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Impacts of Culverts on the Distribution and Movement Patterns of Fish and Crayfish in Four Small Tributaries of the Little First Broad River

David Wesley Giddens
Environmental Studies: Ecology and Biology
The University of North Carolina Asheville
One University Heights
Asheville, North Carolina 28804 USA

Faculty Advisors: Dr. David Gillette and Dr. Kevin Moorhead

Abstract

Ecological connectivity is vital for the dispersal, colonization, and persistence of species within habitats. Anthropogenic disturbances to the landscape fragment connectivity, resulting in isolated populations of species. Culverted road crossings are barriers that restrict the movement of both species and resources along a stream's length. In anticipation of the future removal of culverts from four first order tributaries of the Little First Broad River, assessments were undertaken to determine the specific impacts culverts have on ecological and biological connectivity. Two sampling methods, baited crayfish traps and single-pass backpack electrofishing, were used to capture fish and crayfish species. Fish species richness was determined via a Before-After-Control-Impact (BACI) design, in which the number of species collected above the culvert at each study site was subtracted from the number below. In-stream movement of crayfish was quantified through a mark and recapture study. Recapture data was analyzed through the Passage Index (PI) equation, which calculated differences in movements between culverted and non-culverted stream sections. Under the BACI design, fish species richness above the culverts was shown to be significantly lower than below (p-value 0.002). PI values of -0.91, -0.55, and -1.0 indicated that while crayfish moved through all sections of the study streams, they were more likely to pass through non-culverted reaches than culverted ones. Comparison of the two sampling methods showed electrofishing to be a far superior estimator of crayfish population numbers than baited traps. The overall results of this study reveal that culverts are playing a role in limiting the distribution and movement of fish and crayfish populations. Limitations to dispersal threaten aquatic biodiversity by fragmenting and isolating populations. Following the future removal of the four culverts, a similar post-assessment study is scheduled. A comparative analysis of pre- and post-removal data will help fully articulate the impacts culverts have on aquatic ecosystems.

1. Introduction

Globally, two of the leading contributors to escalating declines in overall species diversity and persistence are habitat fragmentation and the spread of nonindigenous species[1]. Preserving ecological connectivity is an important tool for counteracting these declines. Defined as the potential of a landscape to support the transport of organisms and resources, ecological connectivity serves as a measure of ecosystem health and sustainability[2]. When applied to river systems, connectivity describes the capacity for the unbroken upstream-downstream movement of fishes, crustaceans, invertebrates, organic matter, and sediment[3]. Growing human populations, and the subsequent expansion of urbanization, has necessitated the large-scale implementation of supportive infrastructures. These infrastructures, of which roads are a dominant feature, threaten biotic linkages by creating barriers to movement that restrict the flow of genes and resources among populations.

Currently, streams in the United States are crossed approximately 13 million times by 6 million kilometers of roads[4]. Such crossings are accomplished through an assortment of engineered structures, including bridges, drain pipes, and culverts[5]. These anthropogenic adjustments to a stream's natural flow can serve as barriers to organismal movement, resulting in habitat fragmentation[6]. Circular culverts can have a fragmenting effect as they constrict natural flow, generate turbulence within the passageway, increase channel homogeneity, and alter streambed substrate[7].

Historically, culverts are relegated to small order streams, where the density of human traffic is low[8]. Headwater streams, which make up two-thirds of a watershed's total stream length, play a vital role in sustaining hydrologic connectivity and providing habitat for the varying life stages of aquatic organisms[9]. In a study of the impacts of road crossing designs on fish assemblages in Great Plains streams, Bouska and Paukert showed that changes in sediment accumulation and depth was greater for culverts than any other crossing design[6]. Additionally, they concluded culverts were functioning as constriction points leading to transformations in geomorphological patterns and the reduction of potential passage vectors. Similarly, Burford and McMahon, in an investigation of trout passage through culverts in a large Montana watershed during low flows, found upstream declines in fish density when either the slope of a culvert was greater than 4.5%, or the outlet drop larger than 20 centimeters[10]. While the abundance of culverts, and their subsequent stress on the movement patterns of fishes, has not yet been quantified for North Carolina, data originating from other states serves as a general reference point. In Washington and Oregon alone, there are over ten thousand culverts present in streams on federal lands. Collectively, these culverts are estimated to impede the passage of fish by 54%[10].

Compounding the threats to ecological connectivity, culverts also facilitate the spread of invasive species by creating habitat conditions that exclude the evolutionary adaptations of endemic species. Foster and Keller, in an examination of culvert flows on native and nonindigenous crayfish species, found that culverts generated flows which preferentially favored the movement of invasive crayfish species, as they tolerated higher flow velocities than endemics[1]. Another factor potentially limiting the dispersal of native crayfish through culverts is modification of the light regime[11]. Crayfish behavior is strongly correlated with habitat light intensity, and any changes to this regime may function as behavioral barriers to movement[11]. When native species are discouraged from dispersal because of barriers, vectors are opened for the spread of nonindigenous species, which tend to be generalists adapted to a wider range of habitats and conditions, including light. Consequently, culverts, whether through the drastic reinvention of habitat, or the interruption of physiological processes, serve to both power and exacerbate declines in overall indigenous biodiversity.

If stream ecosystem function and connectivity is to be preserved, resource managers must steadily shift their attention toward the removal or replacement of poorly designed and implemented stream crossings. This is of particular importance for the southeastern United States, which is home to a highly diverse collection of freshwater fishes and crayfish. Currently, there are over 662 native freshwater fishes in the southeast, with approximately 28% in need of conservation management[12]. Furthermore, the Southern Appalachian Mountains are one of two global centers of diversity for freshwater crayfish species[13].

In order to minimize the detrimental impacts of culverts on ecological connectivity and the spread of nonindigenous species, the North Carolina Wildlife Resource Commission is anticipating the decommission of four culverts from the Lone Mountain portion of the South Mountains Game Lands, located in the Piedmont Region of North Carolina. Through removal of these barriers, four tributaries of the Little First Broad River will be ecologically and hydrologically reconnected to their watershed, facilitating the movement of aquatic organisms, including two crayfish species, the Broad River Stream Crayfish (*Cambarus lenati*) and the Broad River Spiny Crayfish (*Cambarus spicatus)*, both classified as priority species under the North Carolina Wildlife Action Plan. The objective of this study was to assess population sizes and movement patterns of fish and crayfish species in the four tributaries prior to the removal of the culverts. Electrofishing and baited traps were used to assess population numbers, while mark and recapture of crayfish yielded trends in upstream-downstream movement patterns. The data collected will be used comparatively in the future to determine whether stream function and health correlates more closely with the presence or absence of culverts.

2. Methodology

2.1 Study Sites

The South Mountain Game Lands (SMGL), stretching between Burke, Cleveland, McDowell, and Rutherford counties, North Carolina, is a 20,000-acre tract of public woodlands owned and maintained by the North Carolina Wildlife Resource Commission (NCWRC). The Lone Mountain portion of the property, which is predominately unfragmented forest, contains culvert road crossings at seven locations. Four of these crossings, each spanning an unnamed first-order tributary of the Little First Broad River, were identified by NCWRC staff as aquatic barriers and prioritized for removal (Figure 1).

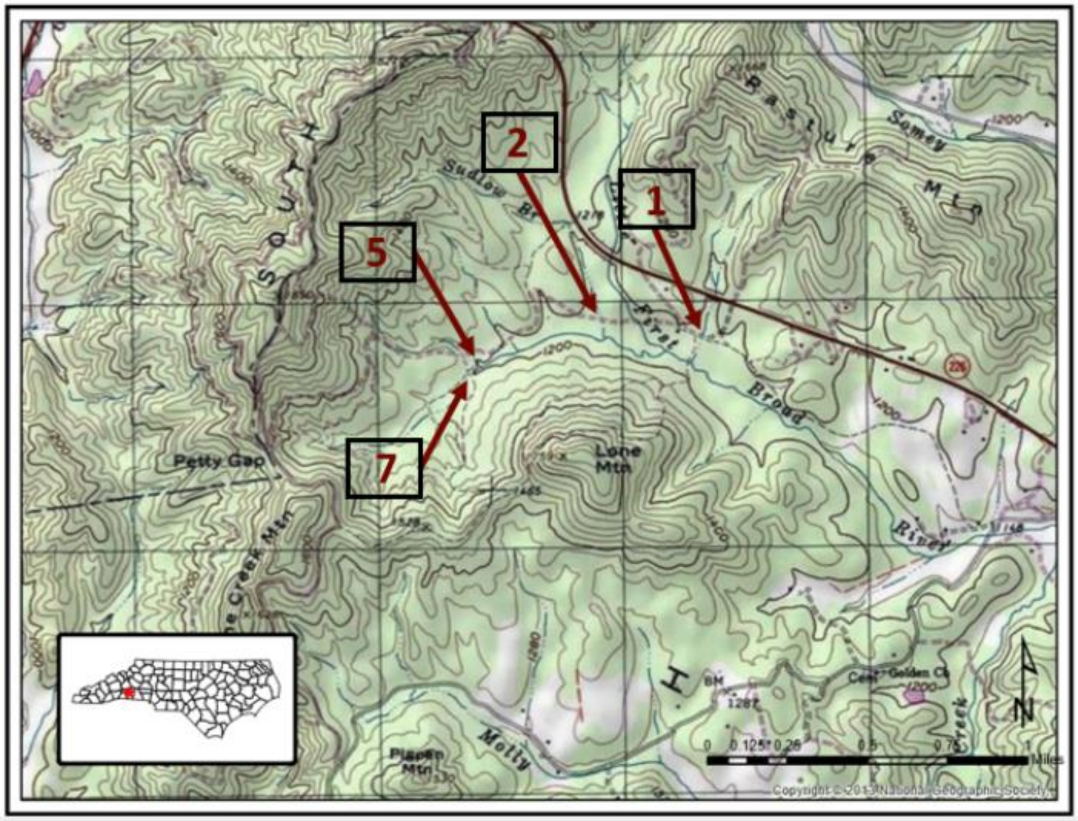

Figure 1. Map of the Lone Mountain section of SMGL with labeled culvert road crossings.

In order to assess the initial impacts of barriers on the movement of aquatic organisms, pre-culvert removal sampling was conducted at each location between May and August of 2015.

2.2 Study Design and Field Sampling

2.2.1 Reach Design

Four sampling sections were delineated for each culvert removal location. Each sample section measured 20 channel-widths in length, or approximately 27 to 30 meters, and included at least two run-riffle-pool sequences. Immediately upstream of the culvert, the Upstream Adjacent (UA) section stretched from the lip of the culvert to approximately 30 meters upstream (20 channel-widths), ending at the next section, Upstream Distant (UD). The UD section, also measuring roughly 30 meters, terminated at the far upstream end of the sample site. This design was continued for the downstream reaches, with the Downstream Adjacent (DA) section extending from the culvert to the next downstream section, termed Downstream Distant (DD). Section DD, originating at the downstream limit of DA, concluded at the far downstream end of the sample site (Figure 2).

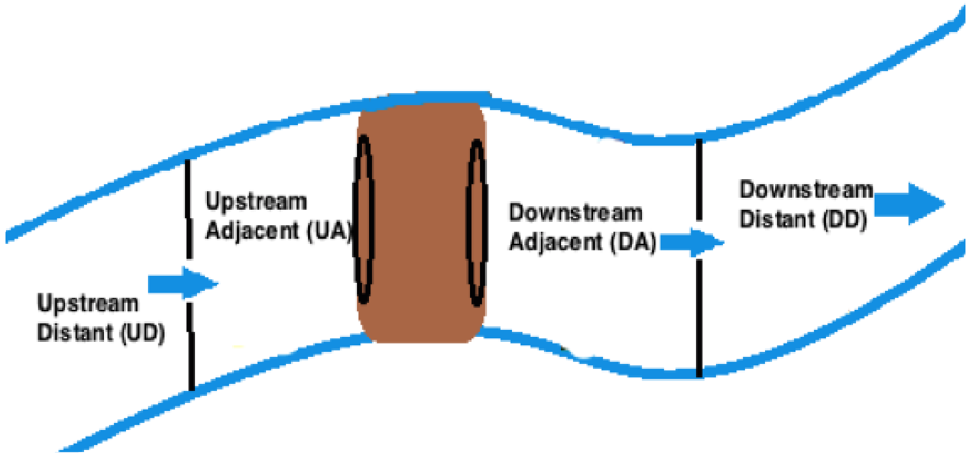

Figure 2. Orientation of the stream sections and culvert for each study site. Each section length (UD, UA, DA, and DD) measured 20 channel-widths, approximately 27-30 meters, and included two run-riffle-pool sequences. (Arrows indicate direction of stream flow).

2.2.2 Habitat Availability

Changes to habitat structure and composition can negatively impact aquatic biota. Substrate composition, which describes the geomorphic makeup of a streambed, is often used to determine habitat availability for aquatic biota. For the upstream and downstream sections of each culvert removal site a quantification of in-stream habitat availability was determined via percent substrate composition. Three 1-meter square subplots, corresponding to a run, riffle, and pool, were randomly selected and assessed via the substrate size categories defined in Somerville and Pruitt[14] (Table 1).

Table 1. Substrate size categories used to calculate percent substrate composition.

Silt	<0.06 mm
Sand	0.06-2 mm
Fine gravel	2-16 mm
Coarse gravel	16-64 mm
Cobble	64-256 mm
Boulder	>256 mm

For each section the randomly selected subplots were combined together and averaged. Percent composition of detritus and woody debris was similarly calculated for each upstream and downstream reach.

2.2.3 Sampling Methods

Beginning with the farthest downstream reach, DD, and extending up to the downstream edge of DA, single-pass backpack electrofishing was administered to capture both fish and crayfish species. Additionally, kickseining of potential habitat was conducted to target crayfish specifically. Collected fishes were identified, tallied, and returned back to the DD section. Crayfish were similarly identified and tallied, but before being released, individuals larger than 40 millimeters were marked by clipping a small hole in the telson[15]. The location of the telson clipping was section specific, with each mark representing either the UA, UD, DA, or DD section. This unique mark allowed the initial capture location of future recaptures to be determined, thus quantifying movement rates between the sections. The crayfish, both clipped and unclipped, were also released back to the original capture section, DD. After completing the DD section, sampling continued upstream, with the outlined sampling protocol observed for the remaining sections. The four sections were sampled and quantified independently, with all collected specimens released directly back to the section of capture. The four streams associated with each culvert removal location were sampled a total of three times, with a three week interval separating samplings.

Baited crayfish traps were also utilized a total of two times between July and August of 2015. In each section of the four streams, two traps were baited with chicken livers and submerged in different pools, with a total of thirty-two crayfish traps used for each sampling. The traps were checked and re-baited after seven days, with all captures clipped and released according to the aforementioned sampling protocol.

2.3 Data Analysis

The data acquired from the sections above and below the culverts were comparatively analyzed to reveal variations in fish species richness along the sample length. Utilizing a Before-After-Control-Impact (BACI) design[16], the number of fish species collected above the culvert at each study site was subtracted from the number collected below. This process was repeated for all three samplings (n=12). For this analysis, the dependent variable was the difference between a control site (downstream of the culvert), and an impacted site (upstream of the culvert). A positive value implies the culverts are playing some role in effecting species richness. The application of a one-sample *t*-test was then used to either confirm or deny the null hypothesis, which predicts the mean of this value is equal to zero for the four culvert removal sites.

Drawing on a study by Burford and McMahon, which assessed trout passage through semi-permeable barriers, the impact of culverts on crayfish movements was determined via the Passage Index (PI) equation (1), with P_t representing the proportion of crayfish passing through the treatment reaches, i.e., the culverts, and P_r representing the proportion of movements occurring between adjacent sections above or below the culvert[10].

$$PI = (P_t-P_r)/(P_t+P_r) \tag{1}$$

For this study, the reference reach (P_r), classifies movements between either UD and UA, or DD and DA. A PI value of +1 indicates some crayfish passed through the treatment reach, but none passed between adjacent sections. A PI value between 0 and 1 specifies that crayfish passed through both the treatment and reference reaches, but more crossed the former than the latter. Conversely, a PI value of -1 indicates some crayfish passed through the reference reaches, but none through the treatment reaches; and a PI value between -1 and 0 demonstrates that crayfish crossed both the treatment and reference reaches, but more through the latter than the former. A PI value of exactly 0 indicates equal numbers of crayfish passed through both the treatment and reference reaches. In order to compare the effectiveness of the two sampling methods utilized by this study, crayfish numbers were separately quantified for both electrofishing and baited trapping.

3. Results

Analysis of percent substrate composition for each study site revealed sand (0.06-2 mm) to be the dominant substrate at Sites 1, 2, and 5, and silt (<0.06 mm) the dominant substrate at Site 7. Detritus formed the main allochthonous input, with an average percent composition of 12.9 for each section of the four streams. One substrate size category, bedrock, was omitted, as it was absent from the streams (Table 2).

Table 2. Percent composition of substrate, woody debris, and detrital composition for each upstream and downstream section of the four SMGL study sites.

Site 1	**DD**	**DA**	**UA**	**UD**
Silt (<0.06 mm)	31.7	11.7	30.0	15.0
Sand (0.06-2 mm)	31.7	50.0	48.3	61.6
Fine gravel (2-16 mm)	10.8	16.6	21.7	21.7
Coarse gravel (16-64 mm)	13.3	6.7	0.0	1.7
Cobble (64-256 mm)	11.7	10.0	0.0	0.0
Boulder (>256 mm)	0.8	5.0	0.0	0.0
Woody debris	0.0	0.0	10.0	5.0
Detritus	8.3	0.0	20.0	21.7

Site 2	**DD**	**DA**	**UA**	**UD**
Silt (<0.06 mm)	28.3	3.3	8.3	21.7
Sand (0.06-2 mm)	25.0	57.6	50.0	18.3
Fine gravel (2-16 mm)	15.0	18.3	21.7	26.7
Coarse gravel (16-64 mm)	26.7	10.0	18.3	20.0
Cobble (64-256 mm)	5.0	10.8	1.7	12.5
Boulder (>256 mm)	0.0	0.0	0.0	0.8
Woody derbis	0.0	5.0	10.0	3.3
Detritus	1.7	15.0	6.7	6.7

Site 5	**DD**	**DA**	**UA**	**UD**
Silt (<0.06 mm)	46.7	20.0	33.3	45.0
Sand (0.06-2 mm)	35.8	48.4	50.0	43.3
Fine gravel (2-16 mm)	11.6	13.3	11.7	11.7
Coarse gravel (16-64 mm)	4.2	13.3	5.0	0.0
Cobble (64-256 mm)	1.7	5.0	0.0	0.0
Boulder (>256 mm)	0.0	0.0	0.0	0.0
Woody debris	10.0	3.3	6.7	1.7
Detritus	18.3	16.7	11.7	3.3

Site 7	**DD**	**DA**	**UA**	**UD**
Silt (<0.06 mm)	40.0	45.0	36.7	33.4
Sand (0.06-2 mm)	18.3	21.7	36.7	43.3
Fine gravel (2-16 mm)	13.3	15.0	26.6	23.3
Coarse gravel (16-64 mm)	20.9	10.0	0.0	0.0
Cobble (64-256 mm)	6.7	8.3	0.0	0.0
Boulder (>256 mm)	0.8	0.0	0.0	0.0
Woody debris	6.7	16.7	3.3	3.3
Detritus	26.7	3.3	21.7	25.0

Fish movement under the BACI design showed that fish species richness above the culverts was significantly lower than below (Figure 3).

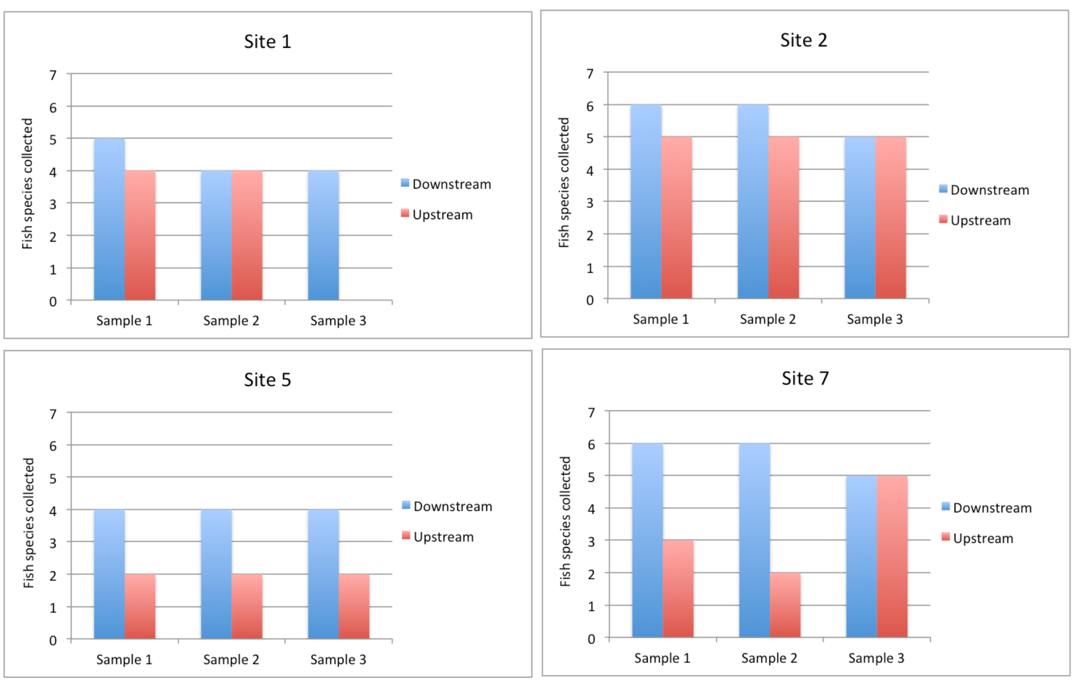

Figure 3. Comparison of the total number of fish species collected downstream and upstream of the culverts at the four study sites. Sample numbers correspond to each of the three electrofishing sample dates, with a three-week interval between each sample. (No fish were captured in the upstream pass for Site 1, Sample 3.)

Application of a one-sample t-test yielded a p-value of 0.002 (t=4.02, 99% CI), allowing the null hypothesis to be rejected.

The calculation of in-stream crayfish movements via the Passage Index (PI) utilized only three of the five total samplings (Figure 4).

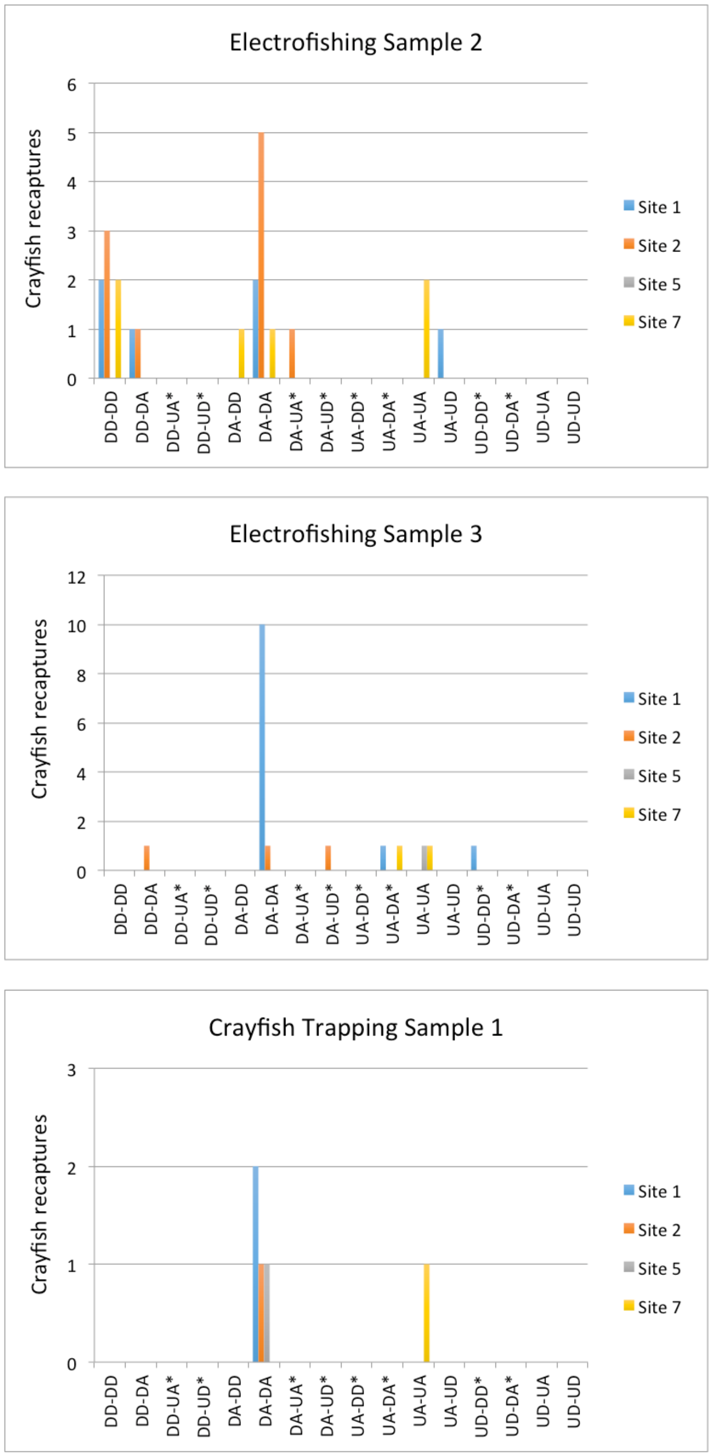

Figure 4. Numbers and locations of crayfish recaptures for the four study sites. (An * denotes movements between sections interposed by a culvert.) The three samples are in order by the date in which they occurred.

Since crayfish movements were determined by comparing the recapture location to the initial capture location, the first round of electrofishing sampling was ignored, as no crayfish were yet marked. The second round of baited trapping was also omitted, as no recaptures were collected at that time. The PI value for Electrofishing Samples 2 and 3 was -0.91 and -0.55, respectively. On the PI scale these values indicate crayfish crossed both the treatment and reference reaches, with more passing through the reference than the treatment reaches. The PI value for Crayfish Trapping Sample 1 was -1.0. This PI value signifies crayfish passed through the reference reaches but not the treatment reaches (Table 3).

Table 3. Summary of the PI values for the electrofishing and baited crayfish trapping samples.

Sample # and Method	**PI Value**
Electrofishing Sample 1	Initial sampling
Electrofishing Sample 2	-0.91
Electrofishing Sample 3	-0.55
Baited Traps Sample 1	-1.0
Baited Traps Sample 2	No recaptures

In a comparative analysis of the two sampling methods, electrofishing yielded more catches than baited traps. For the two baited trap samplings a total of 78 crayfish were captured (Table 4).

Table 4. Combined crayfish capture numbers, separated by species, for the upstream and downstream sections of each study site for the two baited trap samplings.

Site 1	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	4	11	0	2
Cambarus sp. cf. howardi	0	1	1	1

Site 2	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	1	2	6	3
Cambarus sp. cf. howardi	2	1	4	1

Site 5	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	2	3	5	2
Cambarus sp. cf. howardi	2	2	1	0

Site 7	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	6	2	4	0
Cambarus sp. cf. howardi	2	3	3	1

In contrast, 1,117 crayfish were collected during three rounds of electrofishing (Table 5).

Table 5. Combined crayfish capture numbers, separated by species, for the upstream and downstream sections of each study site for the three single-pass backpack electrofisher samplings.

Site 1	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	53	113	30	53
Cambarus sp. cf. howardi	11	22	3	3

Site 2	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	87	128	82	49
Cambarus sp. cf. howardi	2	30	7	2

Site 5	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	26	93	27	6
Cambarus sp. cf. howardi	0	4	2	1

Site 7	DD	DA	UA	UD
Cambarus sp. C (Acuminatus Complex)	92	72	64	51
Cambarus sp. cf. howardi	2	1	0	1

4. Discussion

Disruptions to ecological connectivity limit the dispersal, colonization, and persistence of species within stream habitats[4]. For this study, a quantification of available in-stream habitat revealed the geomorphological changes stream channels undergo in the presence of culverts. Average percent substrate composition at the four sites, both upstream and downstream, was predominately silt and sand. The degradation and accumulation of sediment behind barriers can sever connectivity by impeding the flow of organic matter and debris[6]. At Site 1, a thick deposition of sand above the culvert forces the stream underground, where it later emerges downstream as little more than a trickle. During high flow events this build up of sand is transported and redeposited in the downstream pools. Increased concentrations of suspended sediment have been shown to negatively impact fish assemblages by decreasing hatching success and short-term survival[17, 18]. Alterations to the stream channel also restrict colonization by creating conditions that prohibit the spread of species less tolerant to these disturbances. Fantail darters (*Etheostoma flabellare),* for example, persist in low numbers at each study site, where they live in shallow rocky riffles. Influxes of sediment serve to blanket the substrate and alter flow regimes, resulting in less available habitat for the darters[19].

Another dominant trend observed at the four study sites was a non-uniform distribution of fish species above and below the culverts. For each round of sampling the number of species collected below the culverts was greater than the number collected above. The only exceptions were Site 1 during the second sampling, and Site 7 during the third sampling, when equal numbers of species were caught above and below. This overall trend confirms that culverts are playing a role in restricting fish movement patterns, though the mechanics of that role are not fully known. Similar studies have pointed to faulty culvert design as the main culprit[1, 4]. Site 5 is a prime example, as the main culvert is unused except in high flow events. Instead, a secondary concrete culvert, six inches in diameter and partial embedded in the substrate, serves to conduct the flow of water. Vertical outlet drop, measured as the distance between the lip of the culvert and the plane of the water, and in-passage flow velocity are two variables that strongly impact the upstream dispersal of fish species[10]. For the present study, downstream outlet drops for the four sites under normal flow conditions ranged between 1 and 30 centimeters. Successful passage through culverts with excessive outlet drops depends on the leaping abilities of fish[10]. Further complicating this are reduced in-passage flow velocities, due to the accumulation of woody debris at the culverts' upstream entrances.

In addition to restricting fish dispersal and distribution, culverts also limit crayfish movement by fragmenting potential habitat. Negative Passage Index values for the four study sites confirm the isolating effects culverts have on upstream and downstream crayfish populations. Of the 45 marked crayfish recaptured via electrofishing, only 5 used the culverts as a vector for dispersal. In unfragmented aquatic habitats the downstream drift of juveniles and the multidirectional movement of adults combine to preserve crayfish population connectivity[7]. A recent study by Foster and Keller showed that water flow patterns were closely correlated with crayfish dispersal rates[1]. They further concluded that the reductions in stream discharge associated with culverts increased the degree of habitat fragmentation.

While the impact of culverts is generally negative, there are instances in which they contribute to species persistence. At the four SMGL study sites, the presence of plunge pools with outlet drops immediately below each culvert prevent the upstream movement of crayfish. During low flow periods, when the downstream reaches begin to dry, these pools serve as refugias for crayfish migrating upstream toward water. At Site 1, for example, a total of 73 crayfish, 10 of them recaptures, were collected from the plunge pool during the final round of sampling. The retention of water behind a culvert, though capable of supporting crayfish during drought-like conditions, still disjoins the upstream-downstream reaches by isolating crayfish behind impassable barriers. Future removal of the four poorly designed culverts will likely minimize the size and importance of the plunge pools. However, the reestablishment of reliable stream discharges, together with improved habitat continuity, more than compensate for this loss.

In addition to electrofishing, baited crayfish traps were set in each section of the four sites. The purpose of the traps, aside from supplementing recapture data, was to compare the efficiency of this sampling method against electrofishing. A comparison of captures between the two methods revealed electrofishing to be a more effective tool for estimating crayfish populations. This conclusion corroborates the results of a study by Alonso on the efficiency of electrofishing for freshwater crayfish[20]. In that study, over ninety percent of the estimated populations of crayfish in three small streams were captured via electrofishing. Aside from being less effective, the traps also appeared to preferentially filter out smaller crayfish. The bulk of the trappings at each site were larger-bodied crayfish, which may be explained through predation. Once inside the traps, larger crayfish likely predated on smaller ones once the bait was exhausted. Also, smaller crayfish may have been more adept at escaping through the narrow exit passageways.

A potential flaw of the current study is the method used to mark the crayfish. Clipping of the telson to denote original capture locations is a common practice in crayfish mark and recapture studies[14]. However, observations in the lab revealed that molting crayfish with clipped telsons often emerged with fully formed telsons, though the clipping occurred less than two weeks prior. Molting rates for crayfish populations can be difficult to measure, as they are a function of available in-stream food stores. If resources between the sampling intervals were plentiful, it is likely many of the clipped crayfish molted. Given the efficiency of electrofishing as a sampling method, the number of recaptured crayfish with clipped telsons was expected to be high. However, molting may be one of the explanations for why recapture numbers at the four sites was so low.

Pre-removal assessment of the SMGL study sites revealed that culverts were playing a role in limiting the distribution and movement of fish and crayfish populations. Following the future removal of the four culverts, a similar post-assessment study is scheduled. A comparative analysis of pre- and post-removal data will help fully articulate the impacts culverts have on aquatic ecosystems. Equipped with these results, resource managers will be better prepared to both identify and remedy the severances to ecological connectivity created by in-stream barriers. Long-term future monitoring of the SMGL sites must also be prioritized to ensure that the implemented changes continue to positively impact fish and crayfish populations.

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