	10:10	L	3600	340	75	550	72700	73000
5/27/15	12:14	12:25	R	3400	250	52	490	3700	100600
5/27/15	12:14	12:25	L	7040	400	44	290	7400	101300
5/27/15	19:14	19:29	R	19200	520	27	230	2350	18900
5/27/15	19:14	19:29	L	2950	450	33	110	1570	20500
7/20/15	10:12	10:22	R	1900	250	73	640	2500	76300
7/20/15	10:12	10:22	L	2500	308	69	400	83500	71100
7/20/15	12:38	12:47	R	3000	384	51	454	2900	115700
7/20/15	12:38	12:47	L	113400	452	45	211	3800	101500
7/20/15	16:33	16:43	R	48800	627	58	310	3870	50200
7/20/15	16:33	16:43	L	2470	877	66	205	1300	46900
7/27/15	9:35	9:47	R	2700	197	34	191	2820	5800
7/27/15	9:35	9:47	L	1430	103	25	191	1750	6130
7/27/15	12:25	12:39	R	2500	371	40	471	2940	99600
7/27/15	12:25	12:39	L	100700	351	49	251	4200	98800
7/27/15	18:48	19:05	R	1760	108	54	693	40600	49800
7/27/15	18:48	19:05	L	2730	599	62	192	1300	40400
8/17/2015[a]	NR	NR	R	NR	NR	NR	NR	NR	NR
8/17/2015[a]	NR	NR	L	NR	NR	NR	NR	NR	NR

NR=not recorded

[a] High water

Table B.2 Light levels (lux) and time recorded in the Poplar Creek control May through August 2015.

Poplar Creek control		
Date	**Time**	**Full Sun (lux)**
5/21/15	NR	NR
5/28/15	8:19	21600
5/28/15	8:21	25600
5/28/15	13:08	106500
5/28/15	19:01	32900
7/21/15	10:45	82700
7/21/15	12:18	106800
7/21/15	18:02	61200
7/28/15	7:54	2990
7/28/15	12:00	17420
7/28/15	17:20	68500
8/17/15	9:59	12600
8/25/15	10:49	70000
8/25/15	12:17	85500
8/25/15	18:34	29900

Table B.3 Light levels (lux) and time recorded in the Elk Creek culvert May through August 2015. R = right barrel; L = left barrel; M = middle barrel.

Elk Creek culvert

Date	Start Time	End Time	Barrel	Point A (lux)	Point B (lux)	Point C (lux)	Point D (lux)	Point E (lux)	Full Sun (lux)
5/22/15	8:56	9:32	R	6500	85	11	240	69000	75000
5/22/15	8:56	9:32	M	2000	200	21	128	2200	NR
5/22/15	8:56	9:32	L	22000	120	14	229	3100	54000
5/22/15	12:17	12:37	R	90000	430	2	130	8400	100000
5/22/15	12:17	12:37	M	6600	290	19	305	12000	NR
5/22/15	12:17	12:37	L	6500	200	14	230	65000	83000
5/22/15	19:39	19:56	R	3500	50	2	52	3500	6300
5/22/15	19:39	19:56	M	1800	5	3	120	2400	NR
5/22/15	19:39	19:56	L	2000	28	3	69	2100	4300
5/29/15	9:00	9:21	R	3740	79	3	45	2350	6850
5/29/15	9:00	9:21	M	3290	74	4	130	2470	8850
5/29/15	9:00	9:21	L	3400	80	3	42	1690	5600
5/29/15	12:41	12:58	R	1700	49	3	25	1370	NR
5/29/15	12:41	12:58	M	1710	38	12	148	1850	NR
5/29/15	12:41	12:58	L	3860	32	10	99	2260	4480
5/30/15	7:42	8:05	R	5300	187	9	112	6250	11250
5/30/15	7:42	8:05	M	1300	100	11	163	3430	19950
5/30/15	7:42	8:05	L	1930	84	8	57	4730	30260
7/6/15	13:29	13:47	R	11400	200	11	300	1000	37200
7/6/15	13:29	13:47	M	5300	190	28	800	69500	NR
7/6/15	13:29	13:47	L	10500	300	15	370	70000	57000
7/6/15	17:56	18:10	R	6200	180	9	120	4600	18900
7/6/15	17:56	18:10	M	5500	180	12	300	7400	NR
7/6/15	17:56	18:10	L	5100	160	7	210	7500	45000
7/7/15	10:19	10:33	R	8700	290	15	300	84600	NR
7/7/15	10:19	10:33	M	3550	260	25	460	4500	NR
7/7/15	10:19	10:33	L	3000	164	17	390	5500	NR
7/13/15	9:37	9:56	R	2800	146	10	141	80200	83400
7/13/15	9:37	9:56	M	1680	229	18	208	1980	62800
7/13/15	9:37	9:56	L	2100	160	14	199	2700	65800
7/13/15	12:25	12:39	R	4100	201	14	367	105000	109000
7/13/15	12:25	12:39	M	2200	139	23	469	4800	99600
7/13/15	12:25	12:39	L	2700	152	18	362	5230	96200
7/13/15	18:32	18:46	R	1600	125	9	162	1980	36970
7/13/15	18:32	18:46	M	50700	209	15	201	2800	48500
7/13/15	18:32	18:46	L	55800	190	11	131	3820	60400
8/12/15	8:43	8:56	R	52400	151	8	179	3500	44900
8/12/15	8:43	8:56	M	1590	122	16	298	2200	NR
8/12/15	8:43	8:56	L	2500	117	10	122	2170	33500
8/12/15	12:13	12:25	R	3300	153	12	276	90100	93200
8/12/15	12:13	12:25	M	2280	144	21	370	4900	NR
8/12/15	12:13	12:25	L	2600	140	17	309	5000	92300
8/12/15	18:33	18:43	R	1620	100	8	125	1940	38200
8/12/15	18:33	18:43	M	2800	249	14	138	3290	NR

8/12/15	18:33	18:43	L	4820	146	9	158	3200	44200

NR=not recorded

Table B.4 Light levels (lux) and time recorded in the Elk Creek control May through August 2015.

Elk Creek control			
Date	**Start Time**	**End Time**	**Full Sun (lux)**
5/23/15	8:42	8:42	15900
5/23/15	12:31	12:31	41700
5/23/15	17:42	17:42	20000
5/30/15	8:05	8:05	30260
5/30/15	16:20	16:20	92100
5/30/15	19:06	19:06	30500
7/8/15	7:25	7:25	24400
7/8/15	10:33	10:33	94300
7/8/15	12:23	12:23	105000
7/8/15	19:13	19:13	28700
7/14/15	8:15	8:15	41600
7/14/15	12:41	12:41	32300
7/14/15	15:12	15:12	101600
7/14/15	17:30	17:30	61500
8/13/15	8:37	8:37	18100
8/13/15	12:01	12:01	24200
8/13/15	17:00	17:00	26200

Table B.5 Light levels (lux) and time recorded in the Split Rock Tributary culvert May through August 2015. R = right barrel, L = left barrel.

Split Rock Tributary culvert									
Date	Start Time	End Time	Barrel	Point A (lux)	Point B (lux)	Point C (lux)	Point D (lux)	Point E (lux)	Full Sun (lux)
6/9/15	14:58	15:18	R	7400	84.7	1.3	6700	6700	103100
6/9/15	14:58	15:18	L	2380	38.1	1.5	85.8	3670	103900
6/9/15	19:13	19:30	R	399	6.6	0.1	450	2.5	2100
6/9/15	19:13	19:30	L	499	3.4	0.2	1.2	374	NR
6/10/15	8:18	8:45	R	4200	112.9	1.5	53.8	2680	48100
6/10/15	8:18	8:45	L	50800	82.6	0.6	81.1	2700	47400
6/15/15	12:08	12:34	R	38900	72.4	1.5	82.9	11100	54200
6/15/15	12:08	12:34	L	14500	42.6	2.1	75.3	12480	57800
6/15/15	18:22	18:40	R	2100	48.1	1.4	63.3	56700	54200
6/15/15	18:22	18:40	L	1700	26	1.1	94.2	2120	46400
6/16/15	7:51	8:15	R	3370	110.7	1.2	46.8	1500	35500
6/16/15	7:51	8:15	L	35800	50.2	1.9	62.3	1240	37300
7/8/15	12:52	13:07	R	90800	129	0.8	78	5000	100700
7/8/15	12:52	13:07	L	6600	5.8	1.8	108	5100	93800
7/8/15	17:59	18:13	R	6400	29	0.8	46	12900	29800
7/8/15	17:59	18:13	L	3000	16	1.6	181	7500	30600
7/9/15	7:42	7:59	R	3200	95	1	40	1800	26200
7/9/15	7:42	7:59	L	12600	60	0.6	56	3800	15100
7/15/15	7:52	8:14	R	6110	36.9	0.5	42.8	3400	16290
7/15/15	7:52	8:14	L	4360	21.9	0.4	49.6	4880	19800
7/15/15	12:25	12:44	R	14580	47.6	1.5	73.6	8420	32950
7/15/15	12:25	12:44	L	7450	33.8	0.6	107.7	9280	36480
7/15/15	17:02	17:21	R	5440	35.6	1.2	55.7	10200	47800
7/15/15	17:02	17:21	L	3800	28.4	1.6	97.5	7730	74900
8/10/15	9:35	10:01	R	3800	49.6	1.3	52.3	1450	67500
8/10/15	9:35	10:01	L	68800	42.1	1.6	44.1	1300	59900
8/10/15	12:31	12:46	R	95500	51.3	0.1	44.1	2710	112600
8/10/15	12:31	12:46	L	99600	39.6	0.3	56.7	3600	96800
8/10/15	17:13	17:31	R	3900	41	1.4	61.6	6300	65200
8/10/15	17:13	17:31	L	1300	21.8	0.4	78	1880	13900
NR=not recorded									

Table B.6 Light levels (lux) and time recorded in the Split Rock Tributary control May through August 2015.

Split Rock Tributary control			
Date	**Start Time**	**End Time**	**Full Sun (lux)**
6/10/15	8:18	8:18	48100
6/10/15	14:15	14:15	114400
6/10/15	19:22	19:22	7900
6/16/15	10:21	10:21	86400
6/16/15	12:13	12:13	105200
6/16/15	18:29	18:29	5200
7/9/15	10:28	10:28	78800
7/9/15	12:09	12:09	100400
7/9/15	19:28	19:28	18700
7/16/15	8:59	8:59	9400
7/16/15	12:24	12:24	27700
8/11/15	10:01	10:01	76100
8/11/15	12:11	12:11	94900
8/11/15	17:49	17:49	54300

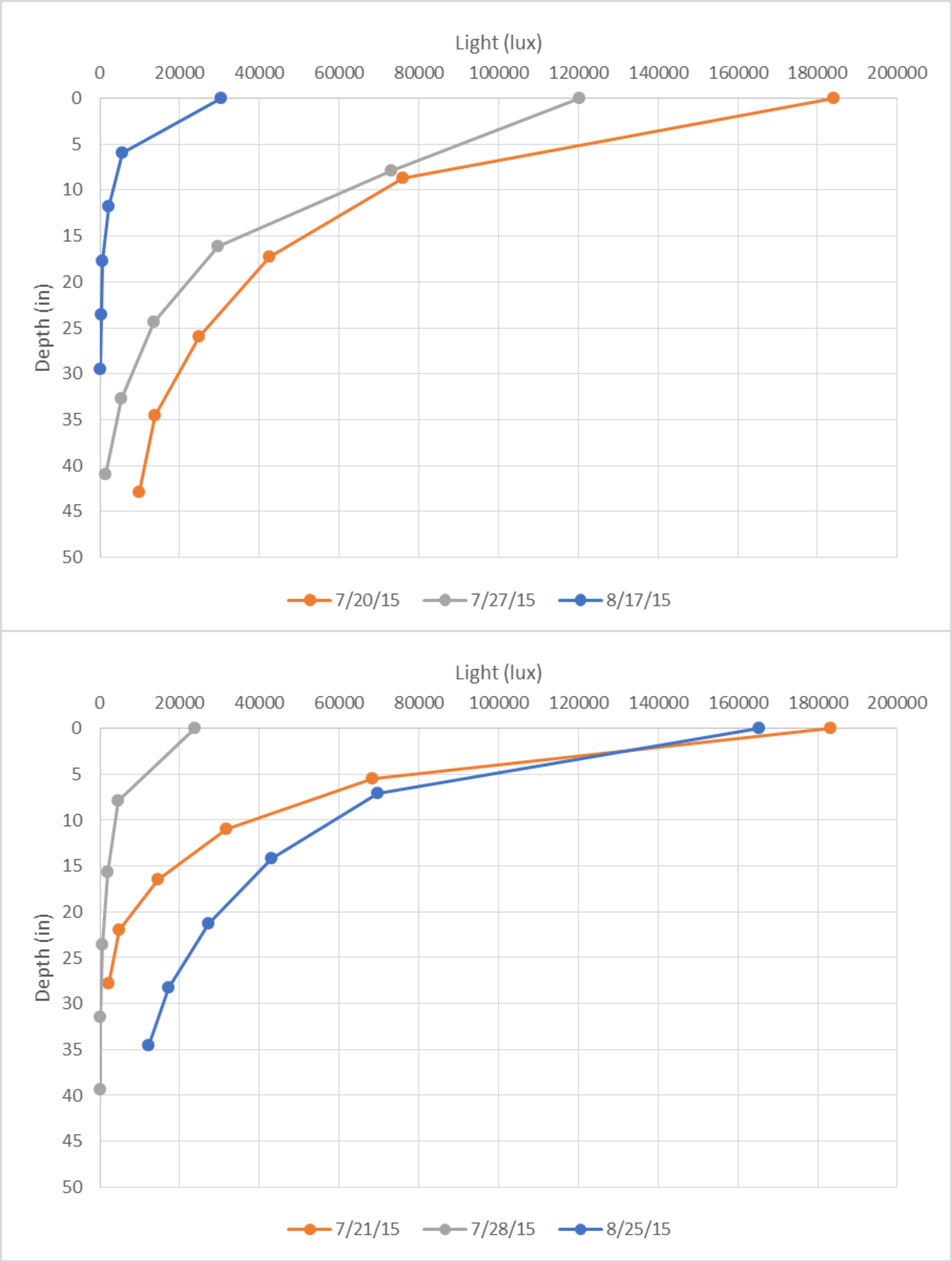

Figure B-1. Light extinction measured with logger pendants. Top: Near culvert 59X09. Bottom: Near control 59X09.

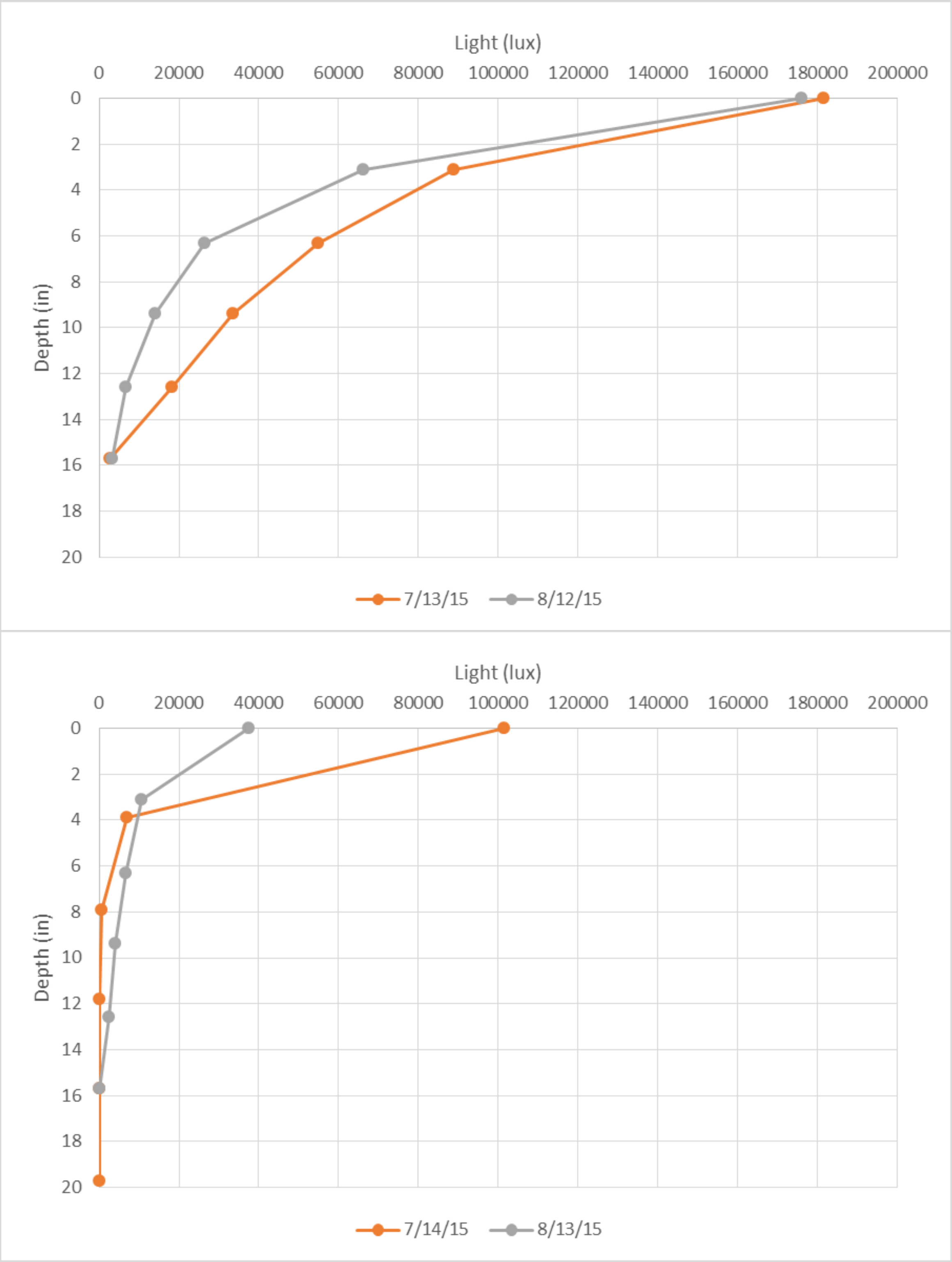

Figure B-2. Light extinction measured with logger pendants. Top: Near culvert 91077. Bottom: Near control 91077.

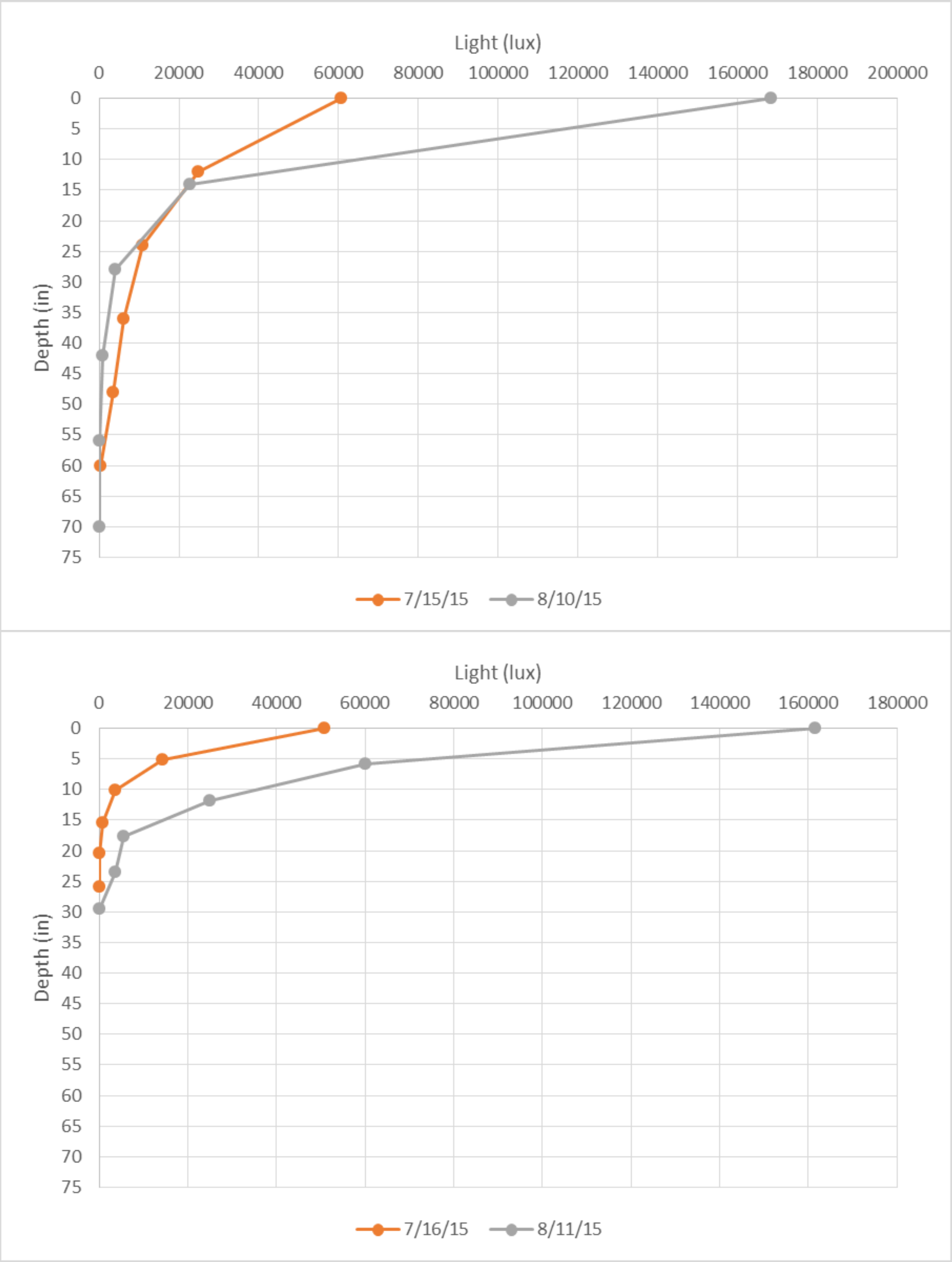

Figure B-3. Light extinction measured with logger pendants. Top: Near culvert 8884. Bottom: Near control 8884.

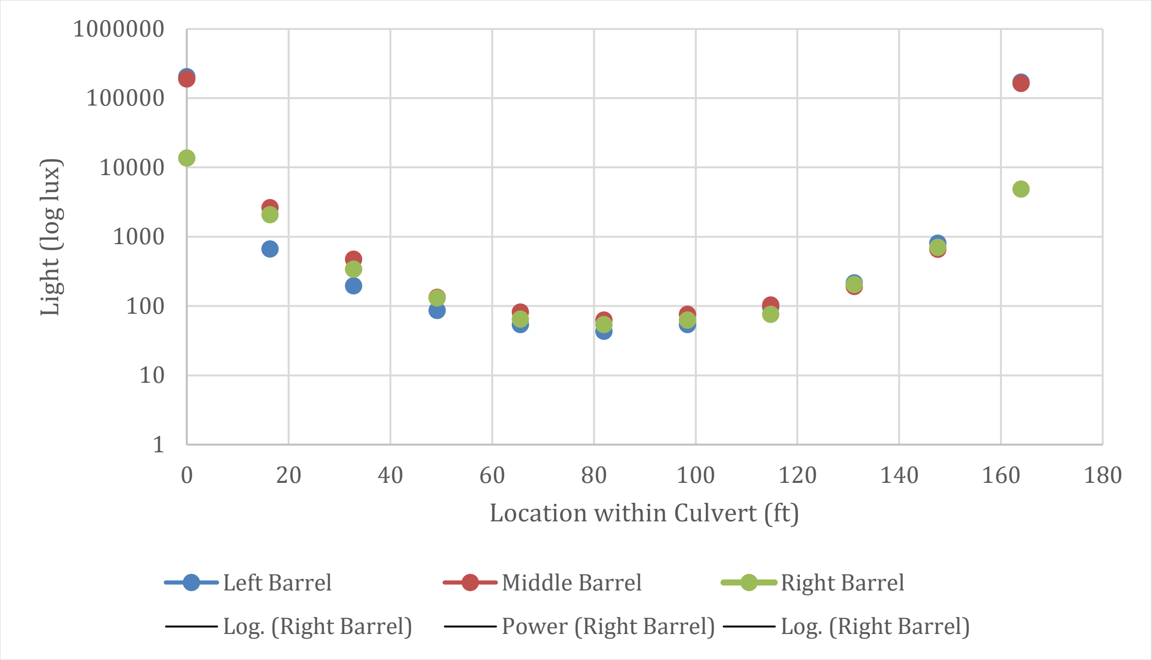

Figure B-4. Longitudinal light measured with measured with logger pendants at the water surface in each barrel of culvert 91077 on 8/12/15. Measurements started at position A or zero feet and moved downstream until point E at increments of 16.4 ft (5 m).

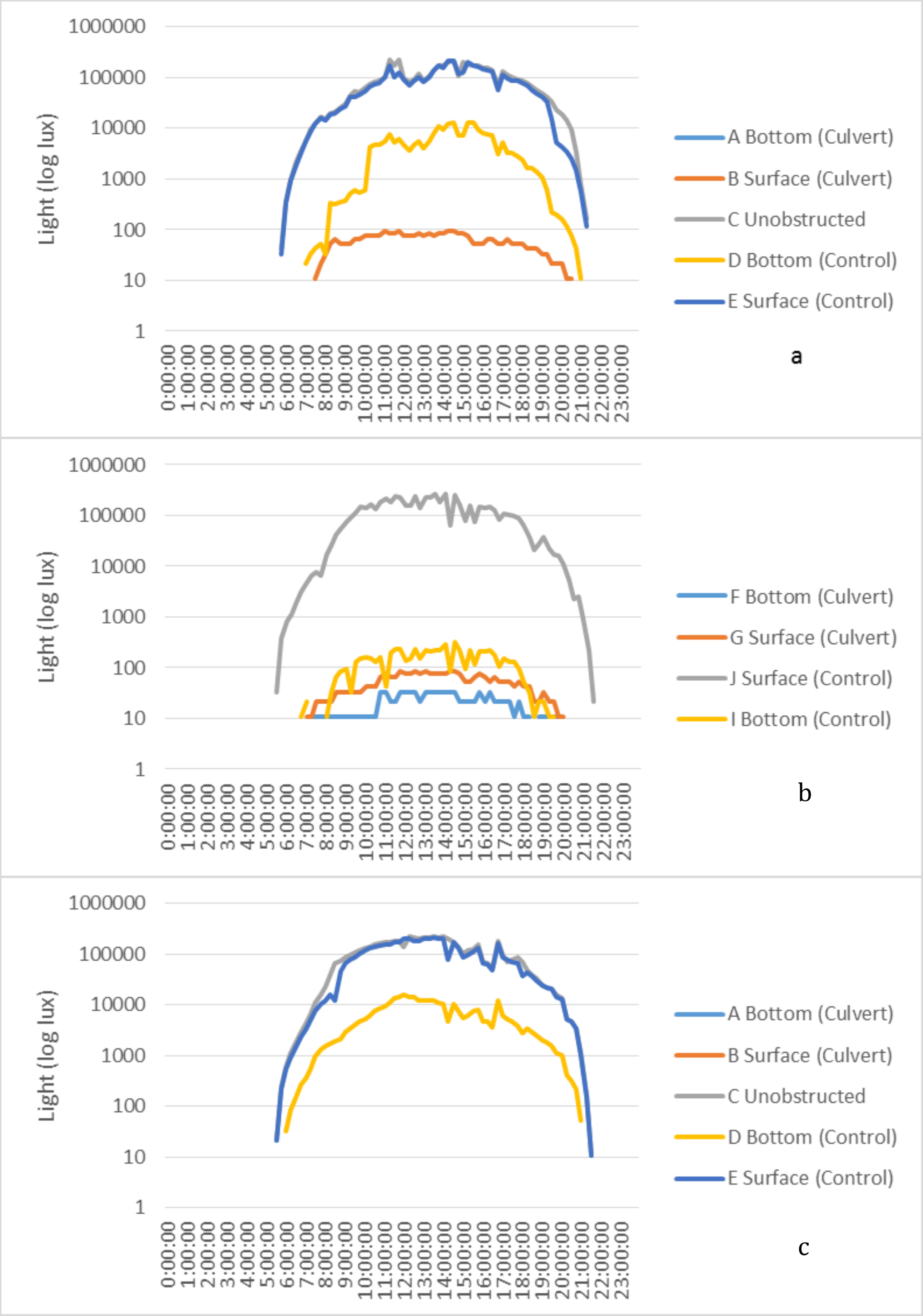

Figure B-5. Comparison of stream bed and stream surface light at midpoint in culvert and control for site a) 59X09 on 7/22/15 (sensor A measured 0 lux for the entire time period. Culvert depth: 41.9 in; control depth: 28.3 in); b) 91077 on 7/8/15 (Culvert depth: 2.4 in; control depth: not recorded.) and c) 8884 on 7/10/15 (Sensor A and B measured 0 lux for the entire time period. Culvert depth: 36.5 in.; control depth: not recorded.)