ROAD CROSSING DESIGNS AND THEIR IMPACT ON FISH ASSEMBLAGES AND GEOMORPHOLOGY OF GREAT PLAINS STREAMS

by

WESLEY WADE BOUSKA

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Major Professor
Dr. Craig P. Paukert

Abstract

Improperly designed stream crossings may prohibit movement of stream fishes by creating physical or behavioral barriers and may alter the form and function of stream ecosystems. A mark-recapture and geomorphological study was conducted to evaluate fish passage and stream morphology at three types of vehicle crossings (compared to control sites) located on streams in the Flint Hills of Northeast Kansas. We investigated five concrete box culverts, five low-water crossings (concrete slabs vented by one or multiple culverts), and two single corrugated culverts. A total of 6,433 fish were marked April to May 2007 and 709 were recaptured June to August 2007. Fish passage occurred at all crossing types, but upstream movement of recaptured fish was higher at controls (41.1%) than at crossing reaches (19.1%) for low-water crossings. Control sites had more species in common upstream and downstream than did crossings. There was reduced overall abundance of fish upstream at low-water crossings, commonly percids and centrarchids. A comparison of channel and road crossing dimensions showed that box culverts and corrugated culverts would be more effective than low-water crossings at transporting water, sediments, and debris during bankfull flows, and fish passage at base flows. Upstream passage of Topeka shiner (*Notropis topeka*), green sunfish (*Lepomis cyanellus*), red shiner (*Cyprinella lutrensis*), and Southern redbelly dace (*Phoxinus erythrogaster*) was tested through three simulated crossing designs (box culverts, round corrugated culverts, and natural rock) across 11 different water velocities (0.1 m/s to 1.1 m/s) in an experimental stream. Upstream movement did not differ among designs, except natural rock crossings had lower movement than box or corrugated culverts for red shiners. A greater proportion of Topeka shiners moved upstream at higher velocities. These results suggest that crossing type affects fish passage and the morphology of the stream, although water velocity in different crossing designs alone may not be a determining factor in fish passage. Low-water crossings had the greatest impact on fish community and movement, but barriers to fish movement are likely caused by other variables (e.g. perching). Use of properly designed crossing structures has great promise in conserving critical stream habitat and preserving native fish communities.

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In order to avoid any legal trouble, I feel compelled to mention that all biological organisms used in this research were handled in accordance with IACUC guidelines as stated in the Institutional Animal Care and Use Committee Guidebook, Second Edition, 2002 (#4737). Procurement, transport, and handling of the federally endangered Topeka shiner was conducted under the terms and conditions of Federal Fish and Wildlife permit # TE136943-0.

Preface

This thesis was my own personal work but it was written in the third person for submission to peer-reviewed journals.

Chapter 1: Road crossing designs and their impact on movement and diversity of Great Plains stream fishes, stream function, and stream classification.

Abstract

Improperly designed stream crossing structures can potentially alter the form and function of stream ecosystems and may prohibit the movement of stream fishes. A fish mark-recapture and geomorphological study was conducted to evaluate fish passage and stream morphology at five concrete box culverts, five low-water crossings (concrete slabs vented by one or multiple culverts), two large, single corrugated culvert vehicle crossings, and 12 control sites (below a natural riffle) in the Flint Hills of Northeast Kansas. A total of 6,433 fish including 211 federally endangered Topeka shiners (*Notropis topeka*) were marked in April and May 2007 and 709 (11%) were recaptured from June to August 2007. Fish passage occurred at all crossing designs, but Topeka shiner passage was observed only through box and corrugated culverts. Upstream movement of recaptured fish was higher at controls (41.1%) than at low-water crossings (19.1%). Increased bottom water velocity decreased the probability of fish movement through crossings. A comparison of channel and crossing cross-sectional area showed that box culverts and corrugated culverts would be more effective than low-water crossings at transporting water, sediments, and debris during bankfull flows, and passing fish at base flows. These results suggest that crossing type affects fish passage and stream morphology, with low-water crossings having the greatest impact. Use of properly designed and installed crossing structures has great promise in conserving critical stream habitat and preserving native fish communities.

Introduction

Vehicle crossings can have negative impacts on fishes by reducing or eliminating upstream or downstream movement (Warren and Pardew 1998; WDFW, 2003). Because migration may be critical for foraging (Clapp et al., 1990), spawning (Pess et al. 2003), refuge from predators (Harvey, 1991) or thermal refugia (Matthews and Berg, 1997; Mackenzie-Grieve and Post, 2006), barriers to these migrations may be detrimental to the conservation of fishes. Barriers to migration can result in habitat fragmentation, reduced species abundance and diversity, loss of genetic diversity and even species extirpation (Winston et al., 1991; O'Hanley and Tomberlin, 2005; Sheer and Steel, 2006). In the Lower Columbia River Basin, Washington, barriers have rendered 42% of original stream habitat inaccessible to salmonids, reduced habitat diversity, and reduced the availability of high-quality spawning habitat for several species (Sheer and Steel, 2006). Migration barriers have been implicated in the listing of many salmonids as threatened or endangered under the Endangered Species Act (Nehlsen et al., 1991; Sheer and Steel, 2006), and may also be a threat to stream fishes in the Great Plains (Warren and Pardew, 1998; Toepfer et al., 1999).

Barriers to passage at vehicle crossings can include perching at the crossing inlet or outlet that exceeds the jumping abilities of migrating fish (Mueller et al., 2008), increased turbulence or velocity within the crossing caused by channel constriction or increased gradient, debris and sediment accumulation at or within the crossing, and inadequate water depth within the crossing (Votapka, 1991; WDFW, 2003; Wall and Berry, 2004). Previous studies have shown reduced upstream movement of fish through culverts when compared to streams without crossings (Warren and Pardew, 1998; Coffman, 2005) and also that crossing type and design can influence the amount of fish movement (Warren and Pardew, 1998; Burford, 2005; Cahoon et al., 2005).

Field experiments conducted by Schaefer et al. (2003) found that natural and manmade barriers reduced movement of threatened leopard darters (*Percina pantherina*), and suggested that culverts decrease the probability of movement among habitat patches.

The majority of North American studies involving fish passage have focused on salmonids (O'Hanley and Tomberlin, 2005; Sheer and Steel, 2006) and other anadromous or catadromous species (e.g. Atlantic salmon (*Salmo salar*) and American eel (*Anguilla rostrata*); Beasley and Hightower, 2000; Haro et al., 2000). Much of the data collected on the swimming and jumping abilities of salmonids through crossings has been synthesized by State and Federal agencies to establish guidelines for culvert designs and installation that will allow fish passage (Behlke et al., 1991; WDFW, 2003). Although this research is important, little has been done to address fish passage concerns in the Great Plains, where awareness on the effects of barriers has increased for the federally endangered Topeka shiner (*Notropis topeka*). The Topeka shiner was listed as a federally endangered species in January, 1999 (USFWS, 1998), and today occupies only about 10% of its former range (USFWS, 2002). In Kansas, extant populations primarily occur in the Flint Hills region (Minckley and Cross, 1959; Barber, 1986; Schrank et al., 2001).

Improperly designed or installed stream crossing structures can also degrade stream habitat. Jones et al. (1999) found that crossings can alter the starting and stopping points of debris flows in a stream, causing severe disturbance to the stream channel through sediment degradation or aggradation. Wellman et al. (2000) determined that sediment accumulation and sediment depth was greater in streams with culverts than at streams with bridges. Therefore, an inappropriate crossing can alter a streams geomorphological pattern, natural erosion rates, stream deposition, and sediment transport, which can result in changes to aquatic habitat.

Negative effects of road-crossings are minimized if they mimic the form and function of the adjacent stream. Streambed substrate should be continuous throughout the crossing with slope and particle size similar to the adjacent channel. Additionally, the crossing should not constrict the bankfull width in order to allow for transport of all water, sediment, and debris during maximum flows (Clarkin et al., 2005).

The objective of this study was to compare fish passage among different road-stream crossings in the Kansas Flint Hills to determine what effects different crossing designs have on fish movement and assemblage structure of Great Plains stream fishes, and to determine the effect of crossing design on stream classification, and stream channel form and function. This research will provide assistance to current and future road development projects in constructing crossings conducive to fish passage.

Methods

Study Area

Fieldwork was conducted in streams in the Flint Hills of Northeast Kansas that have been classified as critical habitat for the federally endangered Topeka shiner (USFWS, 2002; Mammoliti, 2004). Five box culverts, five low-water crossings, and two large corrugated pipe culverts located on West Branch Mill Creek, Hendricks Creek, Spring Creek, Nehring Creek, and South Branch Mission Creek (Wabaunsee County) and Deep Creek (Riley County) were selected as study sites. Crossings that exhibited obvious barriers to migration (e.g. perching >0.3 m; Figure 1.1) were not considered for testing (Vander Pluym et al. 2008).

Fish Movement Sampling Design

Field sampling was conducted between April and August 2007. At each study site, fish were sampled in the pool immediately downstream of the crossing using straight seines 4.6 m x

1.8 m or 9.1 m x 1.8 m (4.8 mm mesh). Pools were sampled to depletion when possible and an effort was made to collect the majority of fish from each pool. All fish were identified and enumerated by species. A uniquely colored visible implant elastomer (VIE) tag was injected underneath the dermis, parallel to the skin to batch mark fish from sites below the road crossing. After tagging, fish were placed in mesh holding enclosures located in the stream to allow for recovery from handling before being returned to the stream.

Another pool habitat below a natural barrier (riffle) downstream of each crossing was sampled as a control site to compare with the vehicle crossing site (Figure 1.2) and fish were marked with a different colored VIE tag. An effort was made to place control sites at least one stream meander length away from crossings so control sites were not affected by the road crossing, and maintained their natural channel and floodplain.

After the initial tagging in April and May 2007, each site was revisited three times (June, July, and August 2007) to recapture fish and determine passage through the crossings. During recapture sampling, all pools and runs were sampled by at least three seine hauls. The recapture sampling reach extended 500 m upstream of the crossing and 200 m downstream of the control. Any recaptured fish were retagged with another VIE mark to aid in identification during future recapture events. A meter tape was used to record distance from crossing and to measure lengths of seine hauls in order to determine catch per unit effort (CPUE).

Water velocity (cm/s) was measured at five locations across the crossing inlet and outlet with a Marsh-McBirney Flow-Mate 2000 flow meter at the bottom of the crossing and at 60% of the water depth and averaged. Water depth was measured as the maximum depth (cm) at the inlet and outlet of each crossing. Other measurements included length, width, height, perching, and bed slope of the crossing (Figure 1.1). Velocity, depth, and perching were measured during the initial tagging in April or May, and again during the July and the August recapture sampling. We used the mean of these three measurements in our analysis. When crossings included multiple openings (e.g., box culverts with multiple cells and low-water crossings with multiple culverts), we used the means for all the cells combined.

Fish Movement and Community Data Analysis

Fish passage at each site was assessed through the crossing (treatment) and through the natural reach (control). Analysis was conducted using all fish combined, as well as by taxonomic groups. Six taxonomic groups were developed based on Family classification (Pflieger, 1997). Family groups included percids, ictalurids, catostomids, centrarchids, and cyprinids. Cyprinids were further divided into *Phoxinus* which contained Southern redbelly dace (*Phoxinus erythrogaster*), because this species was the most abundant fish sampled (28% of all fish collected). When analyzing movement by taxonomic group, groups with fewer than five recaptured fish at a site were omitted from the analysis. Fish passage was expressed as proportional movement, $(P) = M / R$, where M is the number of fish moving past the treatment or control barrier and R is the number of recaptures at each segment (Warren and Pardew, 1998). A logistic regression with odds ratio determined whether proportional movement differed among crossing designs, and if movement differed between the control and treatments for all months combined. A logistic regression was also used to determine if proportional movement was related to bottom velocity (m/s) through the crossing, depth (cm), culvert slope (%), culvert length (m), velocity/depth, and perching (cm) for all crossings combined. A repeated measures ANOVA was used to determine if mean depth (cm), bottom velocity (cm/s), and perching (cm) differed by crossing design using site as the repeated variable because sites were visited more than once.

We calculated the percent similarity index (PSI) and Jaccard's Index of Similarity (J), above and below the control site and above and below the experimental (crossing) site to determine the effects of crossing design on the fish community. An analysis of covariance (ANCOVA) was used to compare the mean differences in PSI and J above and below the crossing to the differences at the control site using sampling month as the covariate. We also tested if overall CPUE (number of fish / m seined), individual species CPUE, and CPUE by taxonomic group differed by lateral position (upstream or downstream of the control or crossing), and treatment (control or crossing) using a two-way ANOVA for each crossing design. A significant interaction would indicate that CPUE was not consistent above and below the crossing and/or control, and individual ANOVAs were then used to test if mean CPUE differed by lateral location or crossing design. Only samples that were collected within 200 m of crossings or controls were used in movement and fish community analyses. At one site, data from 100 m upstream and downstream of controls and crossings was used because trespass permission prevented sampling 200 m downstream the control.

Geomorphological Sampling Design

Stream Classification

Each study site was classified using the Level II Rosgen method (Rosgen, 1996) from July to October 2007. Level II stream type was determined using five delineative criteria (entrenchment ratio, width to depth ratio, water surface slope, sinuosity, and channel material composition) that were obtained through measurements of the streams longitudinal profile, channel cross-section, sediment composition, and channel plan-form (see below). Measurements of the longitudinal and channel cross-section profiles were taken using a laser level.

We compared our geomorphological measurements to reference reaches that have been established in the same hydrophysiographic province (the Flint Hills) (Rosgen, 1996; EPA, 2005). A reference site characterizes the natural, baseline physical conditions of a stream channel (Harrelson et al., 1994). Measurements from a reference site can be used to monitor fluvial and geomorphic trends, quantify environmental impact, assess the response of a stream to management, and allow for comparisons between streams based on classification type (Harrelson et al., 1994).

Longitudinal Profile - A longitudinal profile (Rosgen, 1996) was developed at each site to measure the mean slope of the water surface over at least 30 bankfull widths (15 above and 15 below each crossing). Water surface slope was also measured separately for reaches upstream and downstream of the crossing. Measurements began and ended at riffle heads as the profile plotted the elevations of the water surface and the channel thalweg every 3-5 m through the entire reach. This described the characteristics of pools and riffles (length and depth) and allowed the measurement of riffle to riffle spacing at each site. Measurements of riffle spacing were reported in mean bankfull widths, bankfull widths were estimated for each site using regional curves (EPA, 2005). At site LW1, the low-water crossing caused a backwater effect resulting in an absence of all riffles in the surveyed reach upstream of the crossing. In this case, riffle spacing was calculated by dividing the surveyed upstream reach (457.2 m) by the estimated bankfull width (25.91 m) and riffle spacing was reported as 17.65 bankfull widths.

Cross-Section Profile - Cross-sectional measurements capture the dimensions of the channel (Rosgen, 1996) by plotting elevation measurements approximately every 0.5 m across a riffle, perpendicular to water flow. Measurements included bankfull width, bankfull mean depth, bankfull maximum depth, flood prone area width, entrenchment ratio, bankfull cross-sectional area, and estimated bankfull discharge (Figure 1.3). Channel shape at the cross-section was indicated by the width to depth ratio (bankfull width / mean bankfull depth). The entrenchment ratio (flood prone width at two bankfull heights / bankfull width) described the vertical containment of the stream channel (Rosgen, 1996). Measurements of cross-sectional area, bankfull width, and mean bankfull depth were compared to estimates generated from the reference reach regional curves (EPA, 2005) to cross check field identification of bankfull features. Cross-sections were performed at one riffle above and one riffle below each crossing.

Substrate Composition - The composition of streambed substrate was also characterized at each site by performing modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis and were classified using a modified Wentworth scale (Harrelson et al., 1994). A longitudinal or reach pebble count was conducted by measuring 100 random samples from pools and riffles over the entire surveyed reach (Rosgen, 1996). The reach count was conducted so the number of samples taken from pools vs. riffles reflected the pool to riffle ratio of the surveyed reach. Pebble counts were also conducted at each of the riffle cross-sections (one upstream and one downstream at each crossing) and also consisted of 100 random samples. These pebble counts characterized the streambed composition by describing particle size class (D50: median substrate particle size in mm). Values from the reach count D50 were used in classification.

Sinuosity - The plan-form or pattern of the channel was measured by sinuosity (stream length/valley length) and meander geometry (Rosgen, 1996). Sinuosity was measured from aerial photographs taken in 1991, and was used in stream classification. Valley types (I-VI; Rosgen, 1996) were also determined for each site using topographic maps.

Crossing Measurements

Measurements were taken at each crossing to compare crossing dimensions to the adjacent channel and to the regional curves. Measurements included height, width, and gradient of crossings. Area of the culverts was calculated at all crossings. At box culverts, area = width x height and at box culverts with multiple cells, the areas of all cells were summed together. Low-water crossings were vented by as many as four culverts and sometimes with culverts of several shapes. Area for circular culverts was calculated as π x radius^2; for elliptical culverts, area = π x A x B where A = the longest radius of the ellipse and B = the shortest radius of the ellipse. Areas of all culverts were summed at each low-water crossing to determine the total area available for transport of watershed products. Cross-sectional area estimates from the regional curves were divided by the crossing widths to determine mean bankfull depths. At low-water crossings bankfull flows exceed the capacity of the culverts, sending water over the road. Cross-sections were conducted on the road at low-water crossings to determine mean bankfull depths and bankfull widths over the crossings during flooding events.

Geomorphological Data Analysis

A discriminant function analysis (DFA) was used to determine if geomorphic metrics collected from stream surveys at our road crossings and 29 established reference reaches in the Flint Hills discriminated among box culverts, low water crossings, single corrugated pipe crossing, and reference reaches. Because of missing data, one low-water crossing and one large single corrugated pipe culvert were removed from the analysis. We compared riffle spacing, substrate composition (riffle D50), mean bankfull depth, width to depth ratio, and water surface slope between the reference reaches and the entire sampled reach at our road crossings. A DFA was also used to determine if the differences in these metrics upstream versus downstream of crossings discriminated among crossing designs with all crossings included, and also with large single corrugated pipe culverts removed. Measurements of crossing mean bankfull depth and average cross-sectional area for each crossing type were compared to the mean bankfull depth and the average cross-sectional area determined for each site by the regional curves using paired t-tests. Statistical results were considered significant at $p < 0.10$.

Results

Fish movement

A total of 6,433 fish including 211 Topeka shiners were marked from 18 April to 31 May 2007 and 709 (11%) were recaptured in June, July, and August 2007 (Table 1.1). Four species comprised 75% of all fish collected: Southern redbelly dace (28%), common shiners (*Luxilus cornutus*) (16%), redfin shiners (*Lythrurus umbratilis*) (15%) and red shiners (*Cyprinella lutrensis*) (15%). Upstream movement was detected for all three crossing designs. Mean proportional upstream movement did not differ between controls and crossings for box culverts ($p = 0.665$) or corrugated pipe culverts ($p = 0.171$). However, fish were 3.3 times less likely to move through low-water crossings than through the control riffles ($p < 0.0001$; Figure 1.4, Table 1.2). Cyprinids also had reduced proportional upstream movement at low-water crossings, and were 2.4 times less likely to move through low-water crossings than through the control riffles ($p = 0.0005$; Table 1.2). There was reduced movement of *Phoxinus* through box culverts, and fish were 0.4 times less likely to move through box culverts than control riffles ($p = 0.05$; Table 1.2). A total of 211 Topeka shiners were tagged and 42 (20%) were recaptured. Movement of Topeka shiners was only observed through box culverts and corrugated culverts and not low-water crossings (Table 1.3).

The physical variables measured at our 12 crossings indicated crossing design also affected stream characteristics. Velocities at our crossings ranged from 0.00-1.42 m/s (mean =

0.34 m/s) and were higher at low-water crossings than other designs ($p = 0.023$), depths ranged from 1.0-60.0 cm (mean = 12.7 cm) and did not differ among crossing design ($p = 0.113$), perching ranged from 0.0-25.0 cm (mean = 9.3 cm; Table 1.4) with low-water crossings having greater perching than other crossing designs ($p = 0.0004$). Slopes ranged from 0.26-1.27% (mean = 0.57%; Table 1.5), and crossing lengths ranged from 6.05-16.95 m (mean = 10.3 m; Table 1.6). Increased bottom velocity was associated with lower proportional fish movement ($p = 0.04$; Figure 1.5) but depth, slope, length, velocity/depth, and perching were not related to the proportion of fish that moved upstream for all fish combined (Table 1.7). However, *Phoxinus* movement increased with water depth ($p < 0.0001$; Table 1.7).

Fish Community

Control sites had more species in common (based on Jaccard's index) upstream and downstream of the natural riffle than experimental sites regardless of crossing design ($p = 0.086$; Figure 1.6). However, mean PSI did not differ between control and experimental sites ($p = 0.339$; Figure 1.6). There was no interaction between crossing and control for overall fish CPUE at box culverts ($p = 0.737$) or corrugated culverts ($p = 0.242$) but there was an interaction for low-water crossing ($p = 0.058$), indicating that CPUE was not consistent between upstream and downstream locations for control and low-water crossings. Individual ANOVAs showed that overall fish CPUE was lower upstream than downstream at low-water crossings ($p = 0.004$) but CPUE upstream versus downstream of controls did not differ ($p = 0.547$; Figure 1.7). Mean CPUE by taxonomic groups produced mostly non-significant interactions ($p > 0.243$) indicating CPUE was consistent between upstream and downstream locations for control and low-water crossings. However, percids had a significant interaction at low-water crossings ($p = 0.06$) and centrarchids had significant interactions for low-water crossings ($p = 0.065$) and corrugated culverts ($p = 0.003$). Further analysis showed mean CPUE of percids ($p = 0.002$) and centrarchids ($p = 0.030$) was lower upstream of low-water crossings compared to downstream of the crossing and to control reaches, and that CPUE of centrarchids was greater downstream of controls ($p = 0.0001$) at box culverts than upstream (Figure 1.7).

Stream Geomorphology and Classification

Drainage areas for the study sites ranged from 2.87 to 138.62 km^2 (Table 1.5). Eight sites classified as F4 streams and four sites classified as B4c streams, stream types commonly found in the Flint Hills (Table 1.5). Stream reaches upstream and downstream of the crossing were also classified separately (see Appendix 1) which resulted in some classification changes. Upstream of the crossings, nine sites were classified as B4c streams and two were classified as F4 streams. At site LW1, there was no riffle present in the upstream reach to obtain the necessary delineative criteria for classification, but classification was estimated at F6 (T. Keane, Kansas State University, personal communication). Downstream of the crossings, seven of the B4c streams changed classification to F4 streams. This classification change is a result of an increasing entrenchment ratio (>1.4) downstream of the crossings, which indicates an incised channel.

Crossing effects on stream form and function – Road stream crossings did not appear to have an effect on riffle spacing, riffle D50, mean bankfull depth, width to depth ratio, or water surface slope at the reach scale ($F = 0.90$, $DF = 18, 80$, $p = 0.582$). Differences in these same variables also did not differ upstream versus downstream by crossing design ($F = 2.75$, $DF = 12, 4$, $p = 0.170$; Figure 1.8). However, when the one large single corrugated pipe culvert was removed, the differences in measured geomorphic variables upstream versus downstream did discriminate between box culverts and low water crossings ($F = 14.5$, $DF = 6, 2$, $p = 0.066$).

Mean riffle spacing upstream of low-water crossings (8.65 bankfull widths) was nearly double that of downstream reaches (mean = 4.4 bankfull widths; Table 1.8), but was similar upstream and downstream of box and corrugated pipe culverts. In addition, box culverts had increased bankfull depth and width to depth ratio upstream of the crossings compared to downstream.

Crossings ability to mimic the adjacent stream channel – The mean total area available at box culverts for conveying water and sediment was 41.2 m^2; however, regional curves indicated the mean cross-sectional areas of the channels at bankfull flow to be significantly less at 8.29 m^2 ($p = 0.0009$; Table 1.9). The mean available area at corrugated culverts did not differ (6.59 m^2) from the surrounding stream (mean = 2.6 m^2; $p = 0.30$). At low-water crossings, mean total area available through the culverts (1.57 m^2) was only about 10% of the mean cross-sectional area of the channel at bankfull flow (17.28 m^2; $p = 0.04$) indicating that bankfull events will cause water to flow over the road and velocities to increase through the culverts. Bankfull depths at box culverts (mean = 0.75 m) did not differ from the regional curves (mean = 0.62 m; $p = 0.14$). Corrugated pipe culverts did not have mean bankfull depths different from the surrounding streams ($p = 0.66$). However, mean bankfull depth over the road surface at low-water crossings (0.39 m) was shallower than the regional mean of 0.9 m ($p = 0.04$).

Discussion

Fish Movement and Community

We found that crossings acted as semi-permeable barriers, with some designs having a greater affect on fish movement and community structure. Overall proportional upstream movement and movement by cyprinids was reduced by low-water crossings. Crossing design also appeared to affect water velocity and perching, with low-water crossings consistently having higher bottom velocities and greater perching than other crossing designs. As velocity increased, a reduced probability of upstream fish passage was detected. This was not surprising as water velocity has previously been identified as a barrier to fish migration (Votapka, 1991; WDFW, 2003; Wall and Berry, 2004). This mark-recapture study suggests that of the three designs, low-water crossings may have the greatest negative impact on fish passage. These results support the findings of Warren and Pardew (1998) who also found reduced passage through this type of crossing compared to fords (wet crossings) and open-box crossings. In contrast, Vander Pluym et al. (2008) found no differences in fish movement among bridges and arch, box, and pipe culvert crossing designs. However, their results are likely due to extremely low numbers of recaptured fish (Vander Pluym et al., 2008). Rosenthal (2007) found that four large single corrugated pipe crossings and one low-water crossing had limited affects on movement and community structure of prairie fishes, although there was limited perching at these crossings (maximum 5.1 cm).

Topeka shiner movement was not detected through low-water crossings even though the majority of Topeka shiners were tagged downstream of these sites. The lack of Topeka shiner passage is most likely due to the increased perching, and or the increased velocities observed at low-water crossings. The mean bottom water velocity at low-water crossing was 0.64 m/s and the mean length of these crossings was 13.15 m. Using these values, Topeka shiner swimming speed and endurance data calculated from swim chamber tests by Adams et al. (2000), and an equation from Peake et al. (1997) to predict passable water velocities, we would predict Topeka shiner passage at velocities only up to 0.53 m/s, below the mean velocities observed in the field. There is little variation in body morphology among cyprinids, and morphology can affect swimming performance (Billman and Pyron, 2005). Therefore it is likely that other species may also have trouble passing at these velocities.

Control sites had more species in common upstream and downstream than did the crossings, suggesting road crossings may affect community composition. In addition, there was reduced overall CPUE (and reduced centrarchid and percid CPUE) upstream at low-water crossings when compared to downstream of the crossing. This suggests a reduced ability in certain fish to pass through these crossings, resulting in the observed stockpiling of fish downstream of the barrier. Fish swimming ability is influenced by size (Ward et al., 2002; Wolter and Arlinghaus, 2003) and morphology (Schaefer et al., 1999; Billman and Pyron, 2005), and culvert crossings have previously been identified as barriers to other percid species (Schaefer et al., 2003). Some of these differences may also be a result of crossing-induced upstream habitat alterations creating a less suitable environment for fishes. We also found increased CPUE of centrarchids downstream of controls at corrugated pipe culverts compared to upstream reaches. This is likely a result of low sample size (n = 2).

These results conflict with previous studies that found no crossing affects on fish community. Wellman et al. (2000) found that fish diversity, abundance, and richness did not differ upstream and downstream of culverts and bridges. Likewise, Vander Pluym et al. (2008) evaluated population size, diversity, species richness, and fish index of biotic integrity among four crossing designs and control reaches and did not find any differences in these metrics due to crossings. The differences from these studies compared to this study could be attributed to the reduced spatial scale of fish sampling by Wellman et al. (2000) and Vander Pluym et al. (2008) who sampled reaches less than half the length as our study. Lengthening their sampled reaches would likely have increased their number of recaptures, as we consistently recaptured tagged fish up to 500 meters away from their tagging location. If crossings act as barriers to fish movement, then we would expect differences in fish community upstream versus downstream, as evidenced by other studies looking at barriers such as dams and their affects on fish community (Winston et al., 1991; Gido et al., 2002; Sheer and Steel, 2006). All three crossing designs we tested appeared to affect the fish community to some extent, low-water crossings appeared to have the greatest impacts on fish diversity and abundance.

Stream Geomorphology and Classification

It was hard to make any inferences about the effects of large single corrugated pipes on stream geomorphology because missing data lowered our sample size to one. Removing corrugated pipe culverts from the analysis revealed that low-water crossings and box culverts affected stream geomorphology. Box culverts had increased mean bankfull depths and width to depth ratios upstream of the crossings compared to downstream. Differences in riffle spacing and riffle D50 were greater upstream to downstream of low-water crossings than at box culverts. Riffle spacing was nearly double upstream than downstream of low-water crossings, but not for box or corrugated culverts. These geomorphic measurements are directly related to a streams physical habitat (Orth and White, 1999). Because habitat requirements vary by species and by life history stages, crossing induced changes in physical habitat would also be expected to affect fish community structure.

Spacing between pools or riffles should be between five and seven bankfull widths (Rosgen, 1996), which is lower than what our study found upstream of low-water crossings. Riffle spacing is an integral part of stream channel hydraulics and processes, and meander formation; a disturbance in the channel such as a road crossing would likely result in an adjustment of riffle and pool spacing (Gregory et al., 1994). Greater riffle spacing above low-water crossings is likely a result of these crossings acting as partial dams within the stream channel. Low-water crossings caused a backwater effect, water collected upstream and inundated formerly prominent stream features and increased riffle spacing. In one extreme case, the low-water crossing had no riffles in the entire upstream sampled reach. The increased riffle spacing at our sites caused increased pool habitat and a loss of habitat diversity, which can reduce fish abundance (Orth and White, 1999). Increased pool habitat could also provide more habitat for non-native species such as largemouth bass (Pflieger, 1997), and increase predation of native stream fishes.

Crossing design did not appear to affect substrate particle size at the reach scale. However, it did appear that sediment composition was different upstream and downstream of the crossings between low-water crossings and box culverts. Previous studies have identified crossings as vectors for change in the sediment composition of streams (Wellman et al. 2000), and crossings that alter sediment transport and scour can increase erosion rates throughout a stream reach (Wargo and Weisman, 2006). Alterations to substrate composition can affect the spawning success of stream fishes since many have specific requirements for spawning substrate (Plfieger, 1997). A substrate sampling regime that randomly sampled within a closer proximity to the crossing may have better characterized the local affects of crossings on substrate size and sedimentation.

Corrugated culverts and box culverts did not have greater mean bankfull depths compared to the regional curves, and therefore had sufficient area to accommodate bankfull flow events. This indicates that box culverts and large corrugated culverts are allowing water and sediment passage similar to the adjacent channel. Low-water crossings act as constriction points during base flows because the area available through low-water crossings is less than a tenth of that available in the adjacent channel, resulting in extremely high water velocities through the culverts until discharge becomes sufficient enough to go over the road surface. In contrast, box culverts and corrugated culverts were more similar to natural channels than low-water crossings and would be more capable of transporting water, debris, and sediments during all stages of discharge.

Conclusions

Low-water crossings may have the most deleterious effects on fish passage, the fish community, and the form and function of the surrounding stream. Although limited movement was observed at low-water crossings, based on the extreme velocities during base flow, and the presence of other barriers during base flow conditions, such as perching, we hypothesize that the majority of movement observed at low-water crossings likely occurred over the crossing itself during bankfull events in which water covered the road surface. Low-water crossings reduced overall proportional upstream fish movement and proportional upstream movement of cyprinids. Overall abundance and abundance of percids and centrarchids was reduced upstream of low-water crossings. The area of the culverts at low-water crossings was less than the adjacent channel, constricting water and causing higher velocities than other designs. This reduction in channel area caused water to back up, and riffle spacing tended to double upstream of low-water crossings compared to other designs and downstream reaches.

We believe crossing design may be used in prioritizing fish passage projects. In addition, alternatives to low-water crossings may need to be considered in future crossing construction to help maintain fish passage and stream function. Continued use of low-water crossings in Great Plains streams may hamper the recovery of the federally endangered Topeka shiner and may threaten other species by creating migration barriers.

Box culverts and large single corrugated pipe culverts allowed greater amounts of fish passage that were similar to control reaches, and their dimensions were similar to the stream channel. Future work should encompass a greater sample size and larger range of crossing designs to better identify the effects of road crossings on fish passage and stream function. Crossing-related barriers to fish movement and impacts on stream form and function should be considered before the construction of any road-stream crossings.

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Table 1.1: Tagging and recapture statistics for all fishes at 12 road-stream crossings in the Kansas Flint Hills, May to August, 2007.

Crossing Type	Number Tagged Control	Number Recaptured	Number Tagged Experimental	Number Recaptured
Low-Water	1964	218	1859	195
Box Culvert	1643	165	628	70
Corrugated Pipe	97	18	242	43
Total	3704	401	2729	308

Table 1.2: Proportional upstream movement (standard error in parentheses) by taxonomic group and for all species combined at three crossings designs (12 sites) in the Kansas Flint Hills, with p-values from logistic regression indicating significant differences in proportional movement between crossings and controls, N = total number of recaptured fish for control and crossing combined. No standard error was calculated when movement was only detected at only one site.

Crossing Design	Taxa Group	Control	Crossing	p-value	N
Box Culvert	Cyprinids	0.49 (0.03)	0.53 (0.20)	0.87	123
	Phoxinus	0.51 (0.19)	0.39 (0.39)	0.05	120
	Overall	0.41 (0.17)	0.53 (0.17)	0.67	264
Low-Water	Cyprinids	0.44 (0.07)	0.27 (0.14)	0.0005	359
	Phoxinus	0.63 (0.18)	0.47	0.07	93
	Overall	0.41 (0.09)	0.19 (0.09)	<0.0001	462
Corrugated Pipe	Percids	0.00	0.43 (0.23)	0.02	6
	Cyprinids	0.33	0.33 (0.14)	0.78	44
	Overall	0.32 (0.32)	0.17 (0.17)	0.17	75

Table 1.3: Total number of Topeka shiners (*Notropis topeka*) tagged and recaptured by crossing design at 12 sites in the Kansas Flint Hills, including an additional 123 fish marked during the first recapture sampling event, after the initial tagging at control and experimental pools.

Crossing Type	Number Tagged	Number Recaptured	Percent Recapture	Crossed	Not Crossed
Low-Water	173	32	18	0	32
Box Culvert	26	5	19.2	1	4
Corrugated Pipe	12	5	41.6	3	2

Table 1.4: Mean water depths (cm), bottom velocities (m/s), and perching (cm) from May to August, 2007 at 12 sites in the Kansas Flint Hills, LW = low-water crossings, BC = box culverts, and CC = large single corrugated pipe culverts, numbers (e.g. LW1-5) indicate site number. Absence of data indicates a dry stream. No standard error (SE) was reported if all values were zero.

Site	Month	Mean Depth (cm)	Mean Bottom Velocity (m/s)	Mean Perching (cm)
LW1	May	40.33	1.42	23.00
	July	11.27	0.58	23.00
	August	9.53	0.37	24.00
LW2	May	26.55	1.17	16.75
	July	8.00	0.62	16.75
	August	7.28	0.54	16.75
LW3	May	12.06	0.76	9.50
	July	4.00	0.33	14.75
	August	1.67	0.09	20.00
LW4	May	30.63	0.53	25.00
	July	6.00	0.65	4.00
	August	6.50	0.62	4.00
LW5	May	23.79	0.93	10.00
	July	9.40	0.62	10.00
	August	4.00	0.37	10.00
Overall	Mean(SE)	13.40 (2.95)	0.64 (0.09)	15.17 (1.81)
BC1	May	9.60	0.50	15.50
	July	1.95	0.20	17.50
	August	2.20	0.07	19.50
BC2	May	4.40	0.02	0.00
	July			
	August			
BC3	May	9.00	0.03	0.00
	July	11.17	0.00	0.00
	August	6.47	0.00	0.00
BC4	May	1.00	0.00	5.00
	July	2.00	0.05	23.00
	August			
BC5	May	60.10	0.04	0.00
	July	36.10	0.02	0.00
	August	30.00	0.00	0.00
Overall	Mean(SE)	14.50 (5.27)	0.08 (0.04)	6.71 (2.67)
CC1	May	14.50	0.01	0.00
	July	4.50	0.00	0.00
	August	8.17	0.00	0.00
CC2	May	8.90	0.19	0.00
	July	3.30	0.31	0.00
	August	3.38	0.15	0.00
Overall	Mean(SE)	7.12 (1.77)	0.11 (0.05)	0.0

Table 1.5: Site information and Rosgen Level II delineative criteria and classification (Rosgen, 1996) for the entire sampled reach at 12 road-stream crossing sites in the Kansas Flint Hills, BKF = bankfull, D50 = median substrate particle size, LW = low-water crossings, BC = box culverts, and CC = large single corrugated pipe culverts, numbers (e.g. LW1-5) indicate site number.

Site	Drainage Area (km^2)	Valley Type	BKF Width (m)	BKF Mean Depth (m)	BKF Area (m^2)	Width/ Depth Ratio	Entrenchment Ratio	Sinuosity	Reach D50 (mm)	Water Slope (%)	Rosgen Class
LW1	126.81	VI	18.93	1.55	29.09	12.27	1.86	1.87	0.11	0.26	B4c
LW2	49.81	VI	25.44	0.63	15.53	42.15	1.33	1.09	27.8	0.42	F4
LW3	15.8	II	16.12	0.41	6.34	41.46	1.27	1.2	48	0.76	F4
LW4	10.52	II	10.31	0.49	4.94	21.68	1.57	1.7	15.6	0.39	B4c
LW5	138.62	VI	34.16	0.88	29.64	39.16	1.43	1.95	36.2	0.30	B4c
BC1	30.85	VI	16.60	0.63	10.46	26.53	1.36	1.17	37.2	0.60	F4
BC2	22.64	II	12.16	0.67	8.07	18.27	1.37	1.53	33	0.52	F4
BC3	15.62	II	11.48	0.54	6.05	21.4	1.26	1.49	12.5	0.53	F4
BC4	8.47	II	11.72	0.38	4.37	31.81	1.32	1.61	26.4	0.62	F4
BC5	32.22	VI	17.16	0.69	11.73	25.02	1.15	1.17	37.2	0.48	F4
CC1	5.39	II	7.40	0.43	3.17	17.17	1.50	1.31	14.2	0.72	B4c
CC2	2.87	II	7.05	0.28	1.90	26.89	1.33	1.15	11.3	1.27	F4

Table 1.6: Measurements and physical parameters of the culverts or crossing cells at 12 road-stream crossings in the Kansas Flint Hills. Cell placement (L = Left, LC = Left center, RC = Right center, R = Right looking upstream) LW = low-water crossings, BC = box culverts, and CC = large single corrugated pipe culverts, numbers (e.g. LW1-5) indicate site number.

Site	Culvert	Placement	Width (m)	Height (m)	Length (m)	Perching (m)	Slope (%)
LW1	Elliptical	L	0.85	0.88	14.00	0.14	1.63
	Elliptical	C	0.85	0.88	14.00	0.14	1.35
	Elliptical	R	0.85	0.88	14.00	0.14	1.35
LW2	Round	L	0.77	0.77	6.15	0.18	0.74
	Round	LC	0.86	0.86	7.28	0.00	0.59
	Elliptical	RC	0.72	0.47	6.28	0.26	2.90
	Round	R	0.64	0.64	7.03	0.23	4.30
LW3	Round	L	0.96	0.96	6.15	0.90	1.10
	Round	R	0.94	0.94	6.15	0.10	2.32
LW4	Round		0.75	0.75	6.05	0.25	4.28
LW5	Elliptical	L	2.20	1.07	8.50	0.00	2.19
	Round	C	1.03	0.68	6.85	0.08	1.38
	Box	R	0.40	0.86	6.23	0.22	1.32
BC1	Box	L	6.10	3.69	16.00	0.14	0.53
	Box	C	6.10	3.69	16.00	0.14	0.53
	Box	R	6.10	3.69	16.00	0.14	0.53
BC2	Box	L	4.30	3.00	8.70	0.00	0.03
	Box	R	4.30	3.00	8.70	0.00	0.21
BC3	Box	L	3.05	3.00	10.10	0.00	0.17
	Box	C	3.05	3.00	10.10	0.00	0.17
	Box	R	3.05	3.00	10.10	0.00	0.17
BC4	Box	L	4.20	4.25	16.25	0.05	0.15
	Box	R	4.20	4.25	16.25	0.10	0.30
BC5	Box	L	6.20	4.25	16.95	0.00	0.00
	Box	R	6.20	4.25	16.95	0.00	0.00
CC1	Elliptical		3.90	2.40	10.46	0.00	1.22
CC2	Elliptical		3.43	2.24	7.44	0.00	0.03

Table 1.7: Measured parameters at 12 road-stream crossings in the Kansas Flint Hills and their effect on overall proportional fish movement and proportional movement by taxonomic group as determined by logistic regression. Slope is the slope of the line relating proportional fish movement to the measured crossing parameters. SE = standard error.

Taxonomic Group	Bottom Velocity (m/s)	Water Depth (cm)	Crossing Slope (%)	Crossing Length (m)	Velocity/ Depth	Crossing Perch (cm)
Cyprinids						
Slope (SE)	0.05 (0.05)	0.04 (0.05)	-3.26 (35.9)	0.09 (0.14)	-10.3 (21.9)	-0.03 (0.06)
p-value	0.33	0.39	0.93	0.49	0.63	0.54
Phoxinus						
Slope (SE)	-1.6 (3.6)	1.4 (0.02)	-55.0 (98.6)	-0.03 (0.33)	-14.2 (28.4)	-0.11 (0.09)
p-value	0.65	<0.0001	0.09	0.92	0.61	0.22
Overall						
Slope (SE)	-2.03 (1.0)	0.02 (0.04)	-13.7 (28.0)	0.07 (0.10)	-10.7 (14.8)	-0.05 (0.05)
p-value	0.04	0.60	0.62	0.50	0.47	0.31

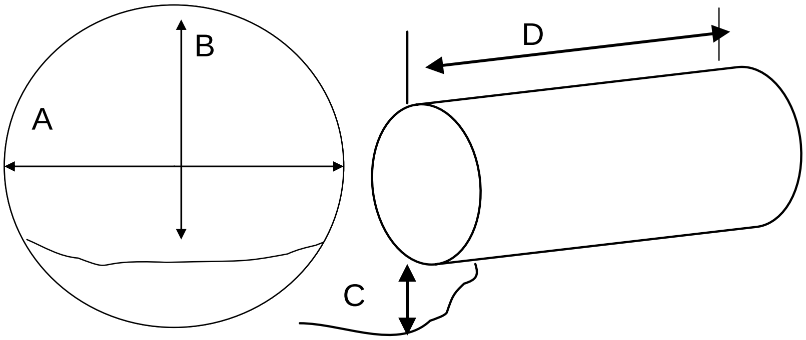
Table 1.8: Mean riffle spacing (bankfull widths) at 12 road-stream crossings in the Kansas Flint Hills. * Site CC2 was a riffle-run dominated stream, so no pools were present to calculate spacing.

Site	Crossing Design	Upstream Spacing	Downstream Spacing
LW1	Low-Water	17.65	4.52
LW2	Low-Water	7.50	6.64
LW3	Low-Water	4.42	4.14
LW4	Low-Water	7.43	4.15
LW5	Low-Water	6.28	2.54
BC1	Box Culvert	4.43	3.15
BC2	Box Culvert	5.06	4.96
BC3	Box Culvert	3.95	5.05
BC4	Box Culvert	5.34	7.52
BC5	Box Culvert	5.54	3.14
CC1	Corrugated Culvert	3.60	4.55
CC2	Corrugated Culvert	n/a *	n/a *

Table 1.9: Dimensions of road-stream crossings, the adjacent stream channel, and estimated values from regional curves at 12 sites in the Kansas Flint Hills, BKF = bankfull, XS = channel cross-section, Xing = Crossing, LW = low-water crossings, BC = box culverts, and CC = large single corrugated pipe culverts, numbers (e.g. LW1-5) indicate site number.

Site	Total Width of Xing Cells (m)	Xing BKF Width (m)*	Riffle XS Average BKF Width (m)	Mean BKF Depth at Xing (m)	Regional Curve BKF Mean Depth (m)	Total Culvert Area (m^2)	BKF Area from Regional Curves (m^2)	Riffle XS Average BKF Area (m^2)	Width/ Depth Ratio at Xing	Mean Riffle Width/ Depth Ratio
LW1	2.55	43.36	18.93	0.63	1.13	1.73	29.14	29.09	68.32	12.27
LW2	2.69	42.27	25.44	0.34	0.82	1.59	15.73	15.53	125.53	42.15
LW3	1.91	27.96	16.12	0.18	0.58	1.37	6.48	6.34	152.78	41.46
LW4	0.75	23.66	10.31	0.20	0.52	0.34	5.09	4.94	121.76	21.68
LW5	3.36	44.90	34.16	0.59	1.46	2.77	29.60	29.64	75.49	39.16
BC1	18.30	18.30	16.60	0.59	0.70	67.24	10.64	10.46	31.25	26.53
BC2	8.60	8.60	12.16	0.97	0.61	25.69	8.33	8.07	8.84	18.27
BC3	9.15	9.15	11.48	0.71	0.58	27.33	6.48	6.05	12.86	21.4
BC4	8.42	8.42	11.72	0.53	0.49	32.36	4.44	4.37	15.86	31.81
BC5	12.41	12.41	17.16	0.94	0.73	52.47	11.56	11.73	13.26	25.02
CC1	3.90	3.66	7.40	0.89	0.40	7.13	3.24	3.17	4.11	17.17
CC2	3.43	3.20	7.05	0.61	0.31	1.73	1.95	1.9	5.25	26.89

* At bankfull flows, water inundates the low-water crossings, bankfull width extends along the road surface.



- A – Crossing Width
- B – Crossing Height
- C – Perching
- D – Crossing Length

Figure 1.1.

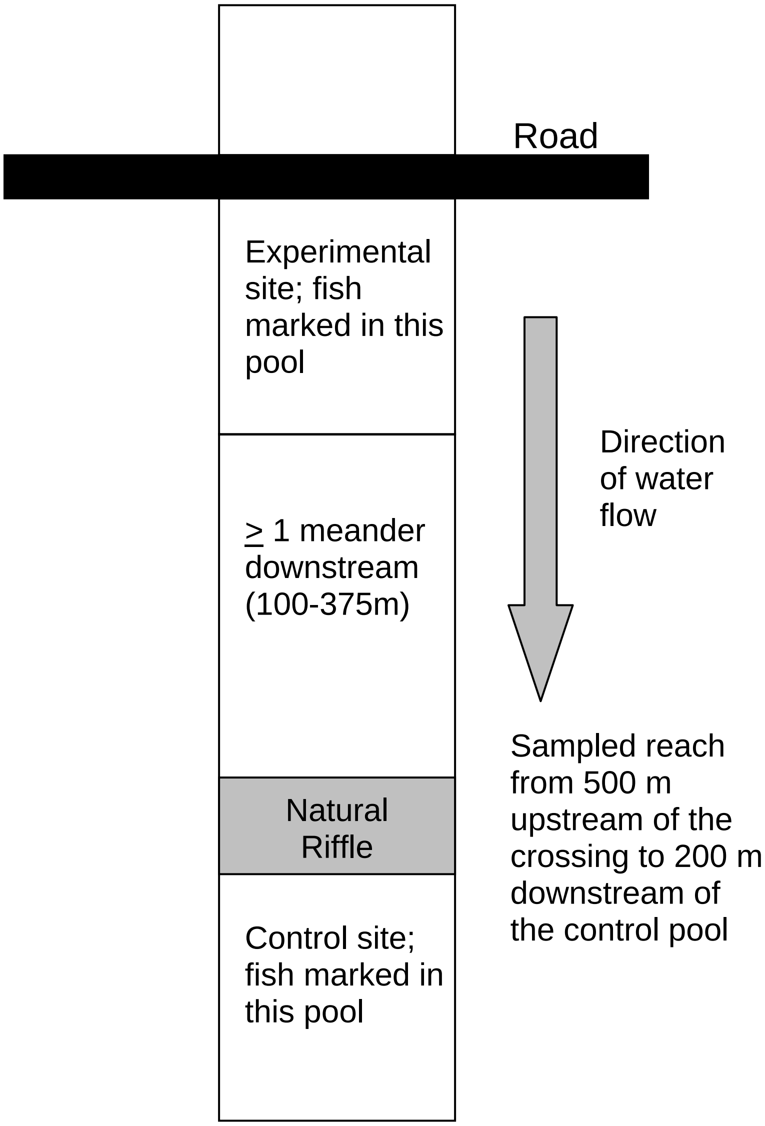
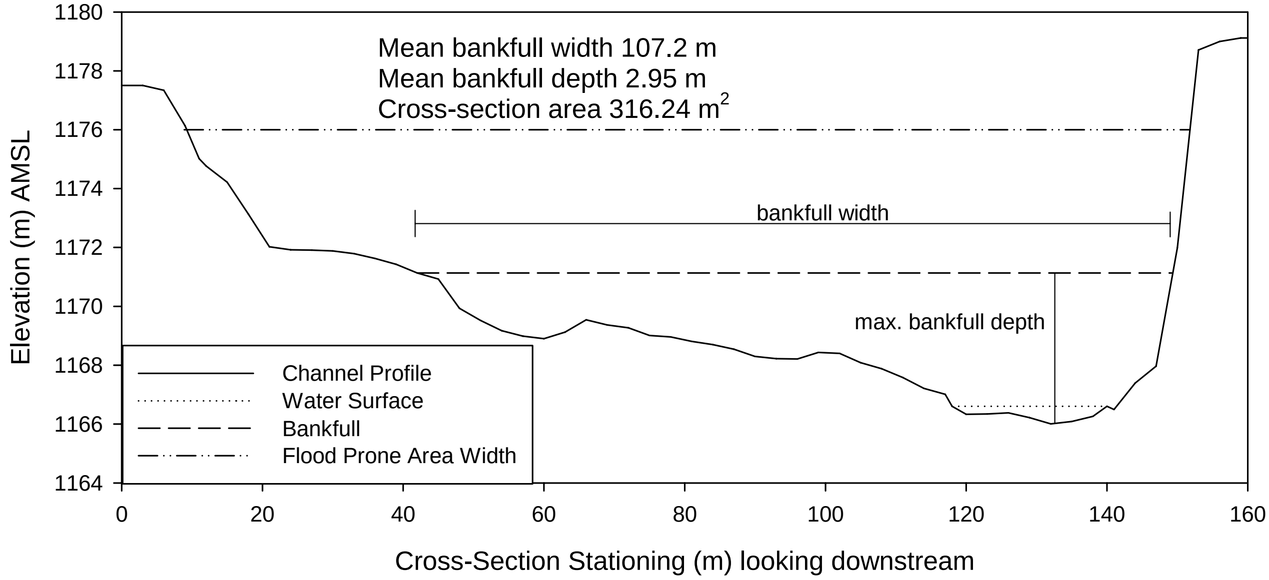

Road
Experimental site; fish marked in this pool
≥ 1 meander downstream (100-375m)
Natural Riffle
Control site; fish marked in this pool
Direction of water flow
Sampled reach from 500 m upstream of the crossing to 200 m downstream of the control pool

Figure 1.2.



1180
1178
1176
1174
1172
1170
1168
1166
1164
Elevation (m) AMSL
0
20
40
60
80
100
120
140
160
Cross-Section Stationing (m) looking downstream
Mean bankfull width 107.2 m
Mean bankfull depth 2.95 m
Cross-section area 316.24 m²
bankfull width
max. bankfull depth
Channel Profile
Water Surface
Bankfull
Flood Prone Area Width

Figure 1.3.

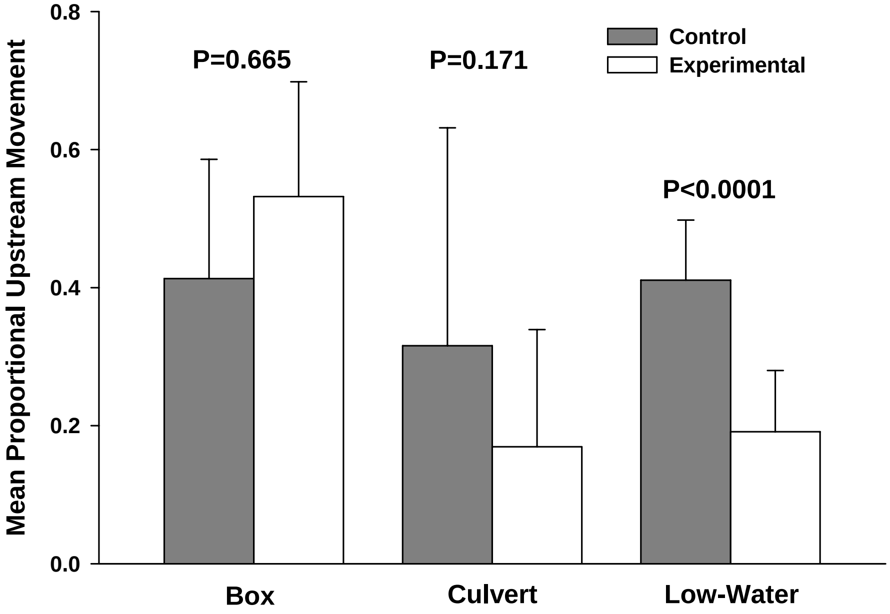

Mean Proportional Upstream Movement
0.0
0.2
0.4
0.6
0.8
Control
Experimental
P=0.665
P=0.171
P<0.0001
Box
Culvert
Low-Water

Figure 1.4.

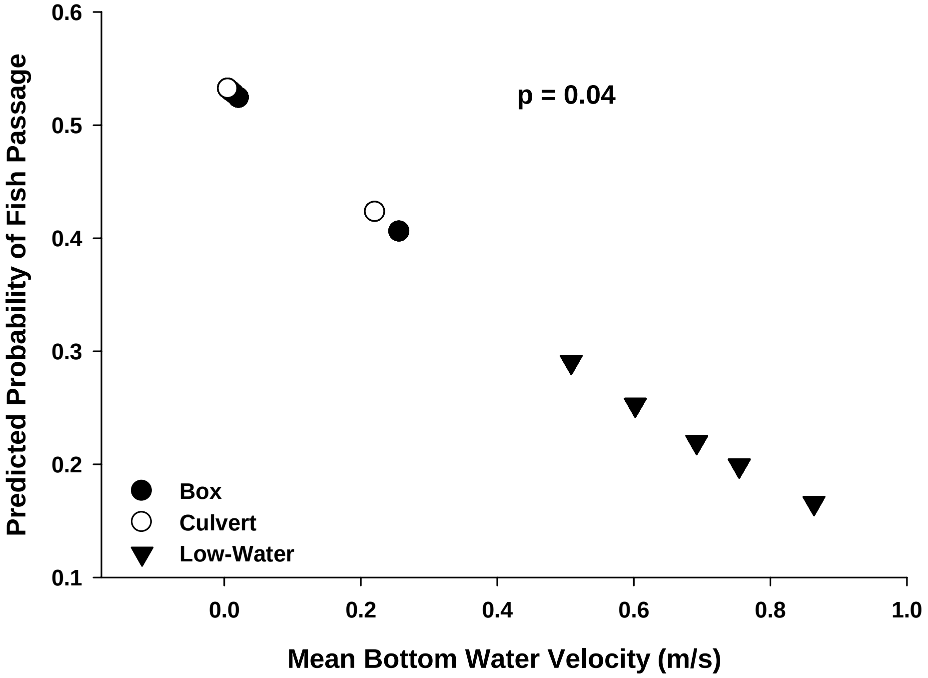

p = 0.04
Predicted Probability of Fish Passage
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.2
0.4
0.6
0.8
1.0
Mean Bottom Water Velocity (m/s)
● Box
○ Culvert
▼ Low-Water

Figure 1.5.

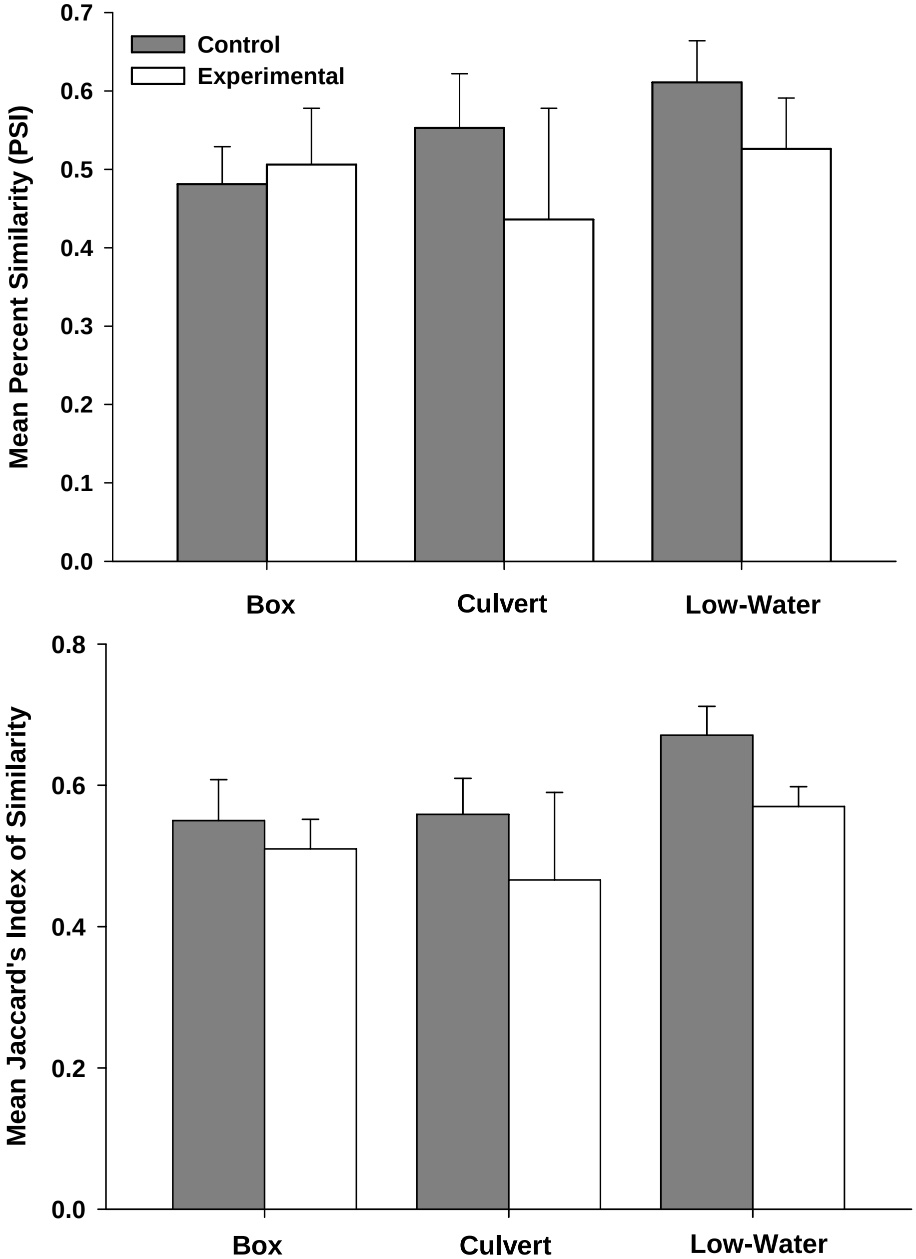

0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
Mean Percent Similarity (PSI)
Control
Experimental
Box
Culvert
Low-Water
0.8
0.6
0.4
0.2
0.0
Mean Jaccard's Index of Similarity
Box
Culvert
Low-Water

Figure 1.6.

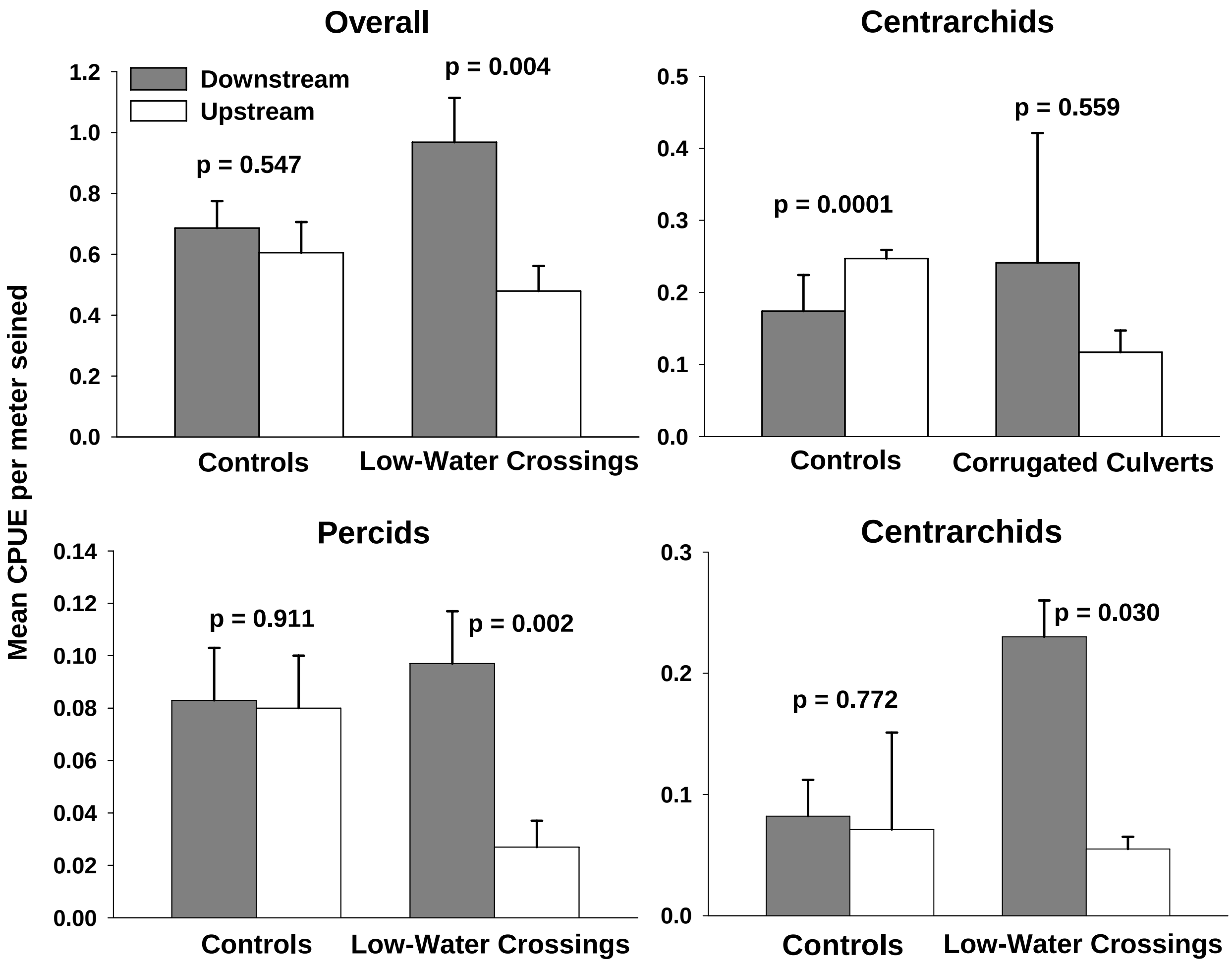

Overall
Centrarchids
Percids
Centrarchids
Mean CPUE per meter seined
Downstream
Upstream
p = 0.547
p = 0.004
p = 0.0001
p = 0.559
p = 0.911
p = 0.002
p = 0.772
p = 0.030
Controls
Low-Water Crossings
Corrugated Culverts
0.0
0.2
0.4
0.6
0.8
1.0
1.2
0.1
0.3
0.5
0.00
0.02
0.04
0.06
0.08
0.10
0.12
0.14

Figure 1.7.

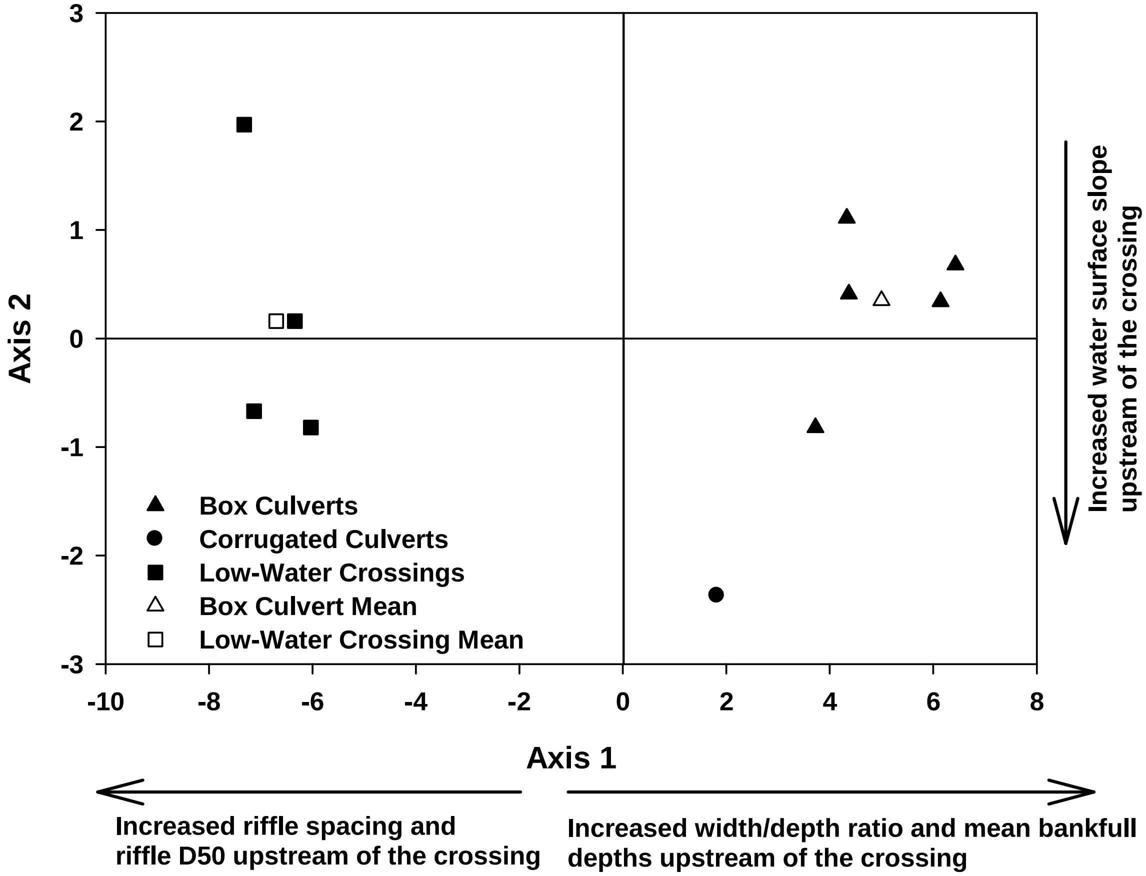

3
2
1
0
-1
-2
-3
Axis 2
-10
-8
-6
-4
-2
0
2
4
6
8
Axis 1
▲ Box Culverts
● Corrugated Culverts
■ Low-Water Crossings
△ Box Culvert Mean
□ Low-Water Crossing Mean
Increased water surface slope upstream of the crossing
Increased riffle spacing and riffle D50 upstream of the crossing
Increased width/depth ratio and mean bankfull depths upstream of the crossing

Figure 1.8:

Chapter 2: The effects of crossing design and water velocity on the movement of Great Plains lotic fishes in an experimental stream.

Abstract

Road-stream crossings may prohibit fish passage by creating velocity barriers to movement. Upstream passage of four fish species native to Great Plains streams; Topeka shiner (*Notropis topeka*), green sunfish (*Lepomis cyanellus*), red shiner (*Cyprinella lutrensis*), and Southern redbelly dace (*Phoxinus erythrogaster*) was tested through three simulated crossing designs (box culverts, round corrugated culverts, and natural rock) at water velocities of 0.1 m/s to 1.1 m/s in an experimental stream. The proportion of fish that moved upstream did not differ among crossing design for Southern redbelly dace, green sunfish, or Topeka shiner, but natural rock crossings had lower proportional movement (mean = 0.19) than box (0.38) or corrugated culvert designs (0.43) for red shiners. Water velocity did not affect proportional upstream movement of any species except that the proportion of Topeka shiners that moved upstream increased with water velocities. These results suggest that water velocity in different crossing designs alone may not determine fish passage, and that barriers to fish movement may be caused by other variables (e.g. perching, slope, crossing length). Nonetheless, water velocities up to 1.1 m/s may not hinder fish passage of many Great Plains fishes.

Introduction

Nearly 40% of North American freshwater fishes are currently imperiled (Jelks et al., 2008) by the effects of urbanization, eutrophication, habitat modification or degradation, and human-induced climate change. In addition, structures such as dams and road crossings may act as barriers to fish migration. Road stream crossings that constrict the natural channel or exhibit steep gradients can potentially create physical barriers to fish passage by increasing the turbulence and water velocity through the crossing (Votapka, 1991; Wall and Berry, 2004; WDFW, 2003). Migration barriers can cause the fragmentation of critical habitats, alter species abundance and diversity, reduce genetic diversity, and even cause species extirpation (Nehlsen et al., 1991; Winston et al., 1991; Sheer and Steel, 2006).

The majority of research on fish passage has occurred with salmonids (Gibson et al., 2005; Mueller et al., 2008). Although state and federal agencies in the western U.S. have established guidelines for culvert installation and design based on swimming and jumping abilities of migrating fishes, these programs may have little utility in other regions with different fish communities (Behlke et al., 1991; WDFW, 2003). Little is known about the effects of road-stream crossings and associated water velocities on prairie stream fish assemblages.

Water velocity and crossing designs may have different effects on fish movement. Velocity through road culverts may affect swimming distance and frequency (Toepfer et al., 1999), and as velocity increases, the likelihood of fish passage through a crossing is reduced while energetic stress is amplified (Adams et al., 2000). Warren and Pardew (1998) found reduced proportional fish passage through culvert and slab crossings compared to open box and ford (submerged roadbed) crossings in Arkansas streams, and research has shown corrugated culvert crossings to reduce fish movement in Virginia and West Virginia (Coffman, 2005). The proportion of trout that were able to pass through corrugated culverts was reduced by increased culvert outlet height in a Montana watershed (Burford, 2005; Cahoon et al., 2005), and increased culvert slope (mean 2.4%, range 0.16 – 6.7%), slope x length, and water velocity (up to 2.0 m/s) reduced the proportional movement of salmonids and cyprinids in the Eastern U.S. (Coffman, 2005). Therefore, fish passage for various fish species can be affected by crossing design, installation, and water velocity.

The objectives of this study were to test upstream passage of four prairie stream fishes through three crossing designs (box culverts, round corrugated pipe culverts, and natural rock substrate crossings) and across 11 different water velocities (0.1 – 1.1 m/s) in an experimental stream system. Our goal was to further identify the physical and or behavioral limitations that crossing design and water velocity have on prairie stream fishes, and provide managers and transportation engineers with information to assist them in constructing fish-friendly crossings.

Methods

We tested three crossing designs in controlled experimental stream systems from June to August 2008 at the Konza Prairie Biological Station (KPBS) near Manhattan, Kansas. The experimental stream system consisted of alternating, round, 1,136 L, 1.8 m diameter by 0.9 m deep fish-culture tanks (pool habitats) connected by straight-sided, 1.83 m long by 0.46 m wide and 0.38 m deep, fiberglass riffles (Mathews et al., 2006). All pool habitats contained river rock substrate from an adjacent natural stream. Each stream unit consisted of an upstream and downstream pool connected by the riffle. A constant supply of water from a natural spring was provided to each pool, and stream units were equipped with overflow drains to maintain water depths. Replicas of common stream crossing designs or natural rock substrate occupied one half of the riffle section while the other half was separated by a wall and contained the hardware necessary for the generation of flow through the stream unit. To generate the desired water velocities we used a combination of variable speed electric trolling motors and large sump and utility pumps.

We tested three common road crossings: 1) box culverts, 2) round corrugated pipe culverts, and 3) a natural rock substrate which was intended to serve as a control. In a survey of 90 road crossings in Northeastern Kansas, 32% were corrugated pipe culverts and 21% were concrete box culverts, with the remainder of crossings being bridges or old stone arch crossings (S. Blackford, U.S. Fish and Wildlife Service, pers. comm.). Box culvert models were constructed by lining the bottom of the fiberglass riffle with concrete landscaping blocks and covering the top of the crossing with plywood to simulate a covered concrete box. Corrugated pipe culvert models were constructed using round, corrugated plastic pipe 15 cm in diameter. To create the natural substrate treatment, the bottoms of the fiberglass riffles were covered with natural river rock and left uncovered to better resemble a natural riffle.

We tested fish movement at all three crossing designs with water velocities from 0.1 m/s to 1.1 m/s at 0.1 intervals. Water velocity was measured using a Marsh-McBirney Flow-Mate 2000 flow meter at 60% of the water depth at nine locations through the model box culverts and the natural substrate treatments and then averaged. Water velocity was only measured at the corrugated culvert crossing exit. Water depth through the crossing in all treatments was maintained at 10 cm. These depths and velocities are comparable to conditions in Northeast Kansas streams where May to August 2007 water velocities at 12 road-stream crossings ranged from 0 – 1.42 m/s (mean 0.34 m/s) with 94% of the measurements below 1.1 m/s. Mean depth at these crossings was 14 cm and ranged 1.2 - 42.1 cm (W. Bouska, unpublished data).

Fish species analyzed for movement were the federally endangered Topeka shiner (*Notropis topeka*), green sunfish (*Lepomis cyanellus*), Southern redbelly dace (*Phoxinus erythrogaster*), and red shiner (*Cyprinella lutrensis*). Southern redbelly dace were collected from Kings Creek on the KPBS and red shiners were collected from Deep Creek, about 20 km from the KPBS. Topeka shiners and green sunfish were obtained from the University of Kansas artificial rearing facility operated by the Kansas Biological Survey, Lawrence, Kansas. Fish length was measured prior to testing to ensure similar sizes of fish were used in each treatment. An effort was made to test fish only once, but due to permitting restrictions, some Topeka shiners had to be used in more than one experiment. Before use in our experimental streams, fish were treated for Asian tapeworm (*Bothriocephalus acheilognathi*) with praziquantel powder (Aquascience Research Group Inc., Kansas City, MO), which is an effective treatment for Asian tapeworm (Koehle and Adelman, 2007; Ward, 2007). Praziquantel powder was first dissolved in ethanol, further dissolved with water, and then added to the holding tanks, with one gram of powder treating 380 L of water.

Fish were first housed in 700 L rectangular fiberglass holding tanks equipped with standpipe drains and fresh water from the natural spring. The holding tanks were partially covered to protect fish from predators and the sun, and captive fish were fed flake food and frozen bloodworms. Fish were allowed to acclimate at least 48 hours to the fiberglass tanks before being used in the experiments. Fish were tested two species at a time (Topeka shiners and green sunfish; Southern redbelly dace and red shiners) with twenty of each species per treatment. Fish were placed in the experimental stream units for a period of 24 hours. Minnow traps were attached in the upstream pool to the top of the model crossings to capture fish that successfully moved upstream through the crossing and prevent fish from returning downstream after passage.

At the end of each 24 hour treatment, fish were collected from the trap and measured, the pools were drained, and the remaining fish were removed.

Data Analysis

Analysis of variance was used to determine if mean fish lengths by species differed among velocity treatments. Upstream fish movement was expressed as proportional movement, (P) = M / R, where M is the number of fish moving upstream through the model crossing, and R is the total number of fish that were placed in the downstream pool (Warren and Pardew, 1998). An analysis of covariance (ANCOVA) with velocity as the covariate, was conducted to determine if the proportion of fish that moved upstream was related to crossing type and water velocity. A significant interaction indicated that the relationship between fish movement and water velocity was not consistent among crossing designs (ANCOVA test for slopes; Zar, 1996).

Results

Mean lengths of fish used in each of the 11 water velocities and three crossing designs did not differ for Topeka shiner (mean 56 mm, range 41-79 mm, $p = 0.612$), green sunfish (mean 44 mm, range 30-83 mm, $p = 0.175$), Southern redbelly dace (mean 46 mm, range 38-60 mm, $p = 0.823$), and red shiner (mean 51 mm, range 40-71 mm, $p = 0.135$). The slopes of the regression lines of the relationship between velocity and proportional fish movement did not differ for Topeka shiner ($p = 0.362$), green sunfish ($p = 0.186$), Southern redbelly dace ($p = 0.268$), or red shiner ($p = 0.569$; Figure 2.1). Therefore the proportion of fish moving upstream was consistent among crossing designs for each velocity tested. The proportion of fish that moved upstream did not differ by crossing design for Southern redbelly dace ($p = 0.146$) and green sunfish ($p = 0.82$) nor by velocity for Southern redbelly dace ($p = 0.184$) or green sunfish ($p = 0.220$; Figure 2.1). Upstream movement of Topeka shiners did not differ among crossing design ($p = 0.322$) but greater movement was observed at higher velocities ($p < 0.0001$; Figure 2.1). Even at velocities of 1.1 m/s, up to 60% of Topeka shiners moved upstream. The proportion of red shiners that moved upstream did not differ by water velocity ($p = 0.927$) but natural rock crossings had lower movement than box or culvert crossings ($p = 0.027$; Figure 2.1; Table 2.1). For all velocities and crossings, Topeka shiners and green sunfish never exhibited movement greater than 60%, while Southern redbelly dace and red shiners displayed movement up to 95% (Figure 2.1). Overall, the mean proportion of fish that moved upstream was 0.17 (SE 0.032) for Topeka shiners, 0.19 (SE 0.024) for green sunfish, 0.36 (SE 0.039) for red shiners, and 0.45 (SE 0.041) for Southern redbelly dace, regardless of crossing design or velocity.

Discussion

The upstream movement of the four prairie stream fishes did not appear to be affected by crossing design; except for red shiners, which surprisingly indicated reduced movement through the natural rock design. The reduced proportional movement by red shiners through this design was unexpected, as this design was intended to mimic a natural riffle. Because the top of the natural rock design was open allowing in light, and the box culvert and corrugated culvert models were enclosed and much darker, there is a possibility that red shiners had an aversion to the uncovered rock substrate (i.e. behavioral barrier) which may explain the reduced movement through this design. Light may attract some species and repel others occupying the same habitat, indicating different responses by different species to light stimuli (Popper and Carlson, 1998).

Water velocity was not a determining factor for upstream movement except for Topeka shiners. Topeka shiners exhibited greater movement at increased water velocities, which may suggest a biological or physiological response to increased flow and the desire to move upstream. Movement during these increased flows could be a spawning cue. Peak spawning in

Topeka shiners begins in May (Pflieger, 1997; Kerns and Bonneau, 2002), which coincides with periods of increased stream flow and higher velocities. All of our tested species exhibit overlapping spawning periods, and green sunfish, red shiners and Topeka shiners are often observed spawning simultaneously (Pflieger, 1997). However, movement of Southern redbelly dace, red shiners and green sunfish was not altered by changes in velocity and was more random across water velocities. Upstream migrations in these species may be triggered by mechanisms other than velocity.

Swimming ability is a factor that may determine fish passage. Adams et al. (2000) found that 45 to 55 mm total length Topeka shiners could swim for about 60 s at 0.75 m/s water velocity. Using this endurance and velocity data, and an equation by Peake et al. (1997) and Adams et al. (2000) for predicted passable water velocities ($V_f = V_s - (D/E_{vs})$, where V_f is the velocity through the crossing (m/s), D is the distance of the crossing (m) and E_{vs} is endurance in seconds at V_s, we would predict passage of Topeka shiners through our crossings only up to 0.72 m/s. However, our study indicated Topeka shiner (of similar sizes to Adams et al., 2000) passage at velocities up to 1.1 m/s through our 1.86 m crossings, suggesting Topeka shiner endurance and swimming performance may be greater than previously reported. Ward et al. (2003) determined average failure velocities (velocity at which fish could no longer maintain position in a recirculating swim tunnel) of 0.775 m/s for red shiners (mean length 68.9 mm), 0.462 m/s for green sunfish (mean length 70.2 mm), and 0.704 m/s for speckled dace (*Rhinichthys osculus*) (mean length 68.4 mm). In contrast, our study revealed that 24-43% of our stream fishes moved upstream even at velocities of 0.8 m/s and greater. Additionally, our tested fish were all smaller compared to those tested by Ward et al. (2003) which would reduce swimming ability (Adams et al., 2000; Wolter and Arlinghaus, 2003). Our results suggest that prairie fishes may be able to pass through various crossing designs at water velocities up to 1.1 m/s. However, other factors (e.g. perching) not measured in this study may still affect fish passage. More research may be needed to determine the factors that affect swimming performance and fish passage for prairie stream fishes.

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Table 2.1. Analysis of covariance (ANCOVA) results and summary statistics testing if the proportion (P) of fish that moved upstream differed by water velocity, culvert design, or their interaction (tests for slopes) of four prairie stream fishes in an experimental stream system. Degrees freedom (DF) 2 for slopes and design, 1 for velocity, SE = standard error.

	Species							
	Topeka shiner		red shiner		Southern redbelly dace		green sunfish	
ANCOVA	DF	p-value	DF	p-value	DF	p-value	DF	p-value
Test for slopes	2	0.362	2	0.569	2	0.268	2	0.186
Test for velocity	1	<0.0001	1	0.927	1	0.184	1	0.22
Test for design	2	0.322	2	0.027	2	0.186	2	0.82
Mean Movement	P	SE	P	SE	P	SE	P	SE
box culvert	0.17	0.059	0.38	0.062	0.35	0.061	0.21	0.032
corrugated pipe	0.12	0.035	0.43	0.076	0.54	0.064	0.17	0.04
natural rock	0.21	0.053	0.19	0.044	0.45	0.081	0.18	0.053

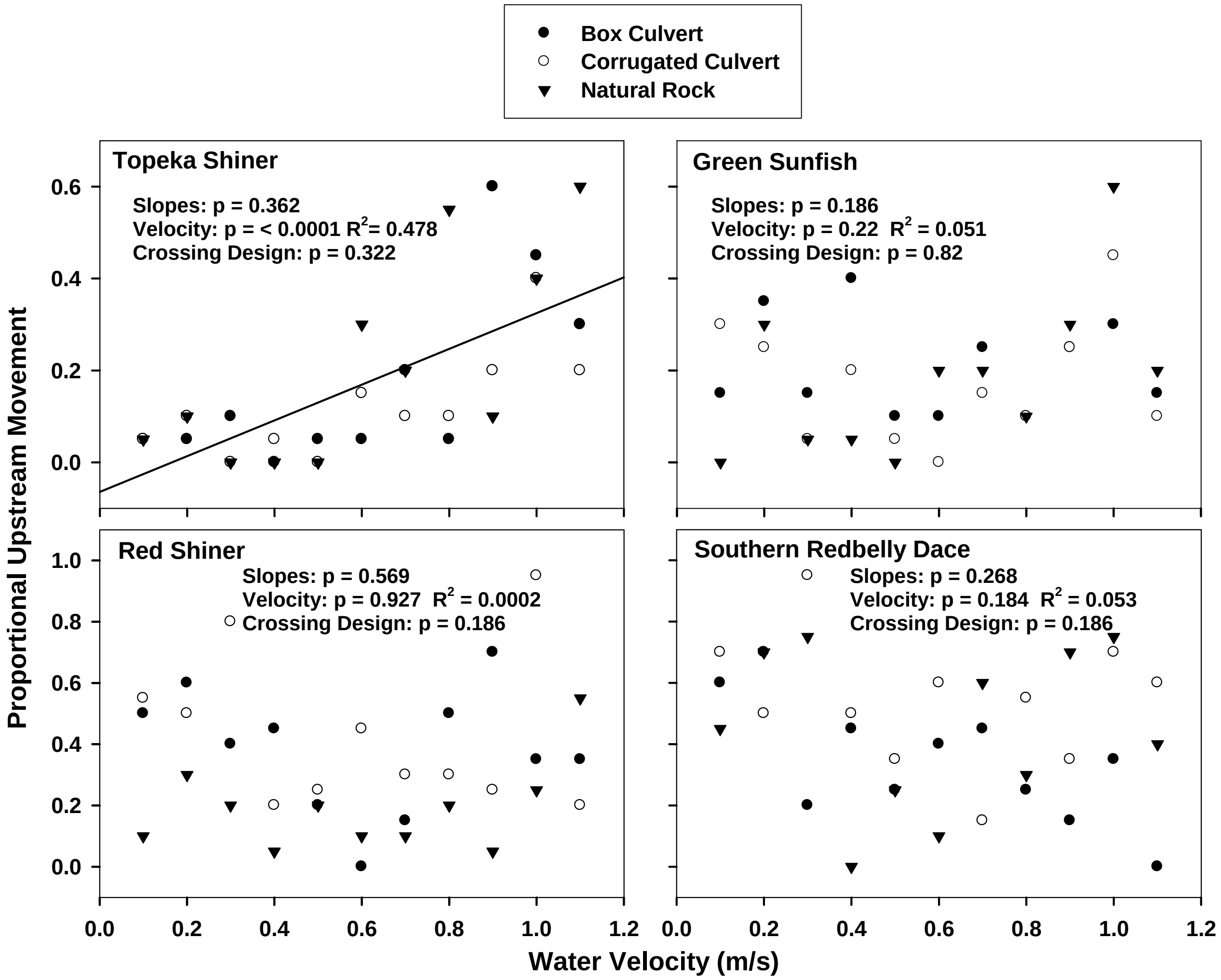● Box Culvert
○ Corrugated Culvert
▼ Natural Rock
Topeka Shiner
Slopes: p = 0.362
Velocity: p = < 0.0001 R2= 0.478
Crossing Design: p = 0.322
Green Sunfish
Slopes: p = 0.186
Velocity: p = 0.22 R2 = 0.051
Crossing Design: p = 0.82
Red Shiner
Slopes: p = 0.569
Velocity: p = 0.927 R2 = 0.0002
Crossing Design: p = 0.186
Southern Redbelly Dace
Slopes: p = 0.268
Velocity: p = 0.184 R2 = 0.053
Crossing Design: p = 0.186
Proportional Upstream Movement
Water Velocity (m/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2

Figure 2.1

Appendix A: Supplemental Tables

Table A.1: Rosgen Level II (Rosgen, 1996) delineative criteria and classification upstream and downstream of road-stream crossings at 12 sites in the Kansas Flint Hills. * No riffle upstream of this crossing, classification estimated. **Both site LW1 riffle cross-sections are located downstream (LW1**) is farthest downstream from the crossing. BKF = bankfull, D50 = median substrate particle size, site designation LW = low-water crossings, BC = box culverts, and CC = large single corrugated culverts.

Site	Valley Type	BKF Width (m)	BKF Mean Depth (m)	BKF Area (sq m)	Width/ Depth Ratio	Entrenchment Ratio	Sinuosity	Riffle XS D50 (mm)	Water Surface Slope (%)	Rosgen Class
Upstream										
LW1*	VI	n/a	n/a	n/a	n/a	n/a	1.87	0.05	0.02	F6
LW2	VI	28.58	0.54	15.43	52.63	1.54	1.09	29.7	0.32	B4c
LW3	II	13.54	0.46	6.16	29.6	1.4	1.2	39.4	0.66	B4c
LW4	II	9.33	0.54	5.01	17.29	1.48	1.7	45.6	0.36	B4c
LW5	VI	35.62	0.85	30.03	42.01	1.52	1.95	59.3	0.28	B4c
BC1	VI	17.65	0.62	10.87	28.51	1.47	1.17	54.5	0.46	B4c
BC2	II	11.89	0.70	8.22	17.1	1.44	1.53	38.5	0.74	B4c
BC3	II	10.36	0.59	6.10	17.5	1.21	1.49	35.7	0.56	F4
BC4	II	10.64	0.43	4.55	24.73	1.5	1.61	38.5	0.71	B4c
BC5	VI	16.72	0.74	12.21	22.7	1.11	1.17	41.8	0.39	F4
CC1	II	6.74	0.45	3.03	14.93	1.9	1.31	37.9	0.76	B4c
CC2	II	6.37	0.33	2.07	19.53	1.56	1.15	41.8	1.09	B4c
Downstream										
LW1**	VI	18.62	1.60	29.69	11.6	2.02	1.87	11.8	0.22	B4c
LW1	VI	19.25	1.49	28.48	12.93	1.7	1.87	3.5	0.22	B4c
LW2	VI	22.31	0.70	15.63	31.66	1.12	1.09	26.05	0.37	F4
LW3	II	18.70	0.35	6.52	53.32	1.13	1.2	54.5	0.78	F4
LW4	II	11.29	0.43	4.86	26.06	1.65	1.7	22.2	0.28	B4c
LW5	VI	32.70	0.90	29.25	36.3	1.33	1.95	38.5	0.3	F4
BC1	VI	15.56	0.65	10.05	23.94	1.24	1.17	66.8	0.73	F4
BC2	II	12.44	0.64	7.92	19.43	1.3	1.53	33.2	0.47	F4
BC3	II	12.60	0.48	6.00	26.3	1.3	1.49	23.9	0.52	F4
BC4	II	12.81	0.33	4.20	38.89	1.14	1.61	40.5	0.45	F4
BC5	VI	17.59	0.64	11.26	27.34	1.19	1.17	41.8	0.56	F4
CC1	II	8.06	0.41	3.32	19.42	1.68	1.31	53.6	0.71	B4c
CC2	II	7.73	0.23	1.73	34.24	1.1	1.15	45.0	1.23	F4

Table A.2: Collected species from 12 sites in the Kansas Flint Hills, May to August 2007.

Common name	Genus species	Number collected	Percent of total
emerald shiner	*Notropis atherinoides*	1	0.001
longnose gar	*Lepisosteus osseus*	1	0.001
river carpsucker	*Carpiodes carpio*	1	0.001
flathead catfish	*Pylodictus olivarus*	2	0.002
white crappie	*Pomoxis annularis*	2	0.002
black bullhead	*Ameiurus melas*	6	0.007
yellow bullhead	*Ameiurus natalis*	6	0.007
channel catfish	*Ictalurus punctatus*	11	0.013
logperch	*Percina caprodes*	19	0.022
golden shiner	*Notemigonus crysoleucas*	24	0.028
suckermouth minnow	*Phenacobius mirabilis*	60	0.069
sand shiner	*Notropis ludibundus*	67	0.077
shorthead redhorse	*Moxostoma macrolepidotum*	71	0.082
fathead minnow	*Pimephales promelas*	118	0.136
longear sunfish	*Lepomis megalotis*	235	0.271
johnny darter	*Etheostoma nigrum*	308	0.356
white suckers	*Catostomus commersonii*	348	0.402
bluegill	*Lepomis macrochirus*	352	0.406
bullhead minnow	*Pimephales vigilax*	356	0.411
green sunfish	*Lepomis cyanellus*	434	0.501
orangespotted sunfish	*Lepomis humilis*	512	0.591
slender madtom	*Notorus exilis*	589	0.680
bluntnose minnow	*Pimephales notatus*	954	1.101
topeka shiner	*Notropis topeka*	1234	1.425
largemouth bass	*Micropterus salmoides*	1275	1.472
orangethroat darter	*Etheostoma spectabile*	1659	1.915
creek chub	*Semotilus atromaculatus*	2983	3.444
carmine shiner	*Notropis percobromis*	3135	3.620
central stoneroller	*Campostoma anomalum*	6216	7.177
red shiner	*Cyprinella lutrensis*	13032	15.046
redfin shiner	*Lythrurus umbratilis*	13892	16.039
common shiner	*Luxilus cornutus*	14129	16.313
southern redbelly dace	*Phoxinus erythrogaster*	24582	28.381
Total		86612	100%

Table A.3: Tagging and recapture statistics by crossing design for 12 sites in the Kansas Flint Hills.

		Recaptures			
Box Culverts	Number tagged	N	%	Crossed	Not Crossed
carmine shiner					
Control	16	3	18.75	1	2
Experimental	22	8	36.36	2	6
common shiner					
Control	163	64	39.26	8	56
Experimental	120	30	25.00	13	17
creek chub					
Control	99	5	5.05	0	5
Experimental	20	3	15.00	0	3
central stoneroller					
Control	144	4	2.78	0	4
Experimental	43	0	0.00	0	0
green sunfish					
Control	30	1	3.33	0	1
Experimental	13	1	7.69	0	1
red shiner					
Control	10	7	70.00	3	4
Experimental	18	1	5.56	1	0
redfin shiner					
Control	29	3	10.34	0	3
Experimental	17	6	35.29	2	4
Southern redbelly dace					
Control	965	84	8.70	18	66
Experimental	257	36	14.01	20	16
Topeka shiner					
Control	6	1	16.67	0	1
Experimental	0	0	n/a	0	0
white sucker					
Control	7	1	14.29	0	1
Experimental	0	0	n/a	0	0

		Recaptures			
Low-Water Crossings	Number tagged	N	%	Crossed	Not Crossed
bullhead minnow					
Control	117	1	0.85	0	1
Experimental	2	0	0.00	0	0
bluntnose minnow					
Control	66	1	1.52	0	1
Experimental	32	2	6.25	1	1
carmine shiner					
Control	83	6	7.23	0	6
Experimental	117	8	6.84	1	7
common shiner					
Control	347	84	24.21	8	76
Experimental	218	33	15.14	16	17
creek chub					
Control	66	3	4.55	0	3
Experimental	32	0	0.00	0	0
johnny darter					
Control	16	1	6.25	0	1
Experimental	2	0	0.00	0	0
red shiner					
Control	73	36	49.32	2	34
Experimental	409	65	15.89	8	57
redfin shiner					
Control	513	30	5.85	0	30
Experimental	253	65	25.69	1	64
sand shiner					
Control	10	1	10.00	0	1
Experimental	0	0	n/a	0	0
Southern redbelly dace					
Control	761	55	7.23	8	47
Experimental	576	38	6.60	16	22
Topeka shiner					
Control	21	19	90.48	0	19
Experimental	49	2	4.08	0	2
white sucker					
Control	10	1	10.00	0	1
Experimental	7	0	0.00	0	0

Corrugated Culverts	Number tagged	Recaptures N	 %	 Crossed	 Not Crossed
bluegill					
Control	2	1	50	0	1
Experimental	13	1	7.69	1	0
bluntnose minnow					
Control	11	7	63.64	5	2
Experimental	6	3	50	0	3
common shiners					
Control	20	9	45	1	8
Experimental	31	21	67.74	15	6
creek chub					
Control	6	0	0	0	0
Experimental	18	2	11.11	0	2
green sunfish					
Control	2	0	0	0	0
Experimental	11	2	18.18	1	1
johnny darter					
Control	0	0	n/a	0	0
Experimental	6	5	83.33	1	4
longear sunfish					
Control	3	1	33.33	0	1
Experimental	1	0	0	0	0
orangespotted sunfish					
Control	2	0	0	0	0
Experimental	21	4	19.05	1	3
orangethroated darter					
Control	27	6	22.22	0	6
Experimental	20	7	35	4	3
redfin shiner					
Control	0	0	n/a	0	0
Experimental	11	9	81.82	1	8
Southern redbelly dace					
Control	1	0	0	0	0
Experimental	43	3	6.98	2	1
Topeka shiner					
Control	0	0	n/a	0	0
Experimental	12	5	41.67	3	2
white sucker					
Control	3	1	33.33	1	0
Experimental	3	0	0	0	0

Appendix 2: Longitudinal Profile Plots

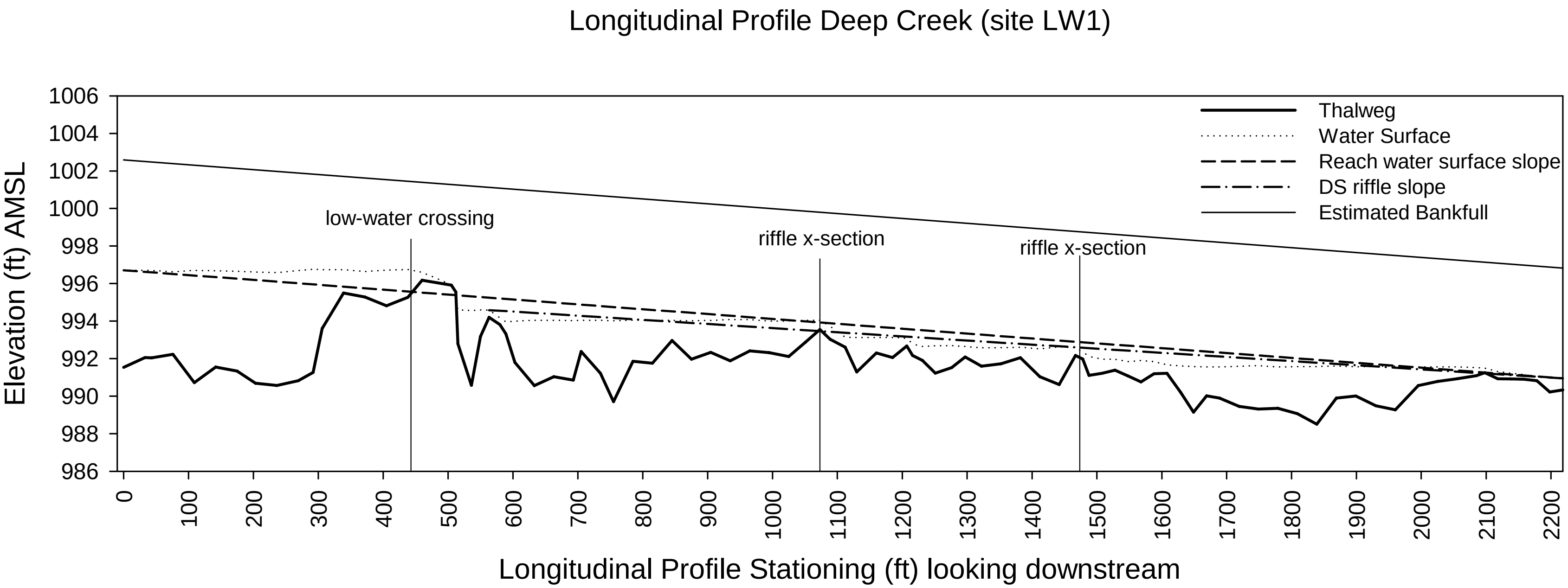

Figure 1: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site LW1. DS = downstream, AMSL = above mean sea level, x-section = cross-section.

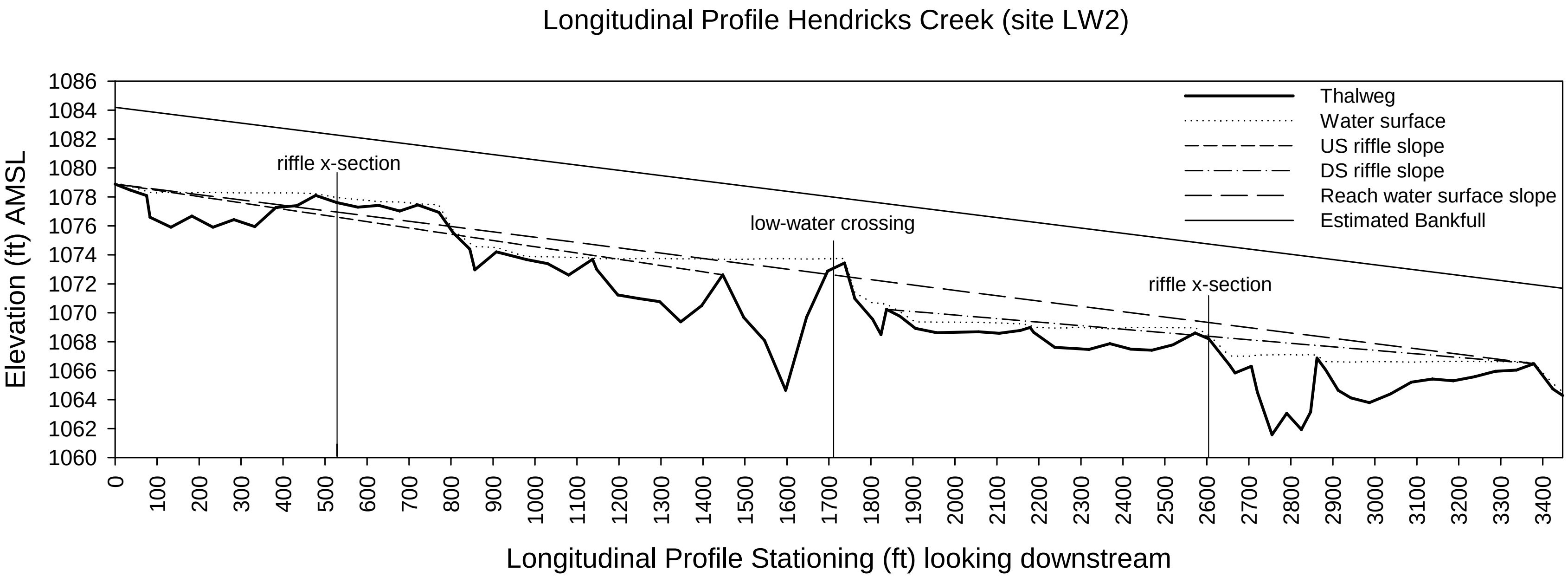

Figure 2: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site LW2. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

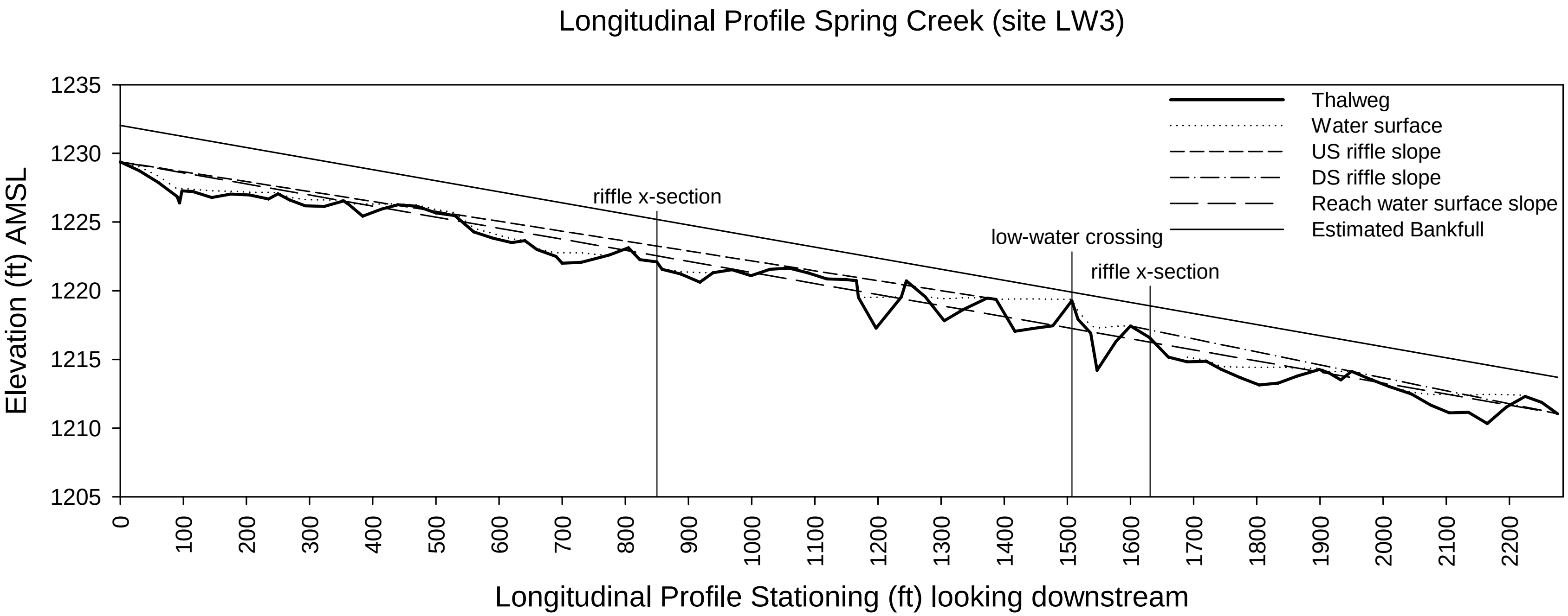

Figure 3: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site LW3. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

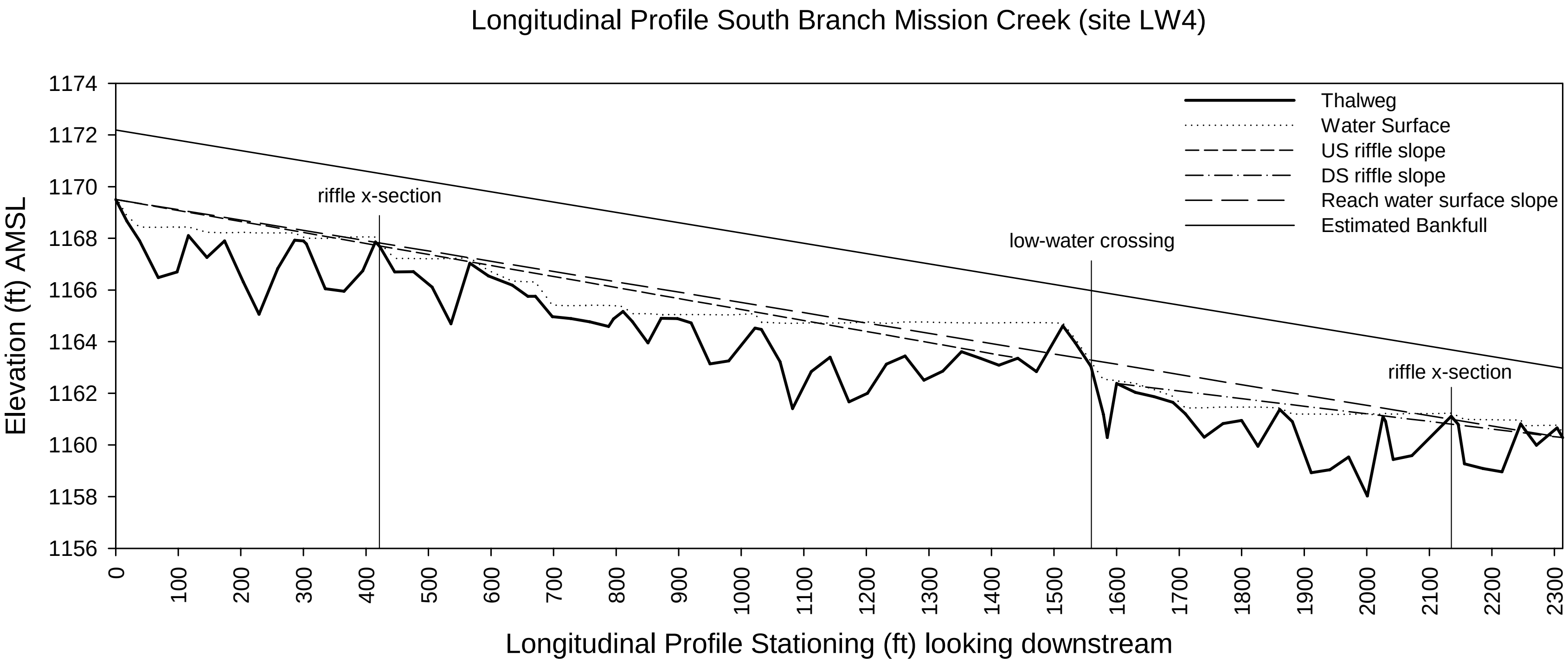

Figure 4: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site LW4. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

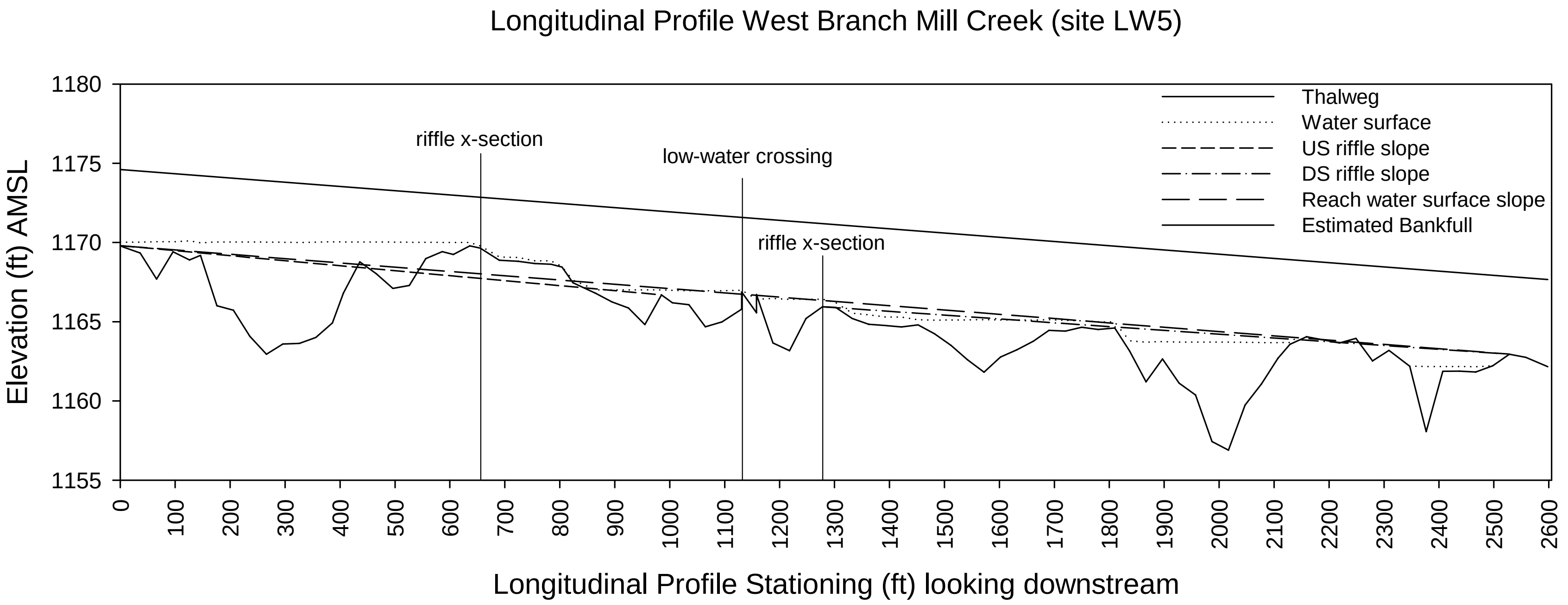

Figure 5: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site LW5. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

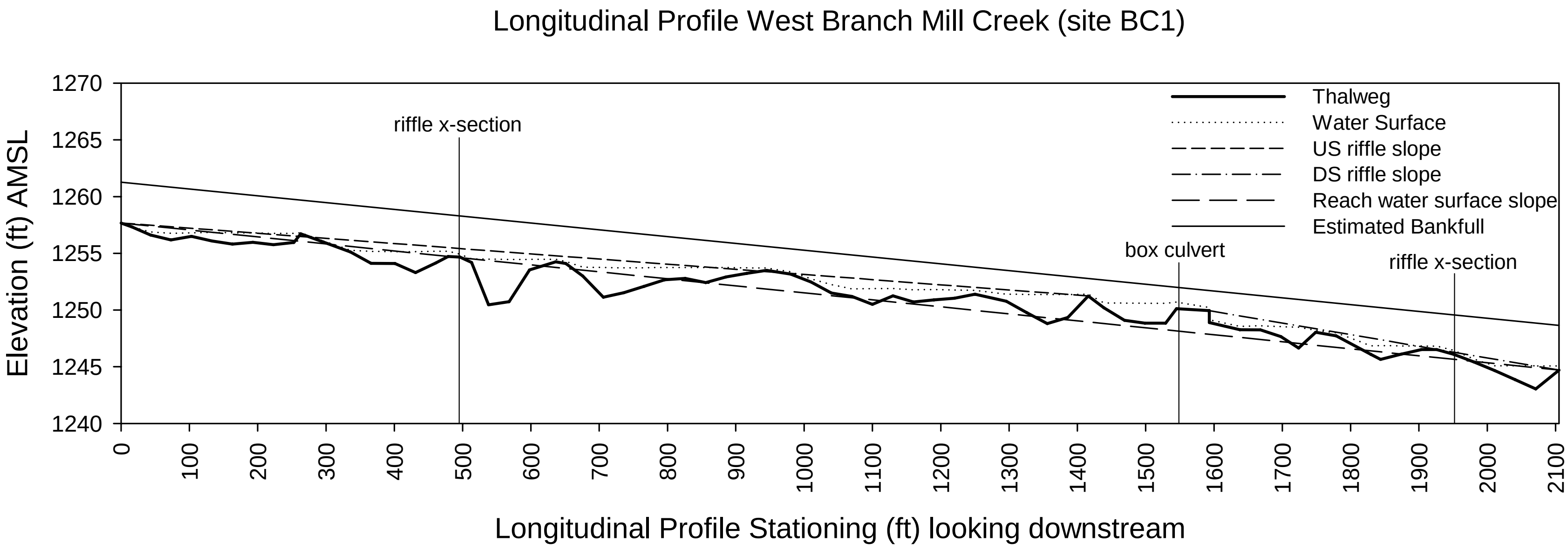

Figure 6: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site BC1. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

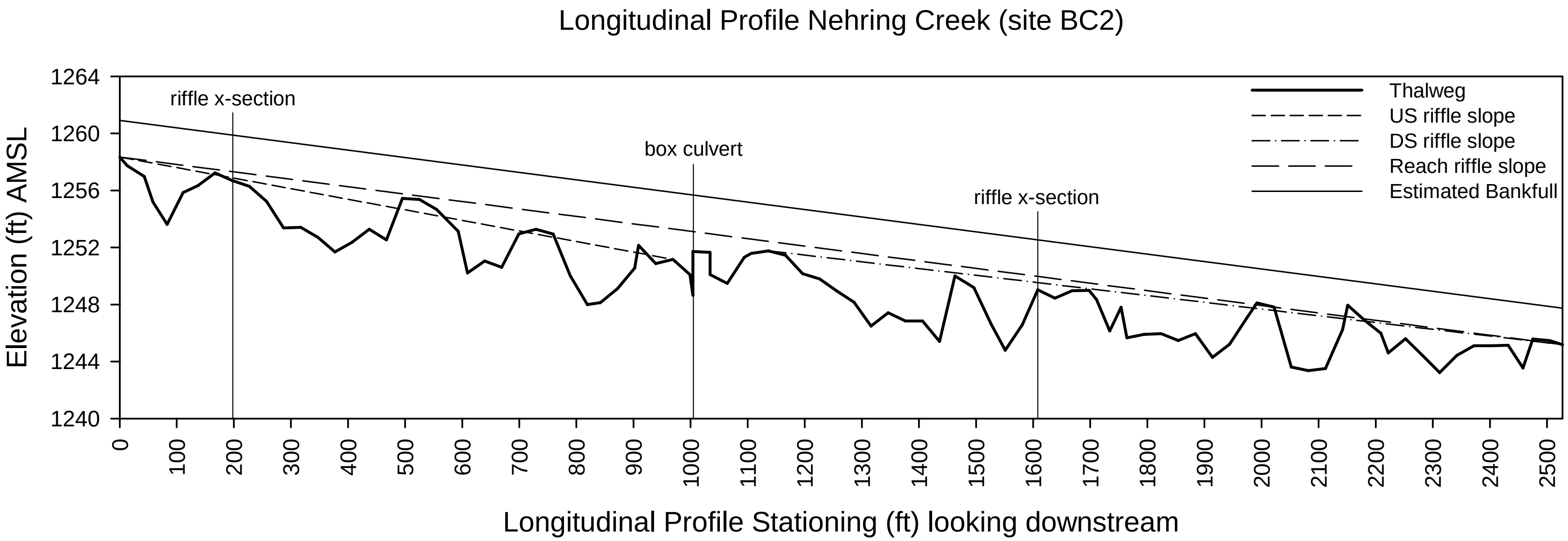

Figure 7: Longitudinal profile plotting the channel thalweg, water surface, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site BC2. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

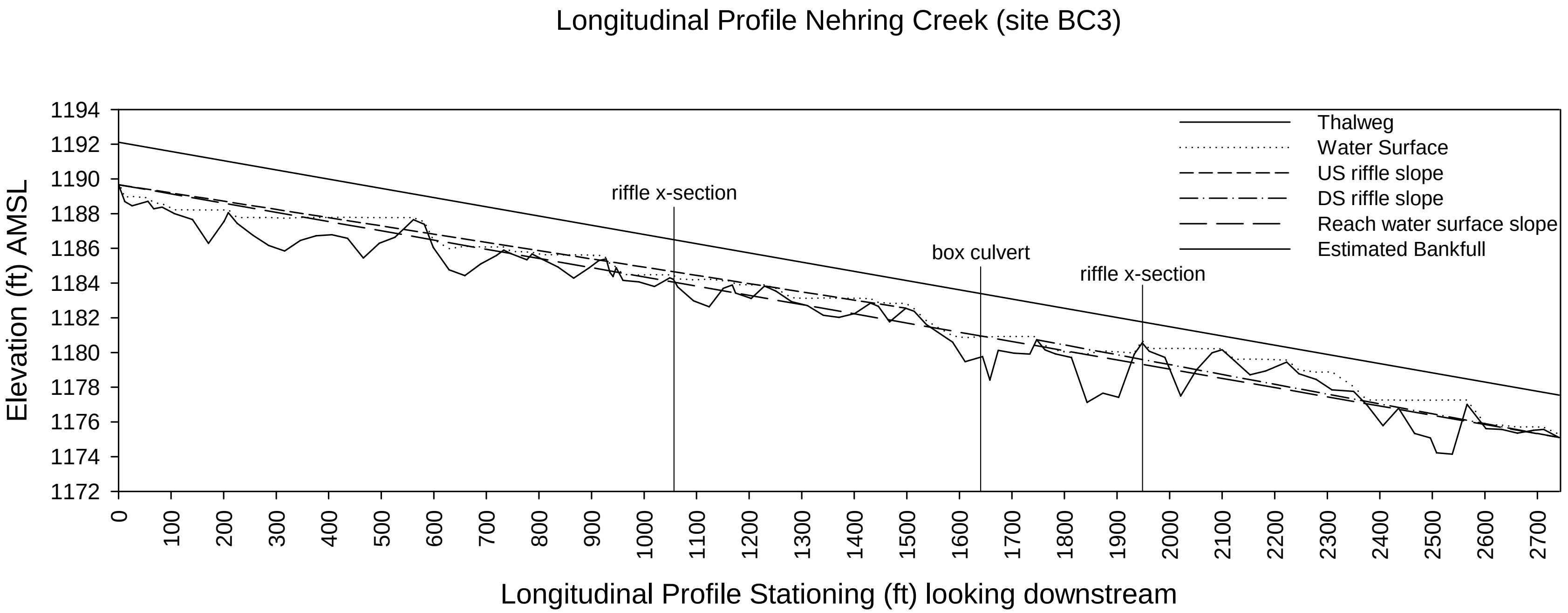

Figure 8: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site BC3. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

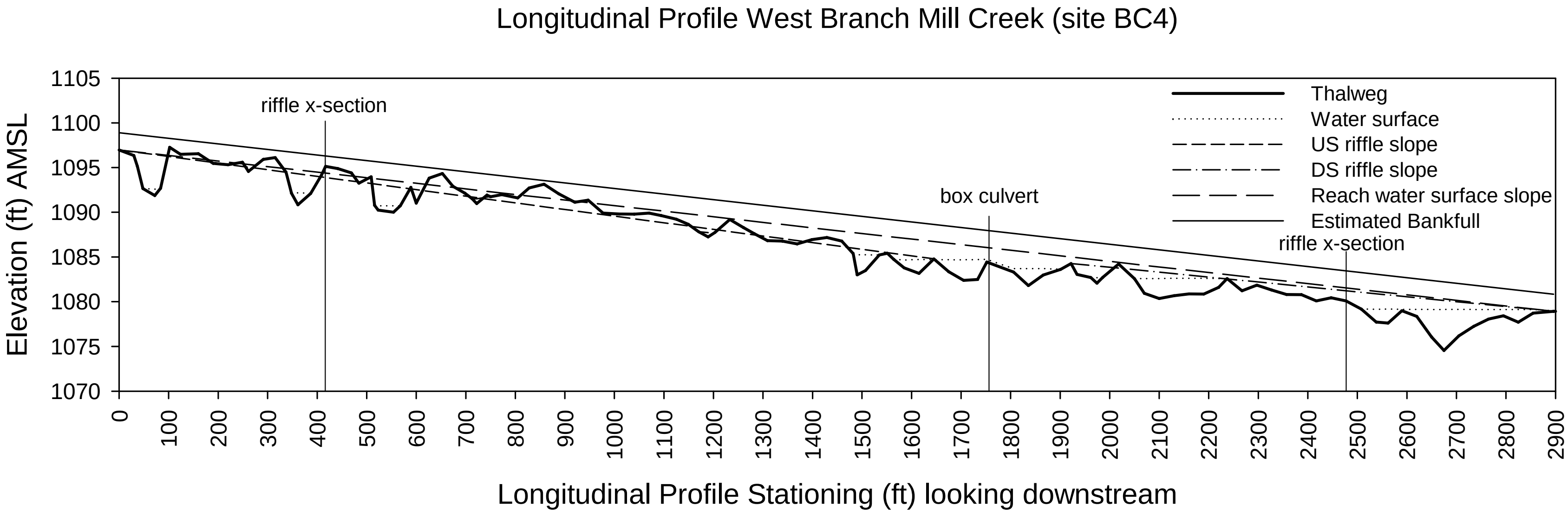

Figure 9: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site BC4. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

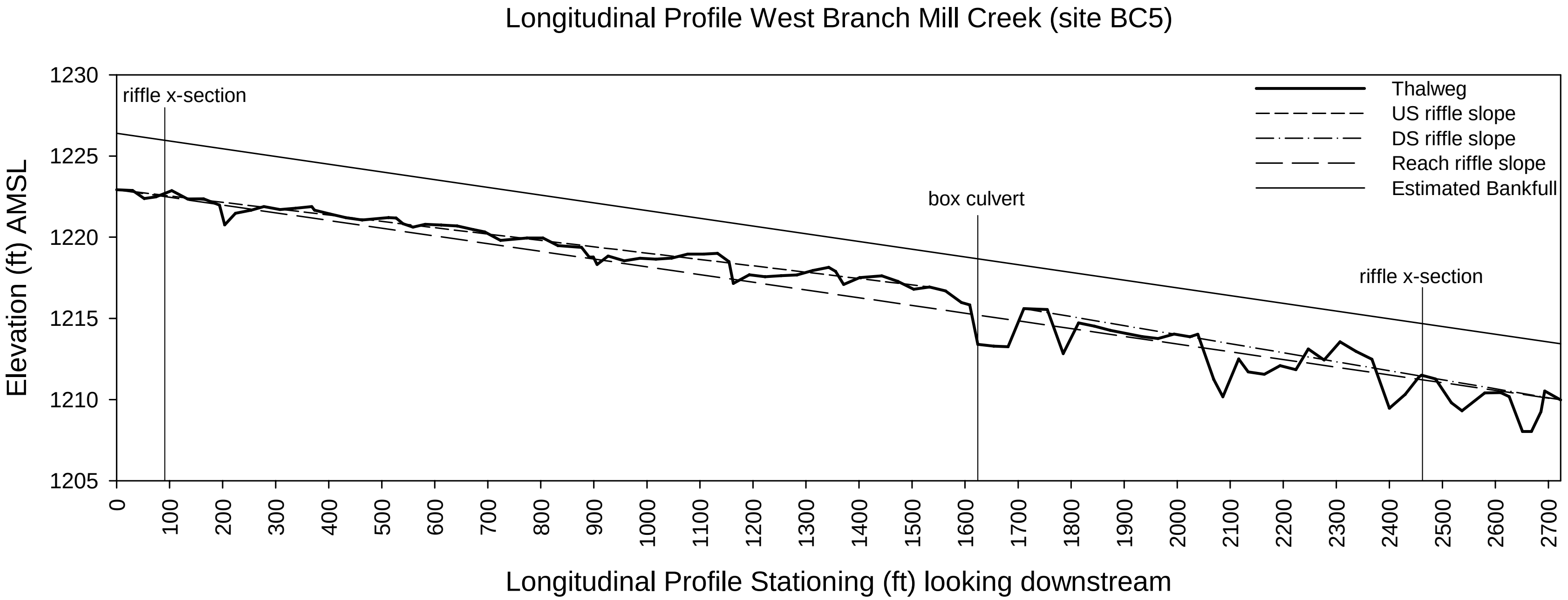

Figure 10: Longitudinal profile plotting the channel thalweg, water surface, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site BC5. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

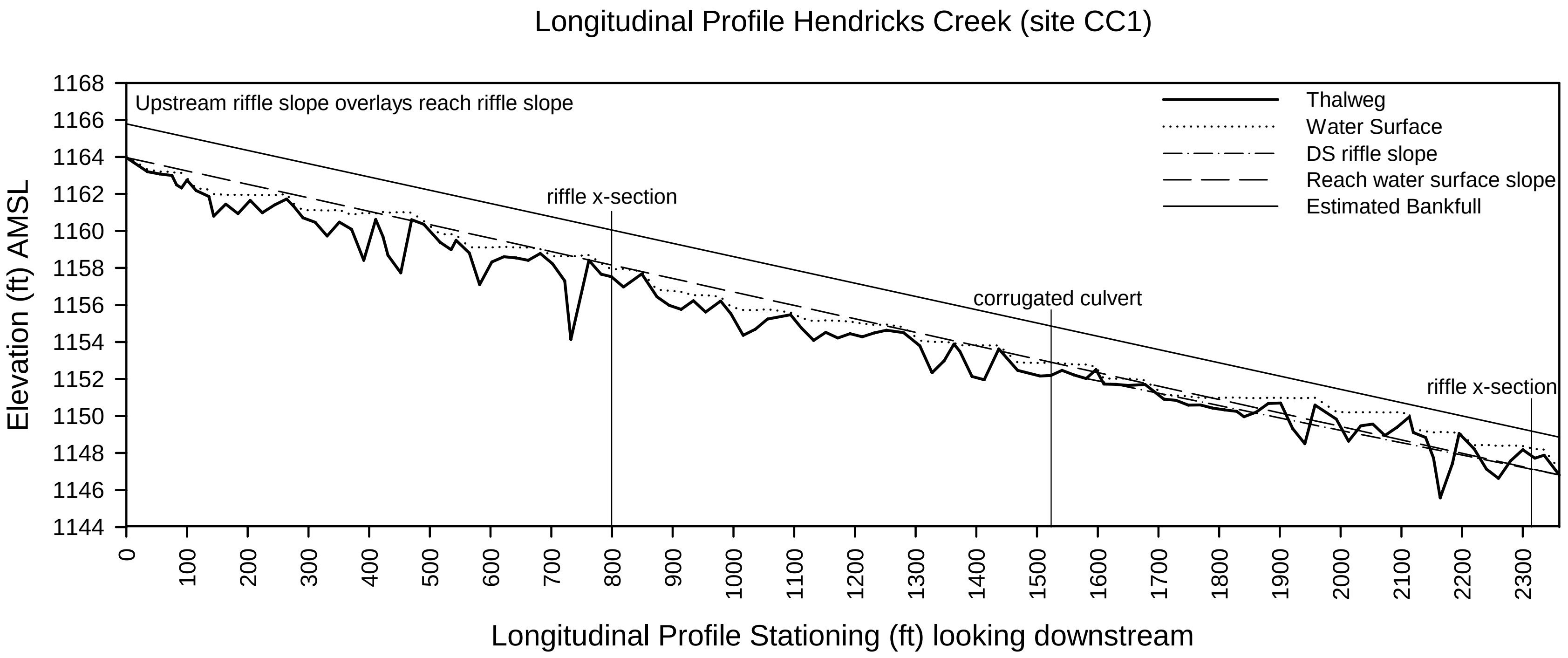

Figure 11: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site CC1. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

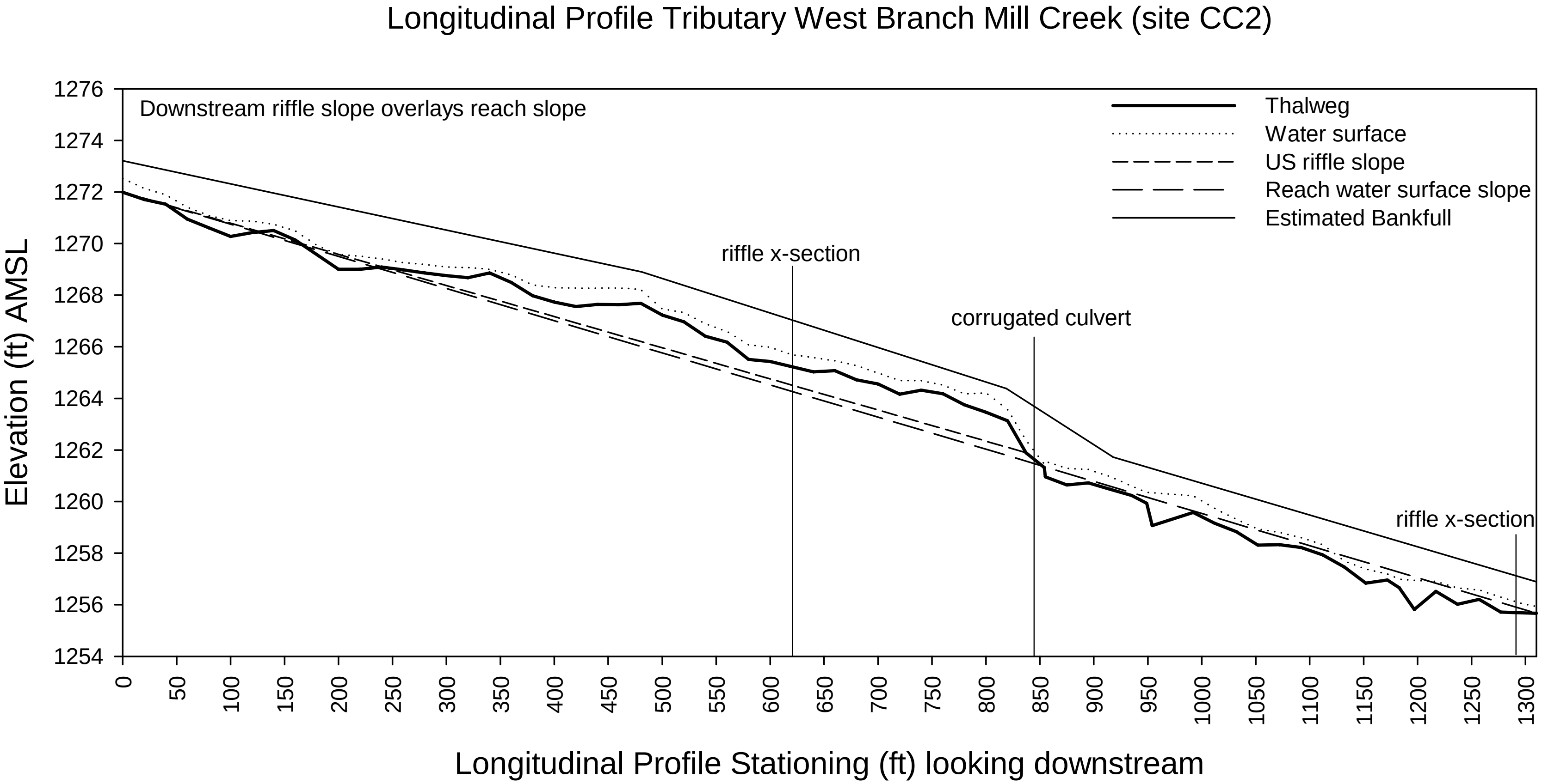

Figure 12: Longitudinal profile plotting the channel thalweg, water surface, water surface slope, riffle slope (measured from riffle head to riffle head), estimated bankfull for the entire sampled reach, and locations of the crossing, and riffle cross-sections at site CC2. DS = downstream, US = upstream, AMSL = above mean sea level, x-section = cross-section.

Appendix 3: Riffle Cross-Sections

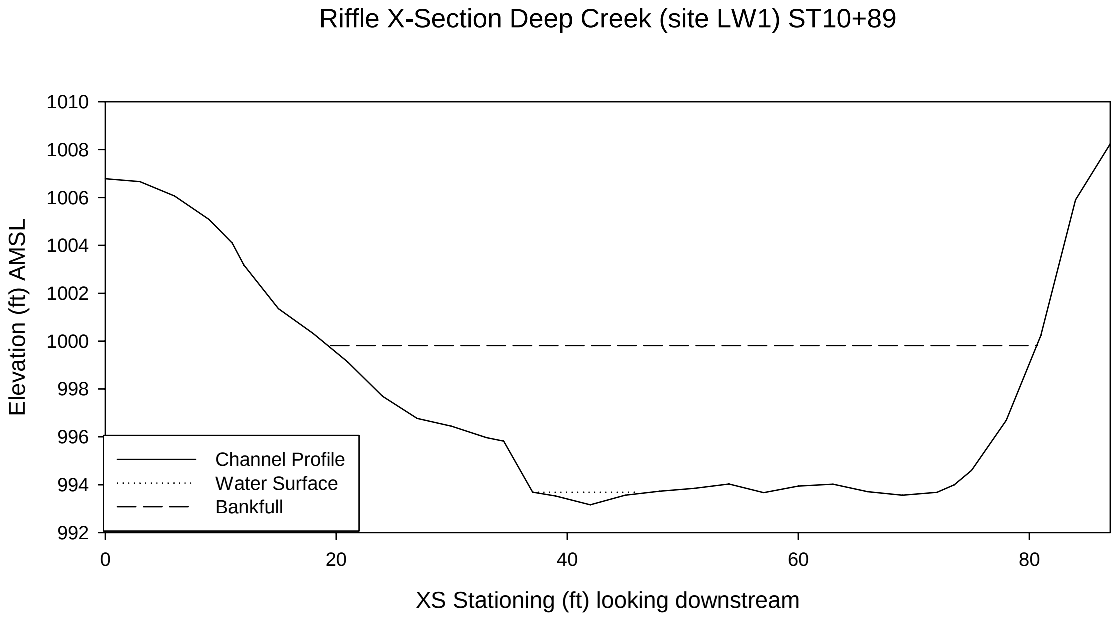

Figure 1: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW1. AMSL = above mean sea level, x-section (XS) = cross-section.

LW1 ST 10+89	
Mean bankfull width (ft)	63.1
Mean bankfull depth (ft)	4.88
X-sec area (ft^2)	307.93
D50 (mm)	3.5
Qbkf (discharge c.f.s)	1300

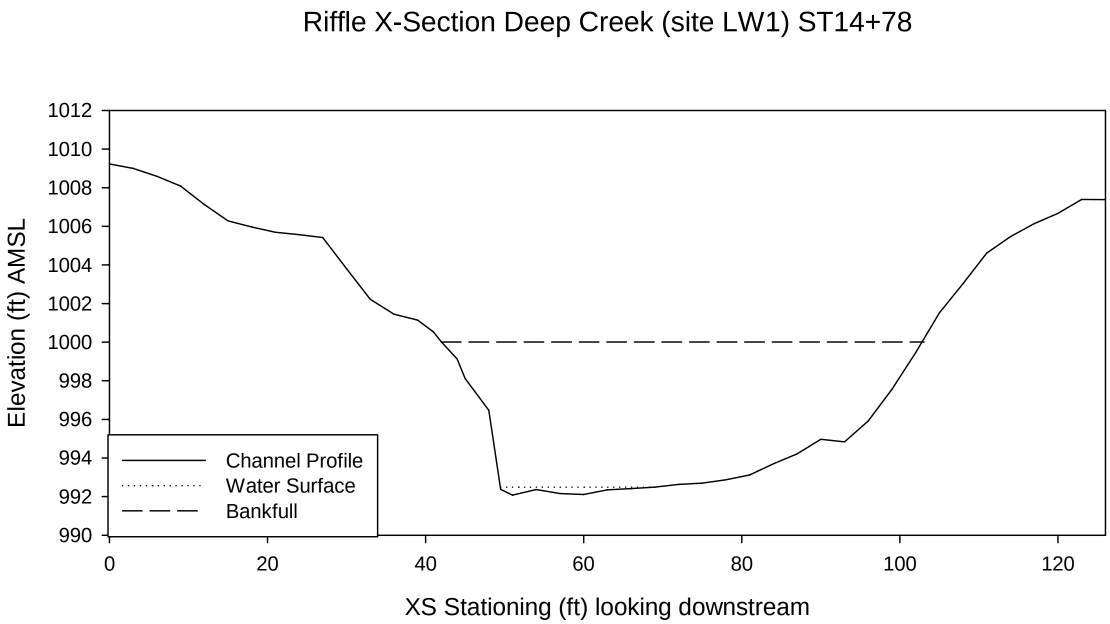

Figure 2: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW1. AMSL = above mean sea level, x-section (XS) = cross-section.

LW1 ST 14+78	
Mean bankfull width (ft)	61.06
Mean bankfull depth (ft)	5.26
X-sec area (ft^2)	321
D50 (mm)	11.8
Qbkf (discharge c.f.s)	1300

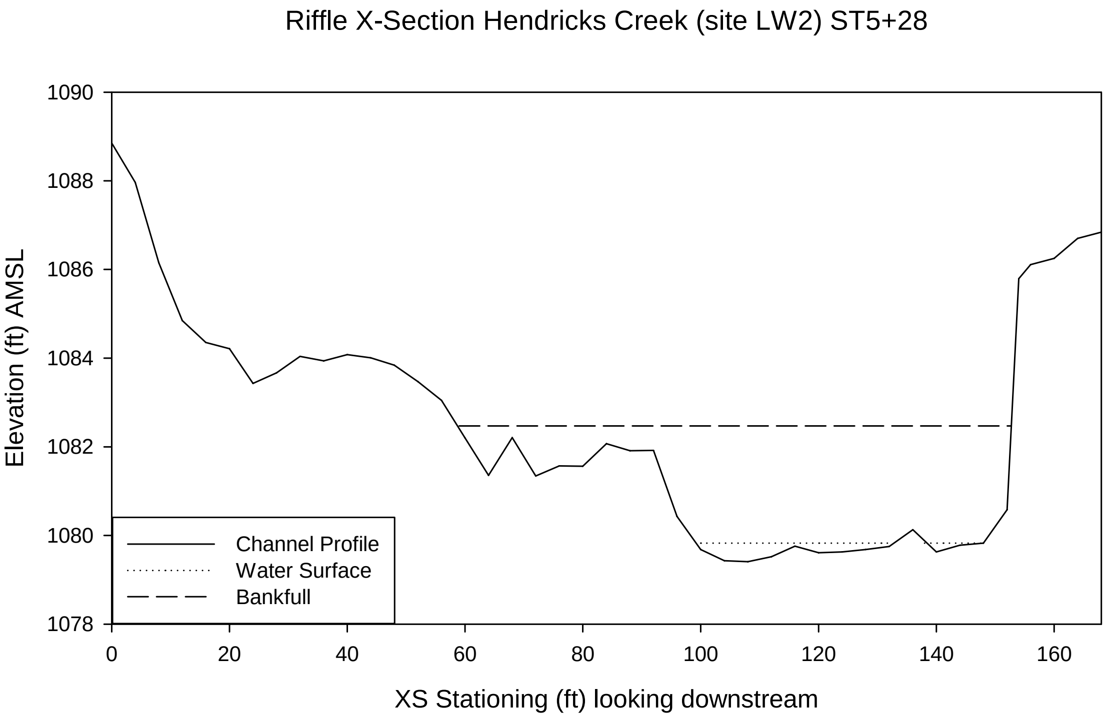

Figure 3: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW2. AMSL = above mean sea level, x-section (XS) = cross-section.

LW2 ST 5+28	
Mean bankfull width (ft)	93.69
Mean bankfull depth (ft)	1.78
X-sec area (ft^2)	166.77
D50 (mm)	29.7
Qbkf (discharge c.f.s)	650

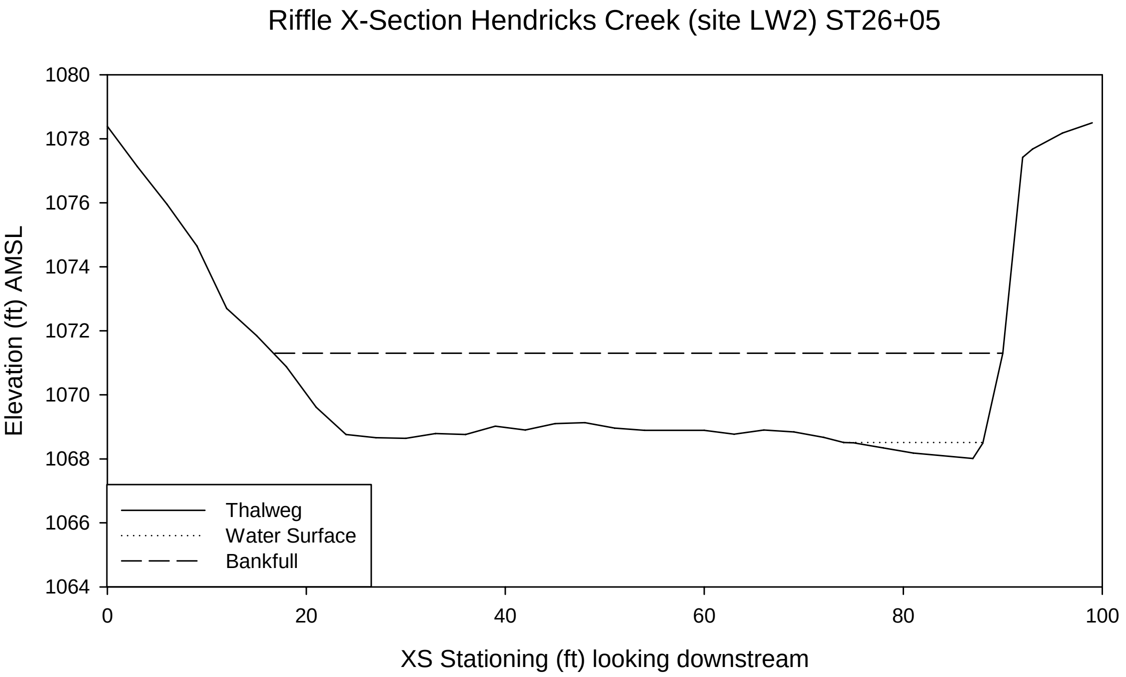

Figure 4: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW2. AMSL = above mean sea level, x-section (XS) = cross-section.

LW2 ST 26+05	
Mean bankfull width (ft)	73.14
Mean bankfull depth (ft)	2.31
X-sec area (ft^2)	168.95
D50 (mm)	26.05
Qbkf (discharge c.f.s)	650

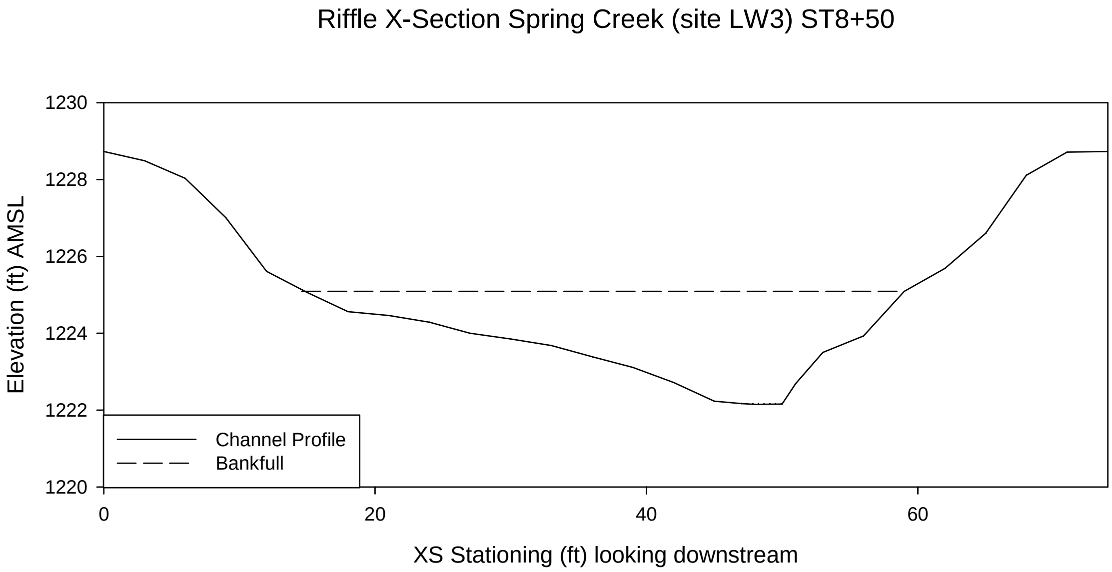

Figure 5: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site LW3. AMSL = above mean sea level, x-section (XS) = cross-section.

LW3 ST 8+50	
Mean bankfull width (ft)	44.4
Mean bankfull depth (ft)	1.5
X-sec area (ft^2)	66.6
D50 (mm)	39.4
Qbkf (discharge c.f.s)	280

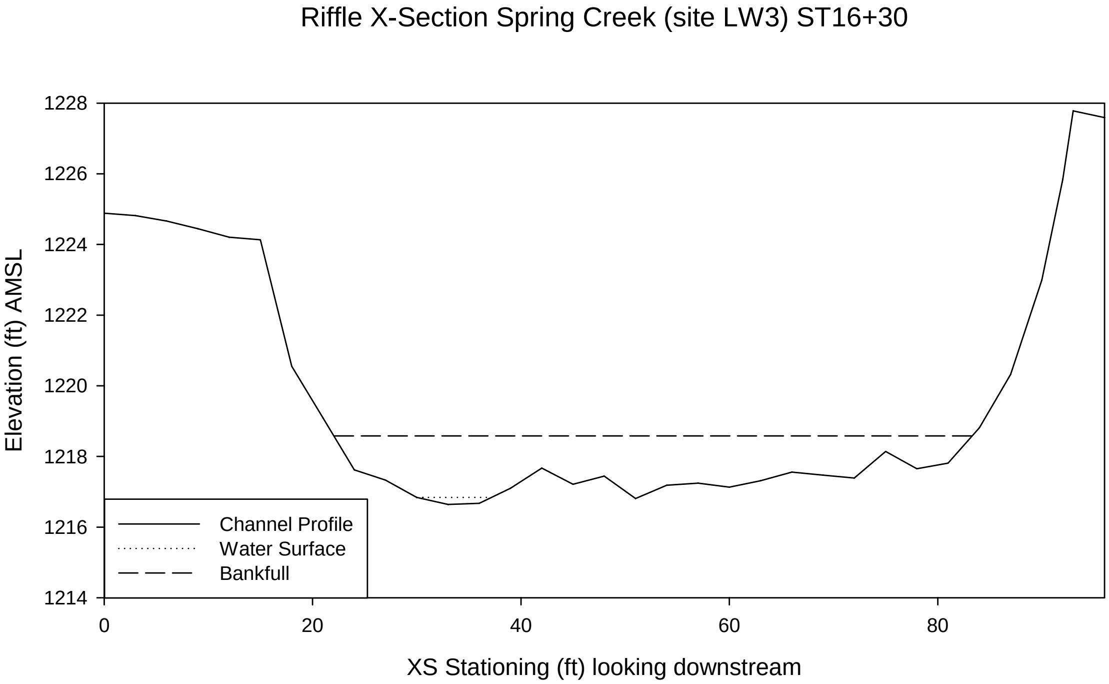

Figure 6: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW3. AMSL = above mean sea level, x-section (XS) = cross-section.

LW3 ST 16+30	
Mean bankfull width (ft)	61.32
Mean bankfull depth (ft)	1.15
X-sec area (ft^2)	70.52
D50 (mm)	54.5
Qbkf (discharge c.f.s)	280

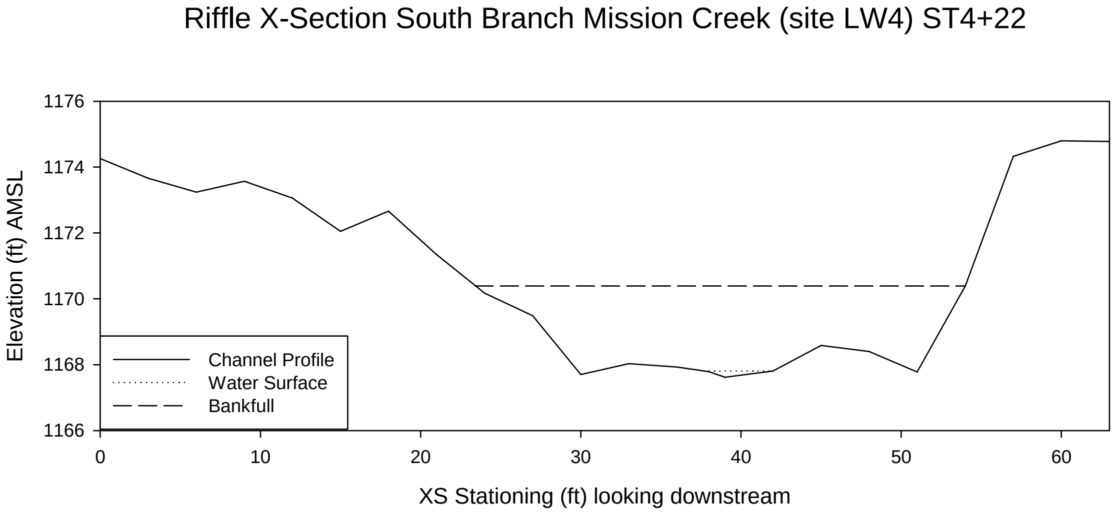

Figure 7: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW4. AMSL = above mean sea level, x-section (XS) = cross-section.

LW4 ST 4+22	
Mean bankfull width (ft)	30.6
Mean bankfull depth (ft)	1.77
X-sec area (ft^2)	54.2
D50 (mm)	45.6
Qbkf (discharge c.f.s)	190

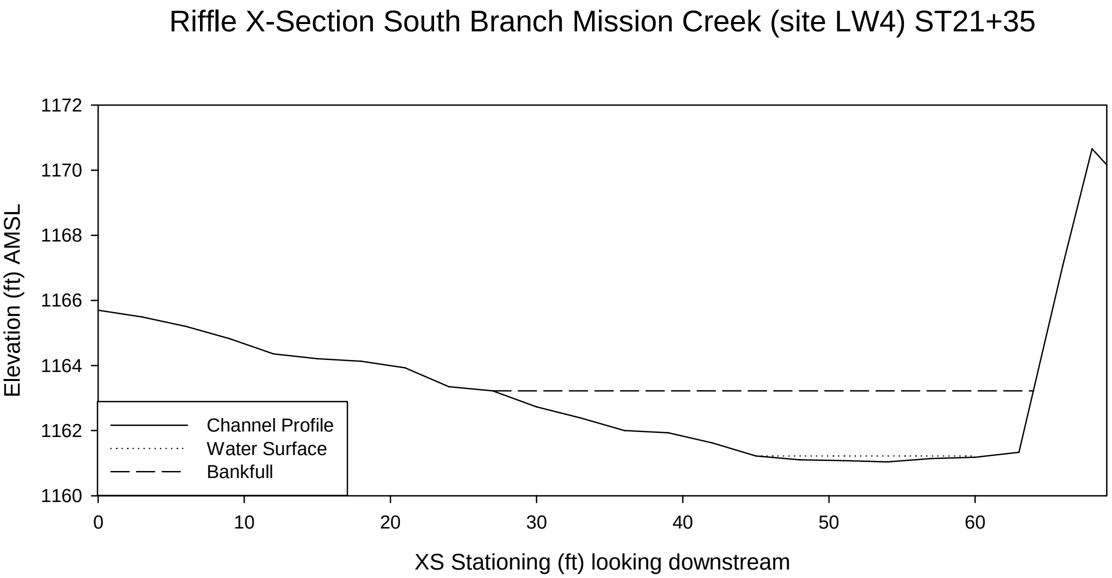

Figure 8: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW4. AMSL = above mean sea level, x-section (XS) = cross-section.

LW4 ST 21+35	
Mean bankfull width (ft)	37
Mean bankfull depth (ft)	1.42
X-sec area (ft^2)	52.54
D50 (mm)	22.2
Qbkf (discharge c.f.s)	190

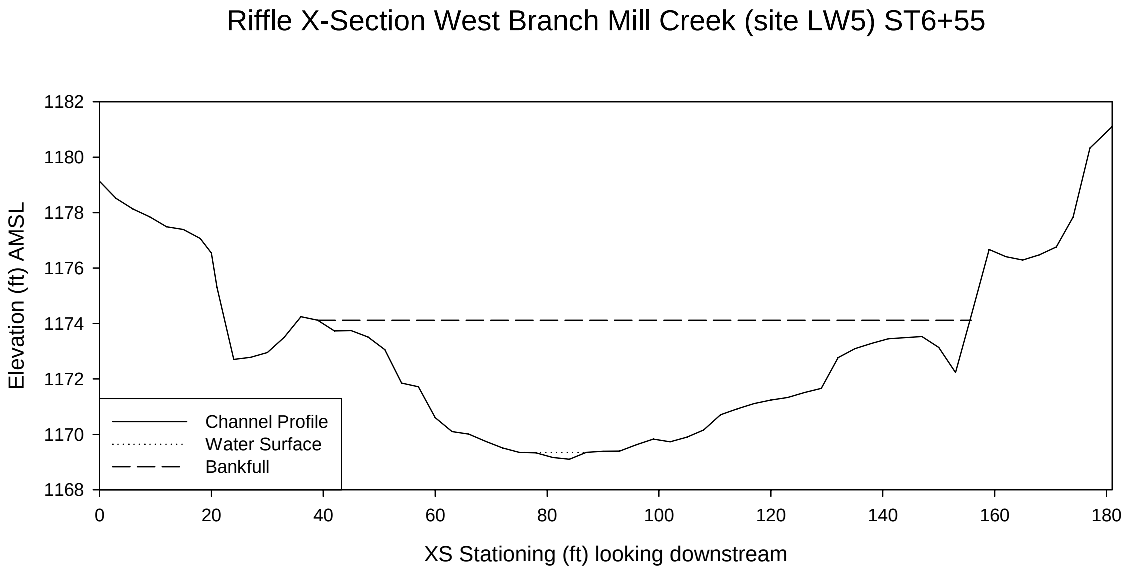

Figure 9: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW5. AMSL = above mean sea level, x-section (XS) = cross-section.

LW5 ST 6+55	
Mean bankfull width (ft)	116.8
Mean bankfull depth (ft)	2.78
X-sec area (ft^2)	324.7
D50 (mm)	59.3
Qbkf (discharge c.f.s)	1500

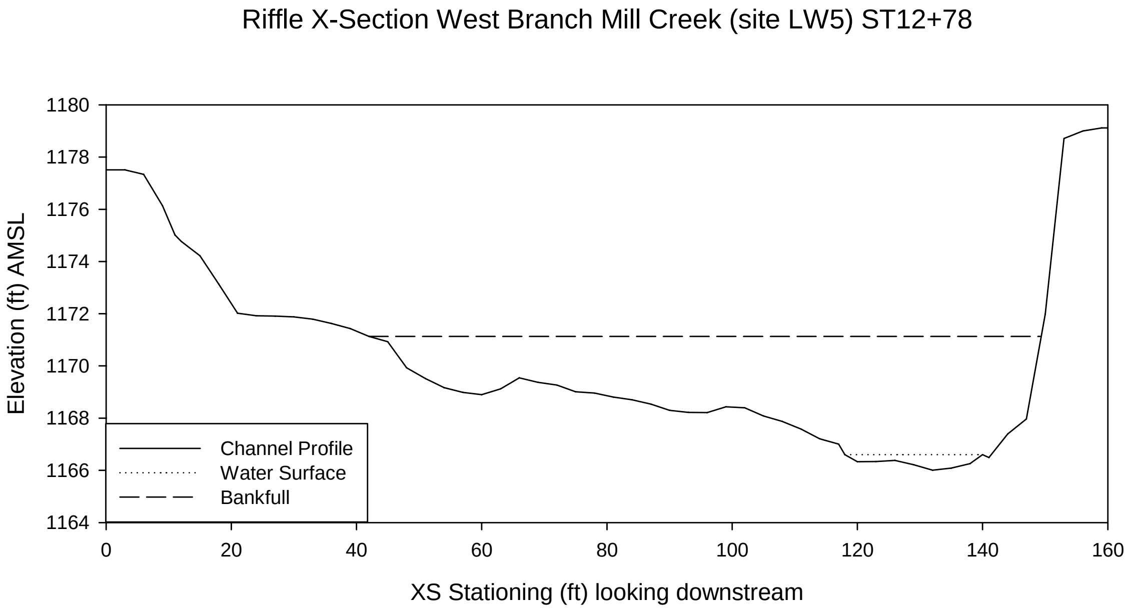

Figure 10: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site LW5. AMSL = above mean sea level, x-section (XS) = cross-section.

LW5 ST 12+78	
Mean bankfull width (ft)	107.2
Mean bankfull depth (ft)	2.95
X-sec area (ft^2)	316.24
D50 (mm)	38.5
Qbkf (discharge c.f.s)	1500

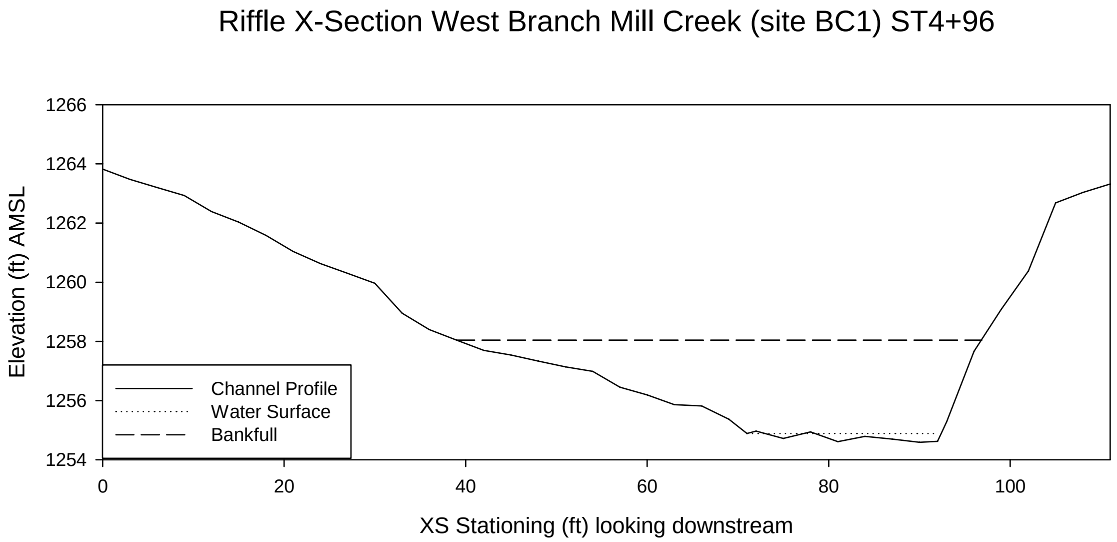

Figure 11: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site BC1. AMSL = above mean sea level, x-section (XS) = cross-section.

BC1 ST4+96	
Mean bankfull width (ft)	57.88
Mean bankfull depth (ft)	2.03
X-sec area (ft^2)	117.5
D50 (mm)	54.5
Qbkf (discharge c.f.s)	430

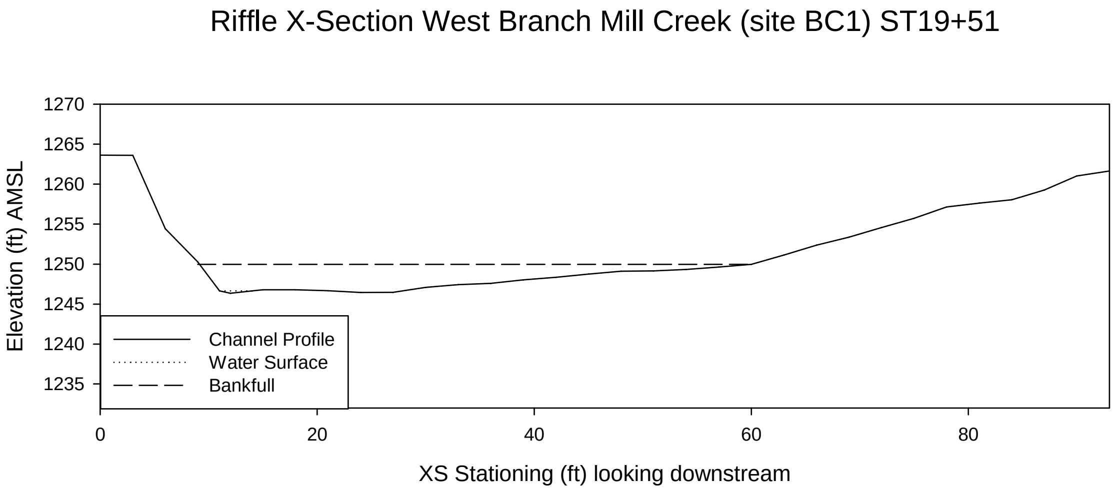

Figure 12: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site BC1. AMSL = above mean sea level, x-section (XS) = cross-section.

BC1 ST 19+51	
Mean bankfull width (ft)	51
Mean bankfull depth (ft)	2.13
X-sec area (ft^2)	108.63
D50 (mm)	66.8
Qbkf (discharge c.f.s)	430

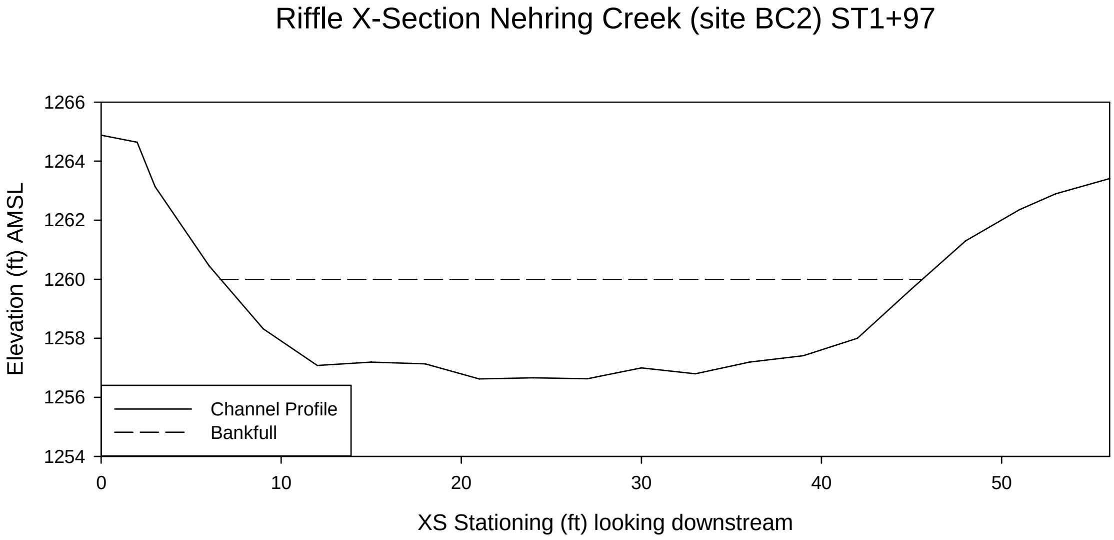

Figure 13: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC2. AMSL = above mean sea level, x-section (XS) = cross-section.

BC2 ST 1+97	
Mean bankfull width (ft)	38.98
Mean bankfull depth (ft)	2.28
X-sec area (ft^2)	88.87
D50 (mm)	38.5
Qbkf (discharge c.f.s)	350

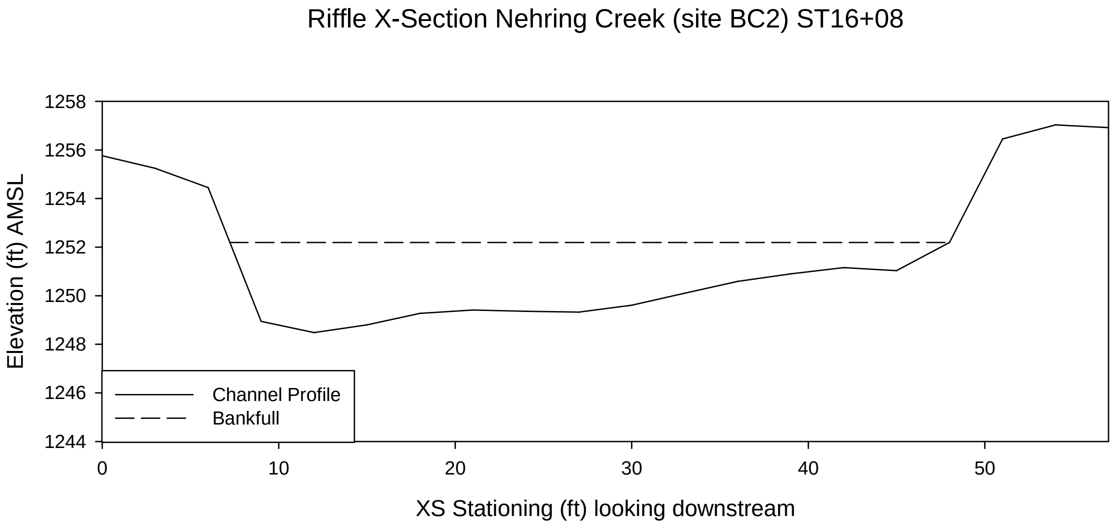

Figure 14: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC2. AMSL = above mean sea level, x-section (XS) = cross-section.

BC2 ST 16+08	
Mean bankfull width (ft)	40.78
Mean bankfull depth (ft)	2.1
X-sec area (ft^2)	85.6
D50 (mm)	33.2
Qbkf (discharge c.f.s)	350

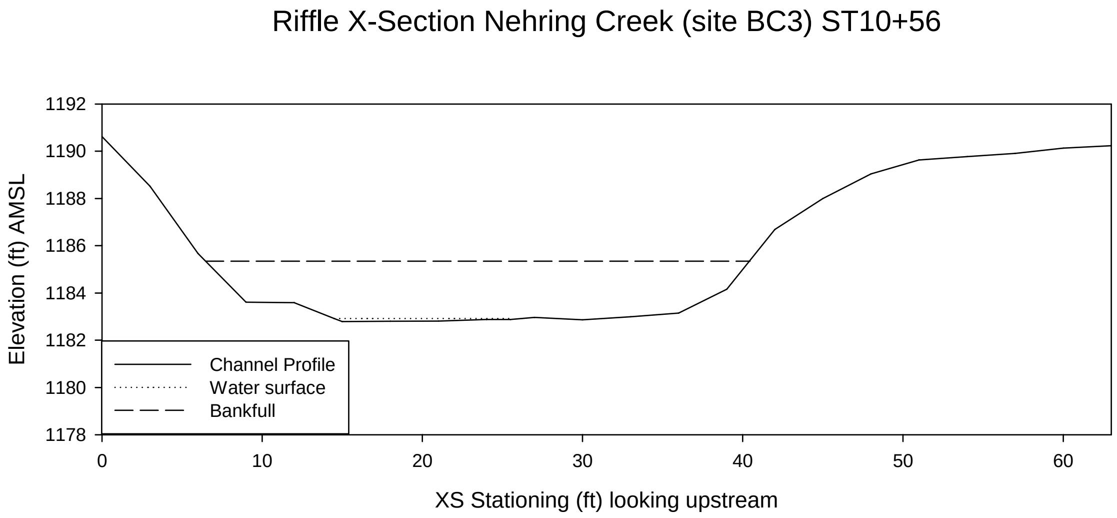

Figure 15: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site BC3. AMSL = above mean sea level, x-section (XS) = cross-section.

BC3 ST 10+56	
Mean bankfull width (ft)	33.97
Mean bankfull depth (ft)	1.94
X-sec area (ft^2)	65.9
D50 (mm)	35.7
Qbkf (discharge c.f.s)	280

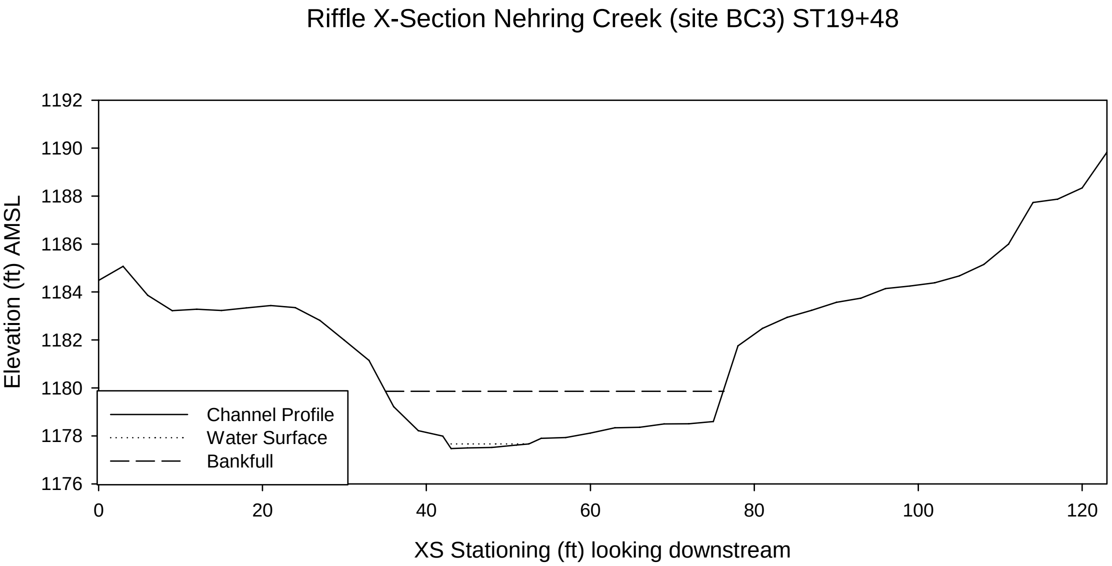

Figure 16: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site BC3. AMSL = above mean sea level, x-section (XS) = cross-section.

BC3 ST 19+48	
Mean bankfull width (ft)	41.3
Mean bankfull depth (ft)	1.57
X-sec area (ft^2)	64.84
D50 (mm)	23.9
Qbkf (discharge c.f.s)	280

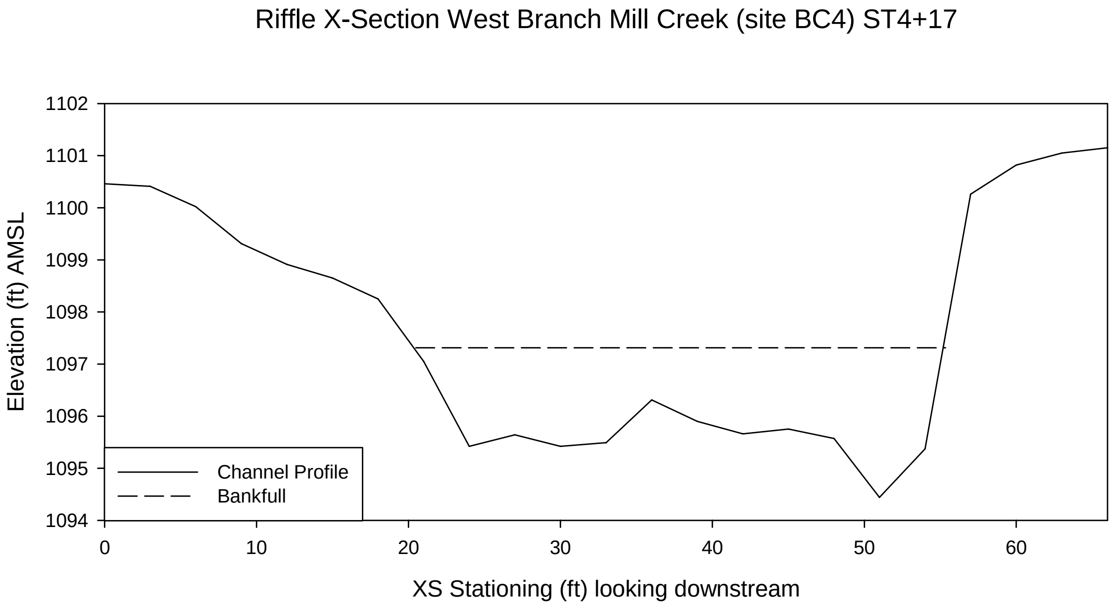

Figure 17: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC4. AMSL = above mean sea level, x-section (XS) = cross-section.

BC4 ST 4+17	
Mean bankfull width (ft)	34.87
Mean bankfull depth (ft)	1.41
X-sec area (ft^2)	49.17
D50 (mm)	38.5
Qbkf (discharge c.f.s)	175

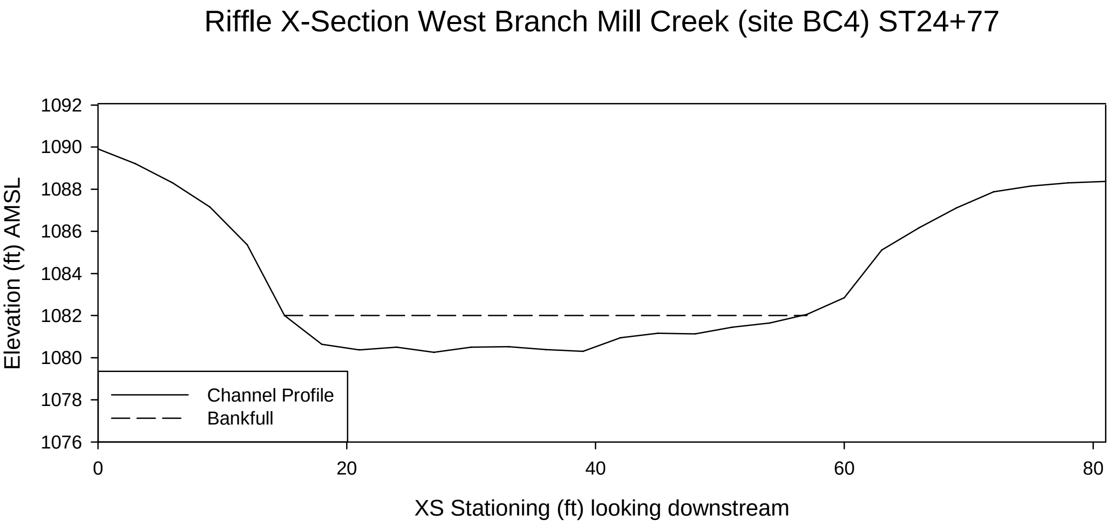

Figure 18: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC4. AMSL = above mean sea level, x-section (XS) = cross-section.

BC4 ST 24+77	
Mean bankfull width (ft)	42
Mean bankfull depth (ft)	1.08
X-sec area (ft^2)	45.36
D50 (mm)	40.5
Qbkf (discharge c.f.s)	175

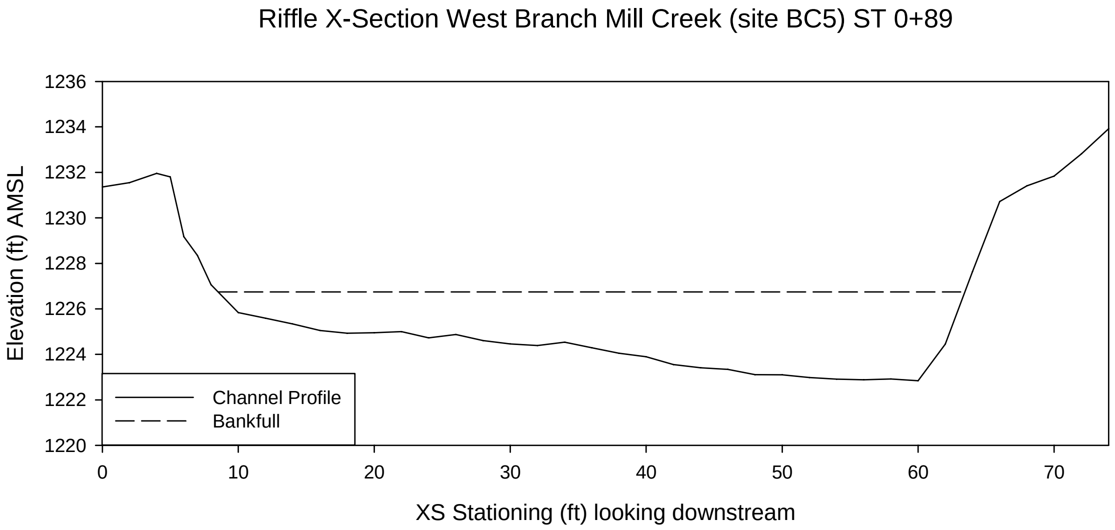

Figure 19: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC5. AMSL = above mean sea level, x-section (XS) = cross-section.

BC5 ST 0+89	
Mean bankfull width (ft)	54.82
Mean bankfull depth (ft)	2.41
X-sec area (ft^2)	132
D50 (mm)	41.8
Qbkf (discharge c.f.s)	480

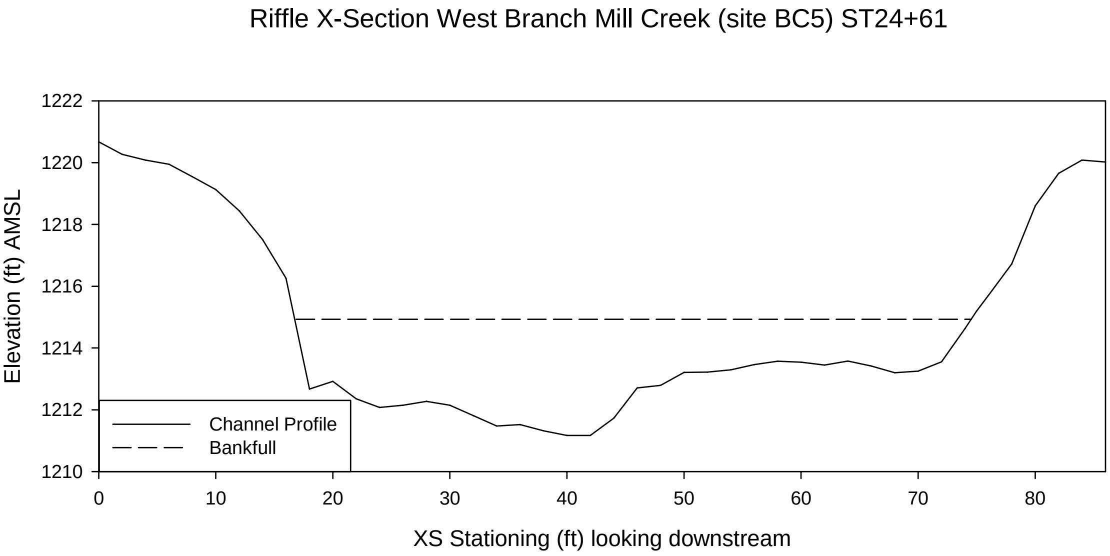

Figure 20: Cross-sectional profile plotting the shape of the stream channel, and bankfull at a riffle at site BC5. AMSL = above mean sea level, x-section (XS) = cross-section.

BC5 ST 24+61	
Mean bankfull width (ft)	57.68
Mean bankfull depth (ft)	2.11
X-sec area (ft^2)	121.7
D50 (mm)	41.8
Qbkf (discharge c.f.s)	480

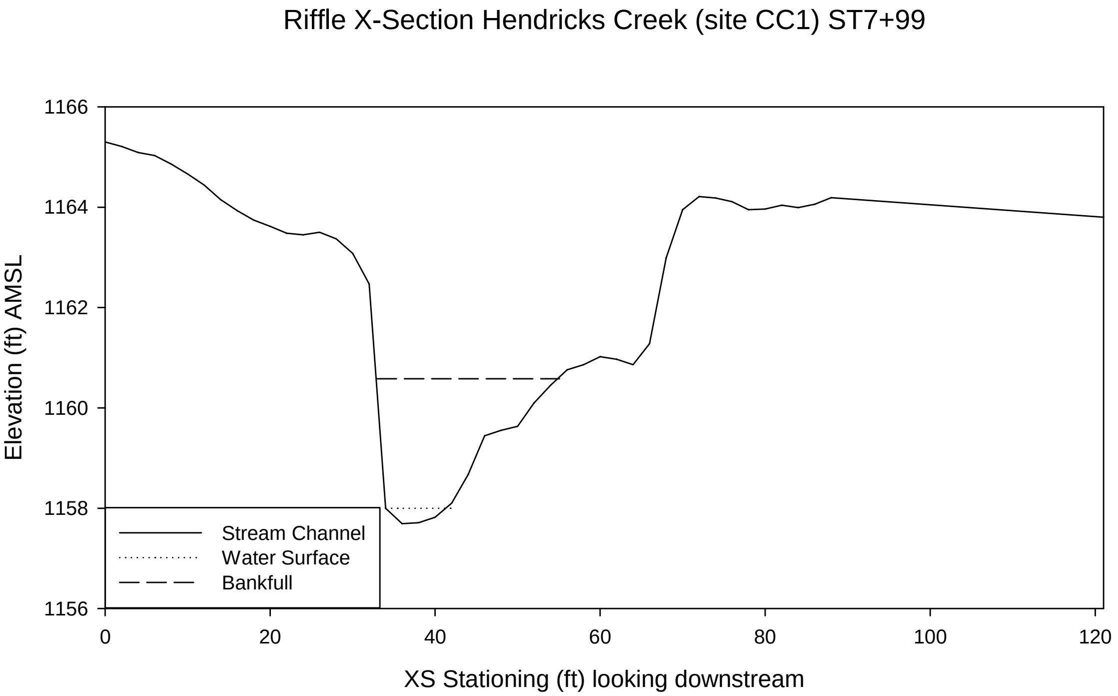

Figure 21: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site CC1. AMSL = above mean sea level, x-section (XS) = cross-section.

CC1 ST 7+99	
Mean bankfull width (ft)	22.1
Mean bankfull depth (ft)	1.48
X-sec area (ft^2)	32.71
D50 (mm)	37.89
Qbkf (discharge c.f.s)	125

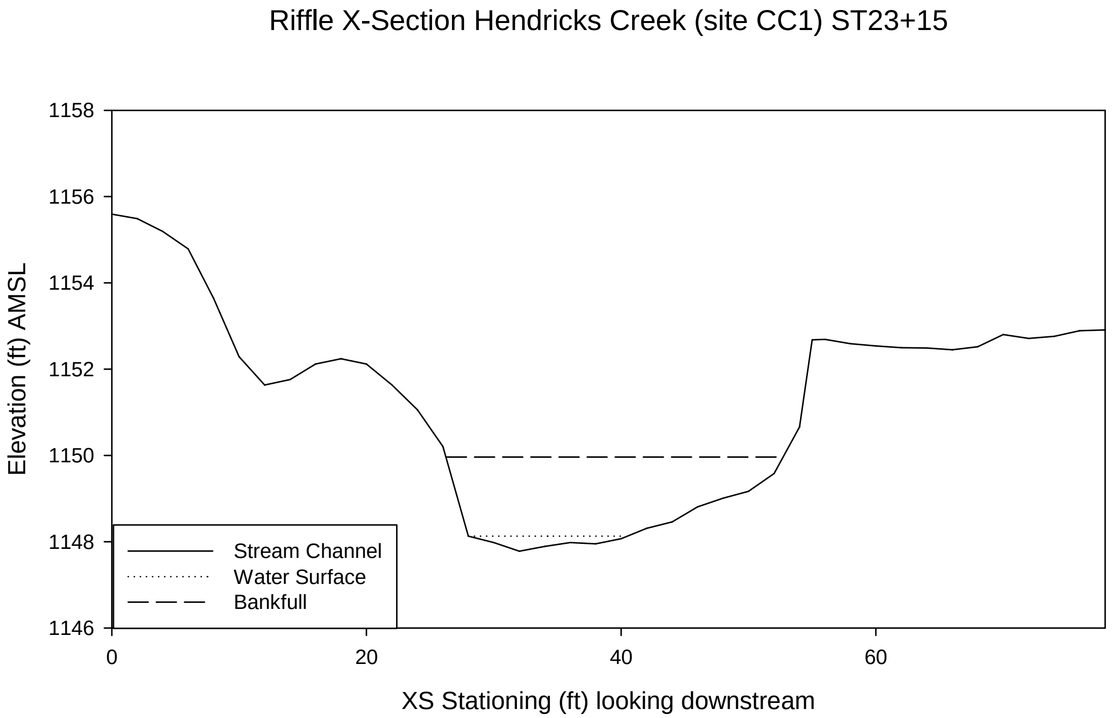

Figure 22: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site CC1. AMSL = above mean sea level, x-section (XS) = cross-section.

CC1 ST 23+15	
Mean bankfull width (ft)	26.41
Mean bankfull depth (ft)	1.36
X-sec area (ft^2)	35.92
D50 (mm)	53.55
Qbkf (discharge c.f.s)	125

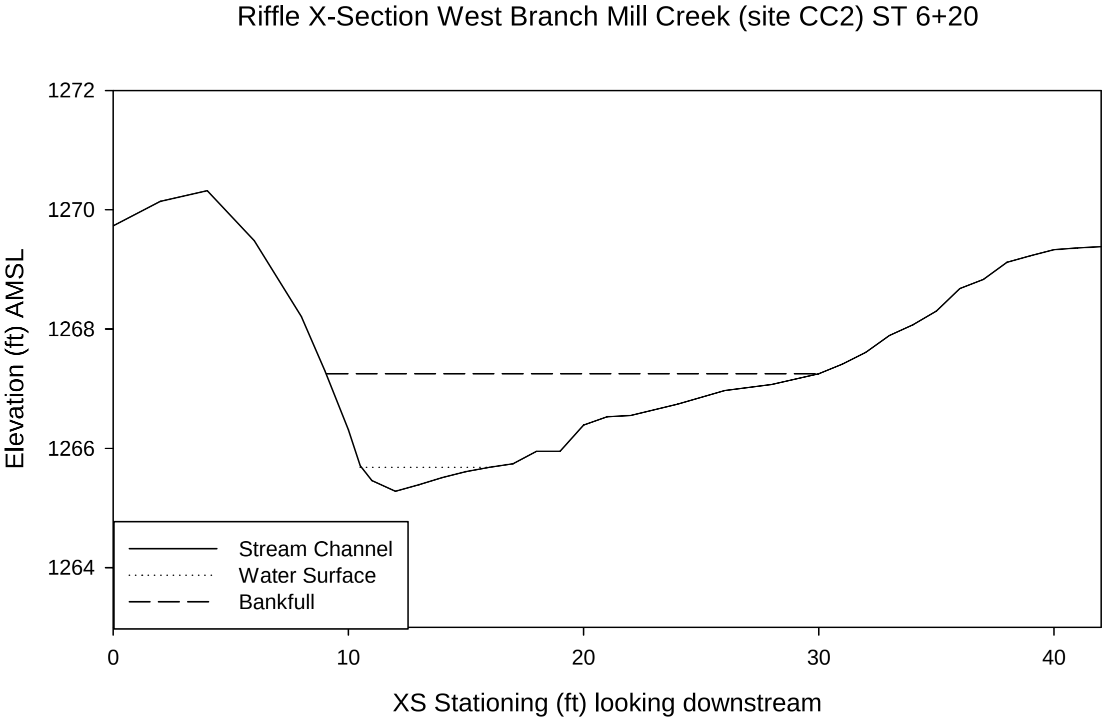

Figure 23: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site CC2. AMSL = above mean sea level, x-section (XS) = cross-section.

CC2 ST 6+20	
Mean bankfull width (ft)	20.9
Mean bankfull depth (ft)	1.07
X-sec area (ft^2)	22.363
D50 (mm)	41.75
Qbkf (discharge c.f.s)	68

Riffle X-Section West Branch Mill Creek (site CC2) ST12+97

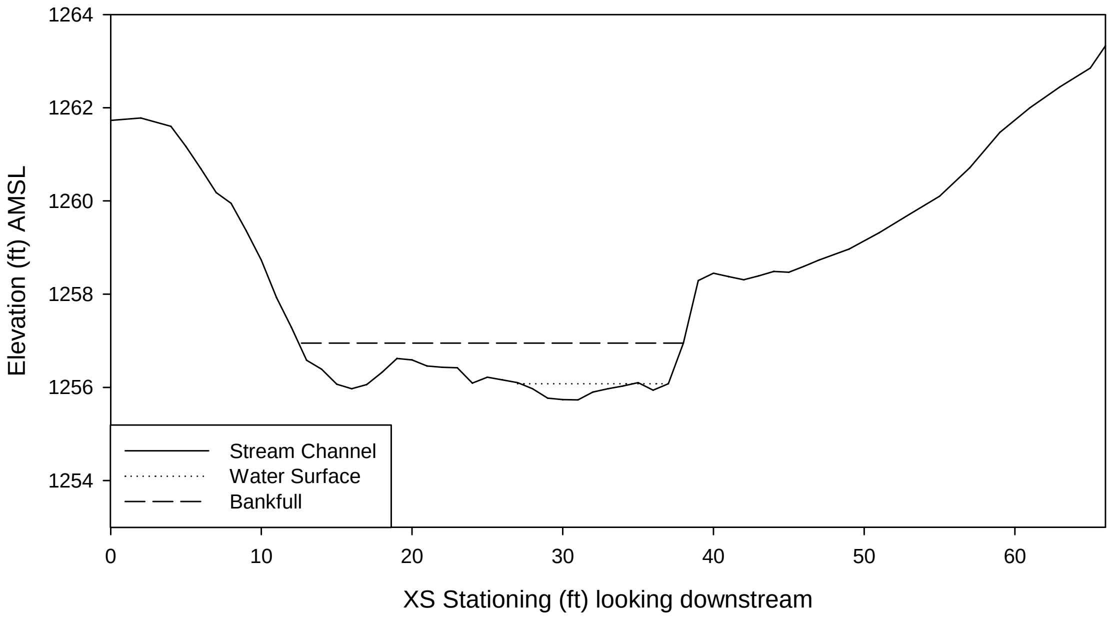

Figure 24: Cross-sectional profile plotting the shape of the stream channel, water surface, and bankfull at a riffle at site CC2. AMSL = above mean sea level, x-section (XS) = cross-section.

CC2 ST 12+97	
Mean bankfull width (ft)	25.34
Mean bankfull depth (ft)	0.74
X-sec area (ft^2)	18.75
D50 (mm)	45
Qbkf (discharge c.f.s)	68

Appendix 4: Low-Water Crossing Road Cross-Sections

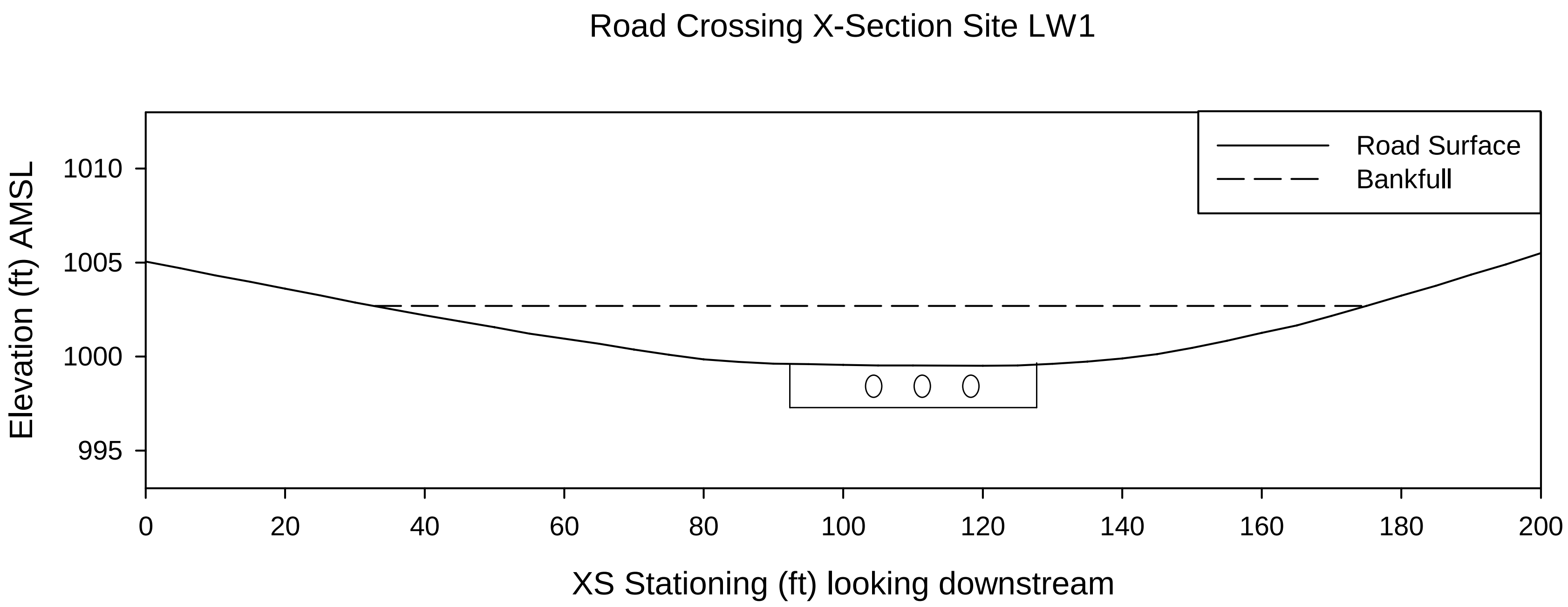

Figure 1: Cross-sectional profile plotting the road surface of the low-water crossing over the stream channel and bankfull at site LW1. AMSL = above mean sea level, x-section (XS) = cross-section.

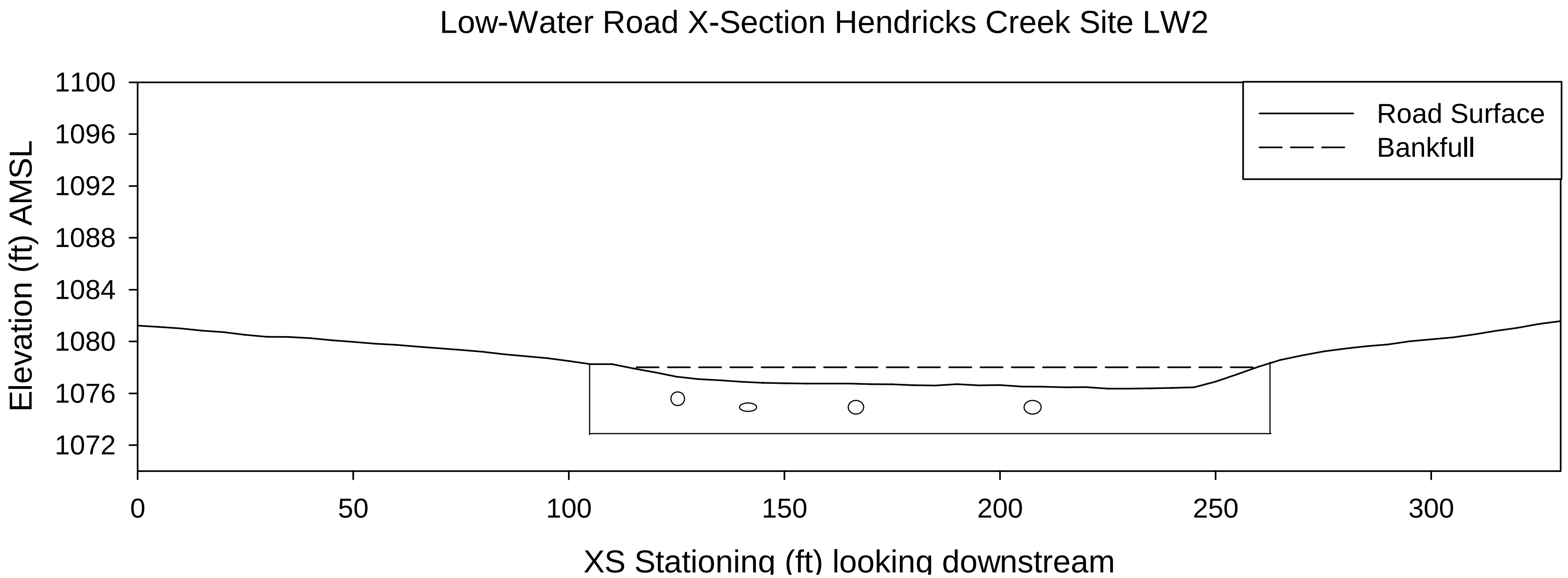

Figure 2: Cross-sectional profile plotting the road surface of the low-water crossing over the stream channel and bankfull at site LW2. AMSL = above mean sea level, x-section (XS) = cross-section.

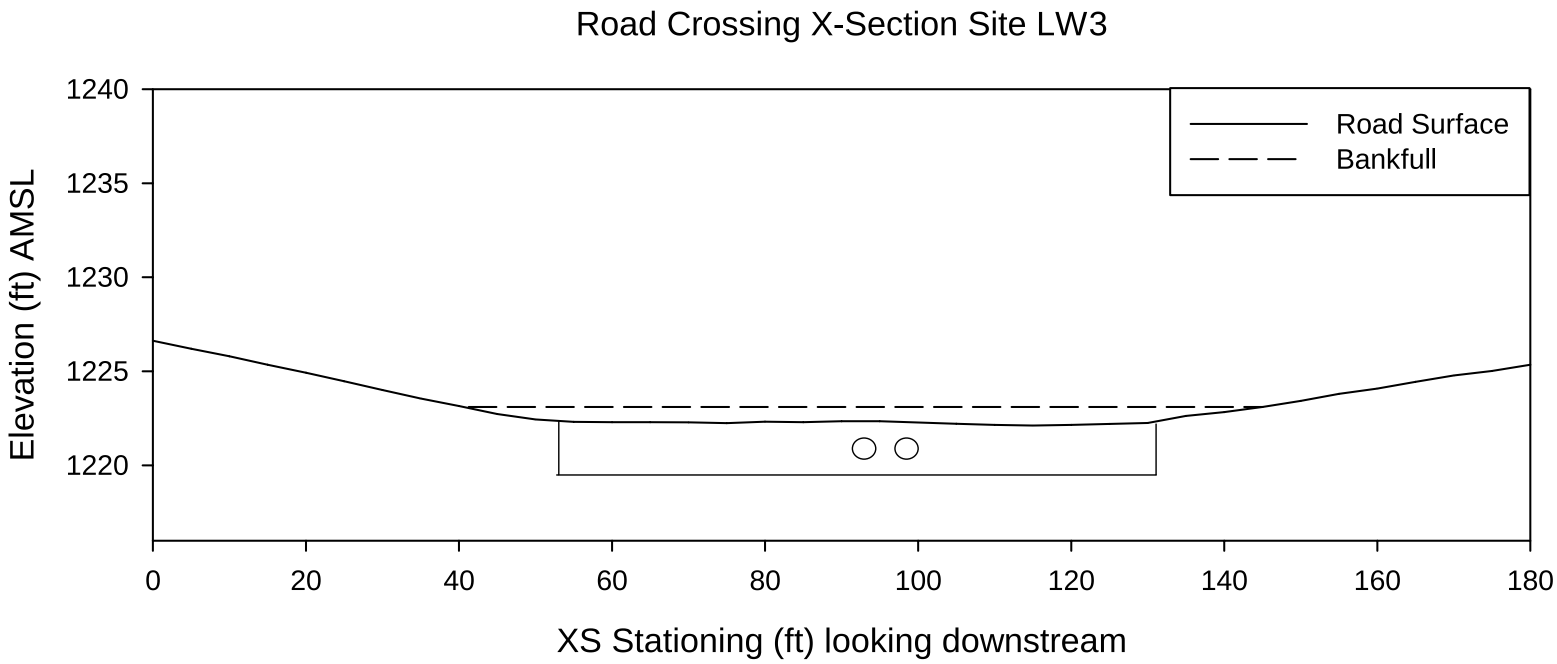

Figure 3: Cross-sectional profile plotting the road surface of the low-water crossing over the stream channel and bankfull at site LW3. AMSL = above mean sea level, x-section (XS) = cross-section.

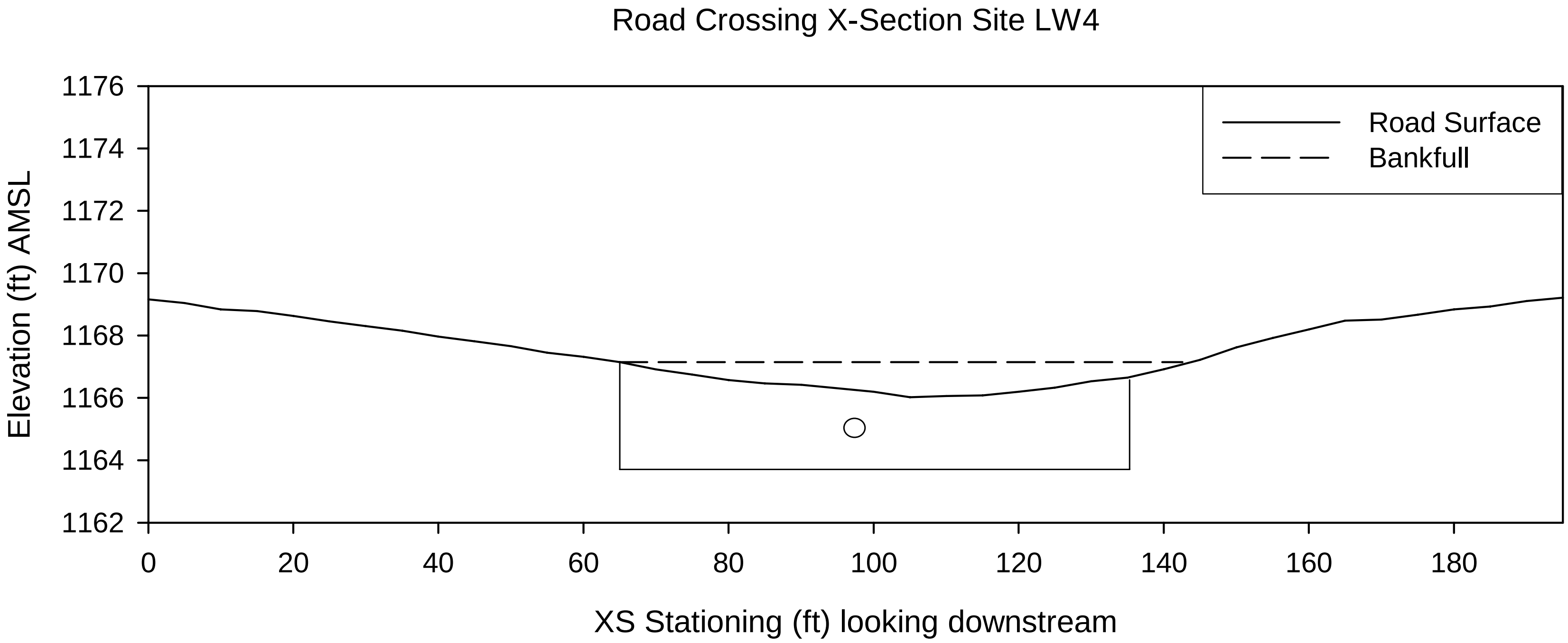

Figure 4: Cross-sectional profile plotting the road surface of the low-water crossing over the stream channel and bankfull at site LW4. AMSL = above mean sea level, x-section (XS) = cross-section.

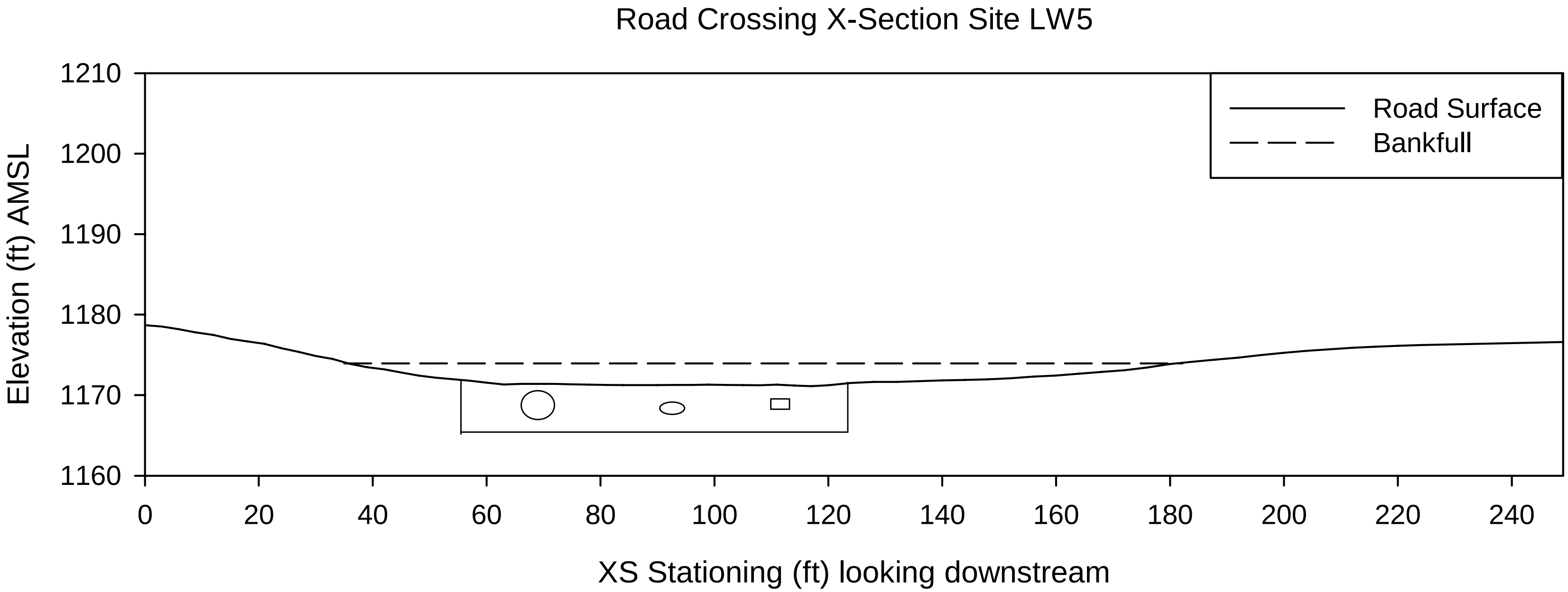

Figure 5: Cross-sectional profile plotting the road surface of the low-water crossing over the stream channel and bankfull at site LW5

Appendix 5: Pebble Count Graphs

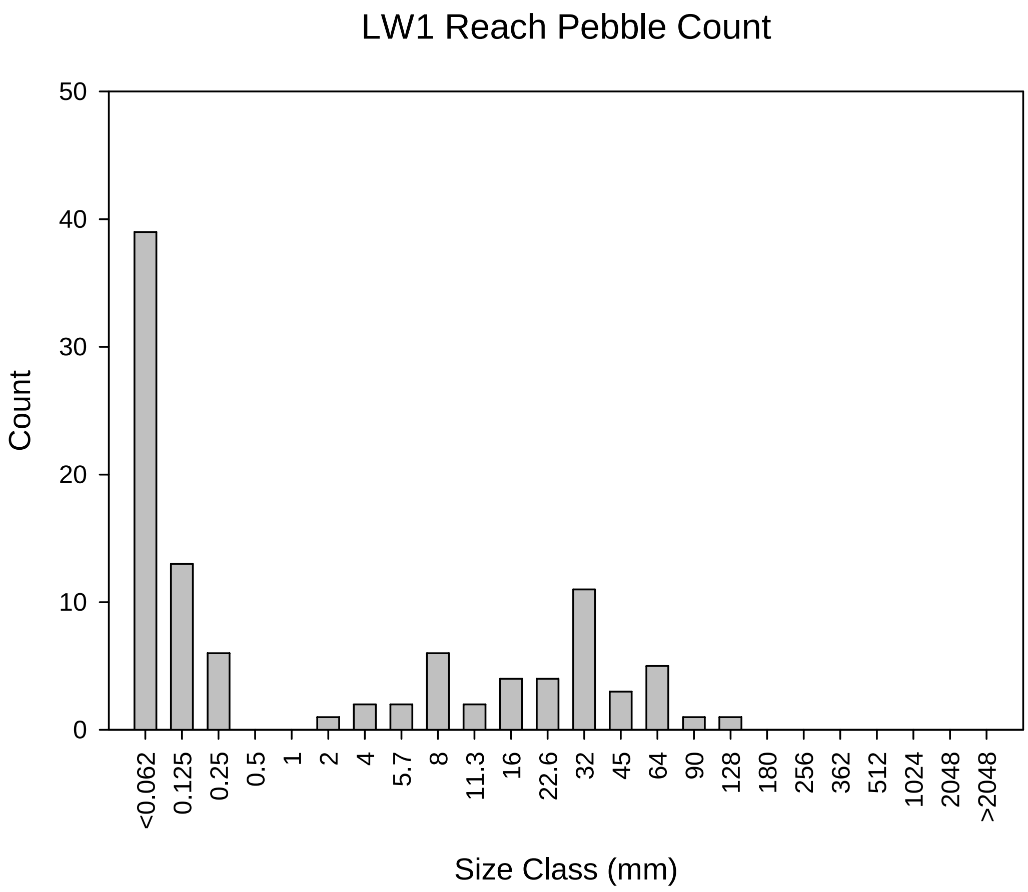

Figure 1: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW1.

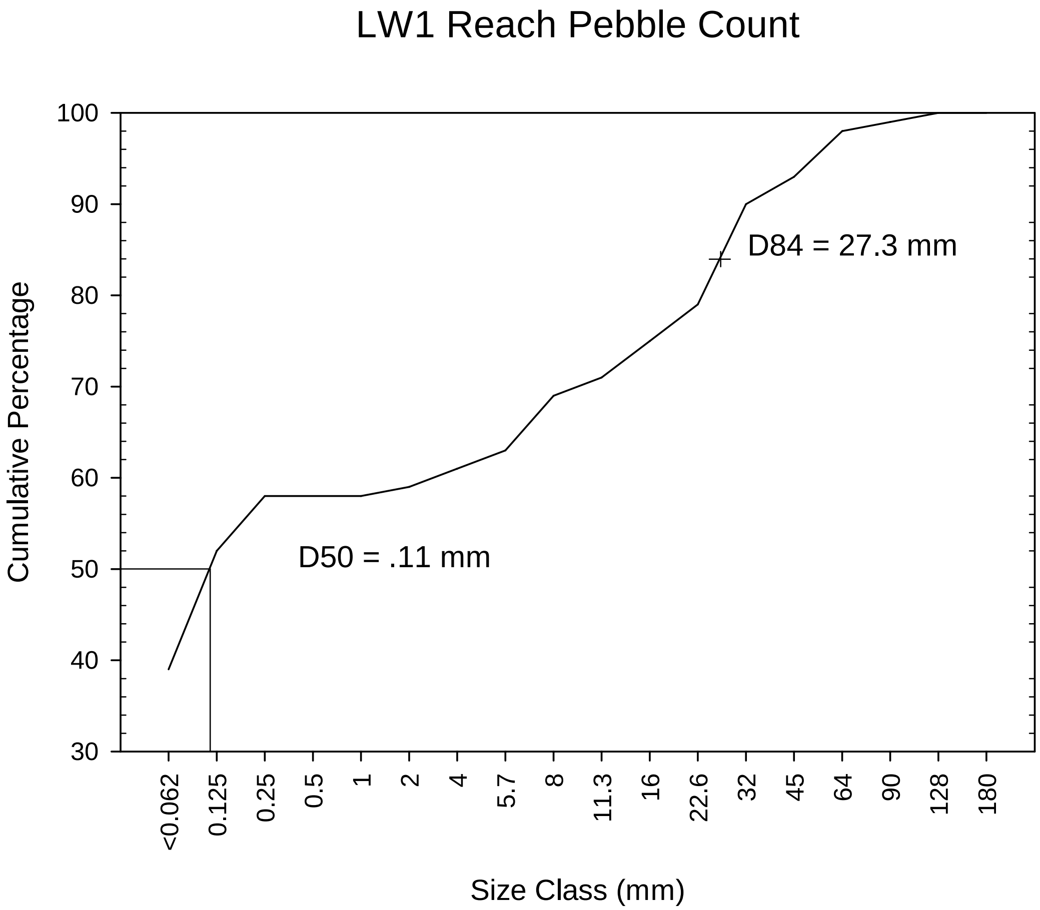

Figure 2: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW1. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

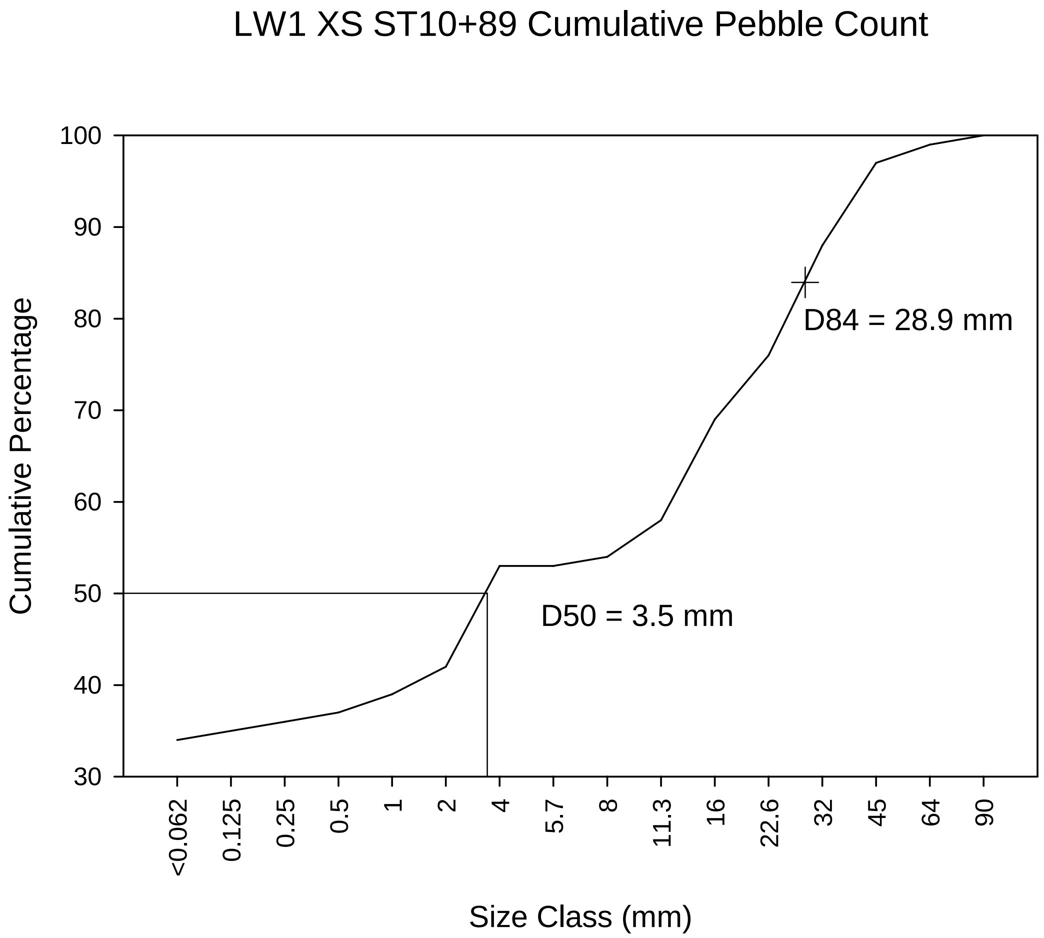

Figure 3: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

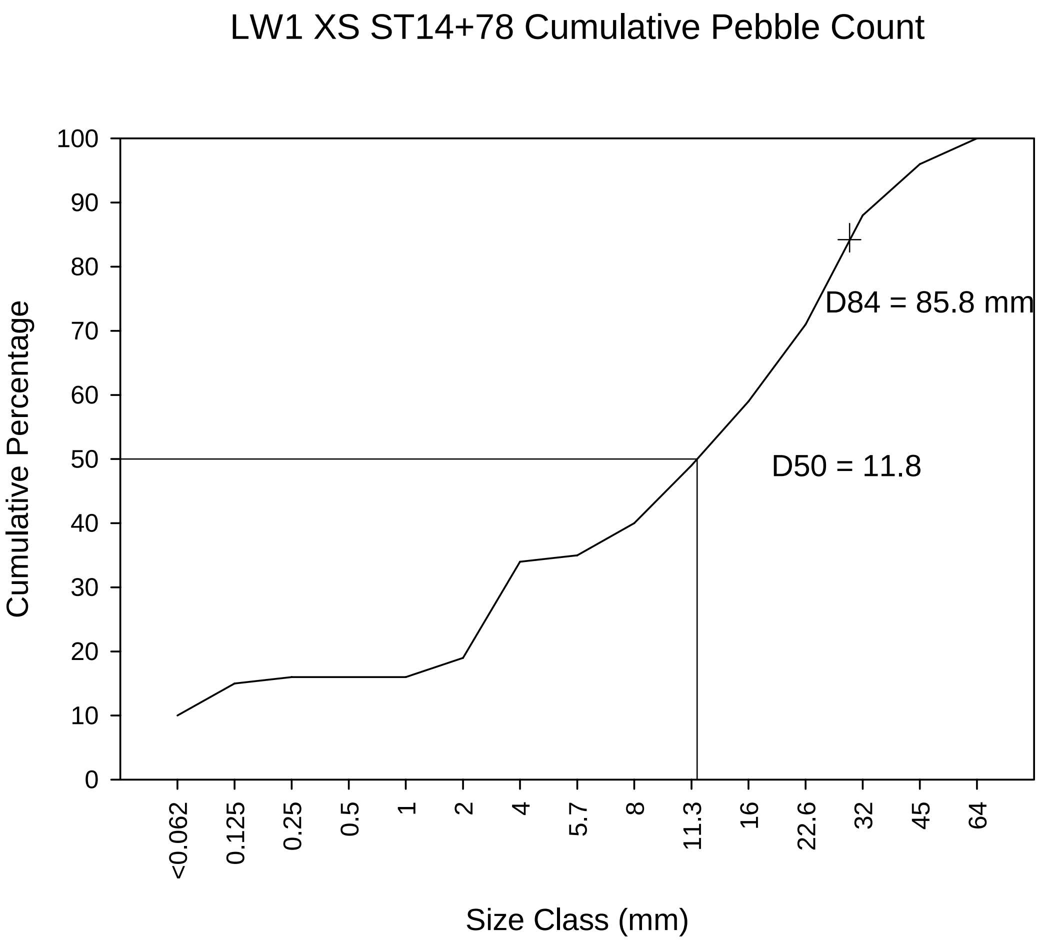

Figure 4: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

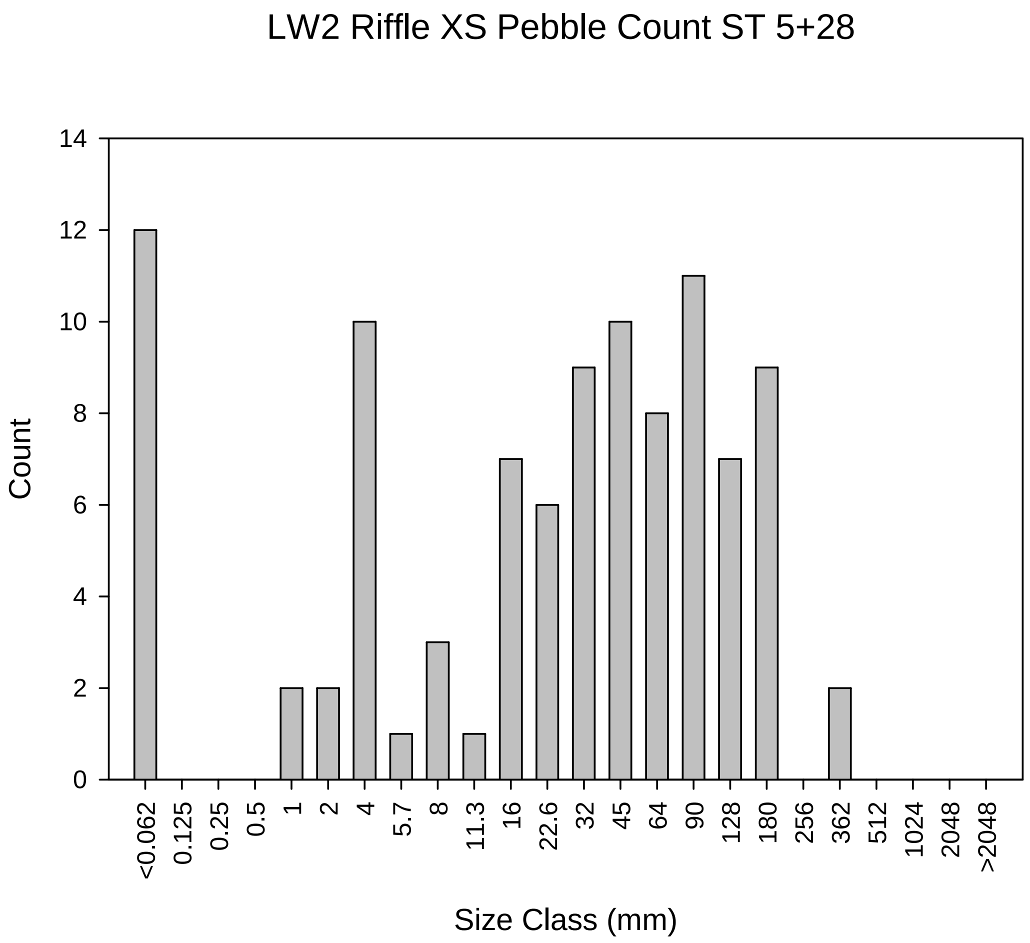

Figure 5: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW2.

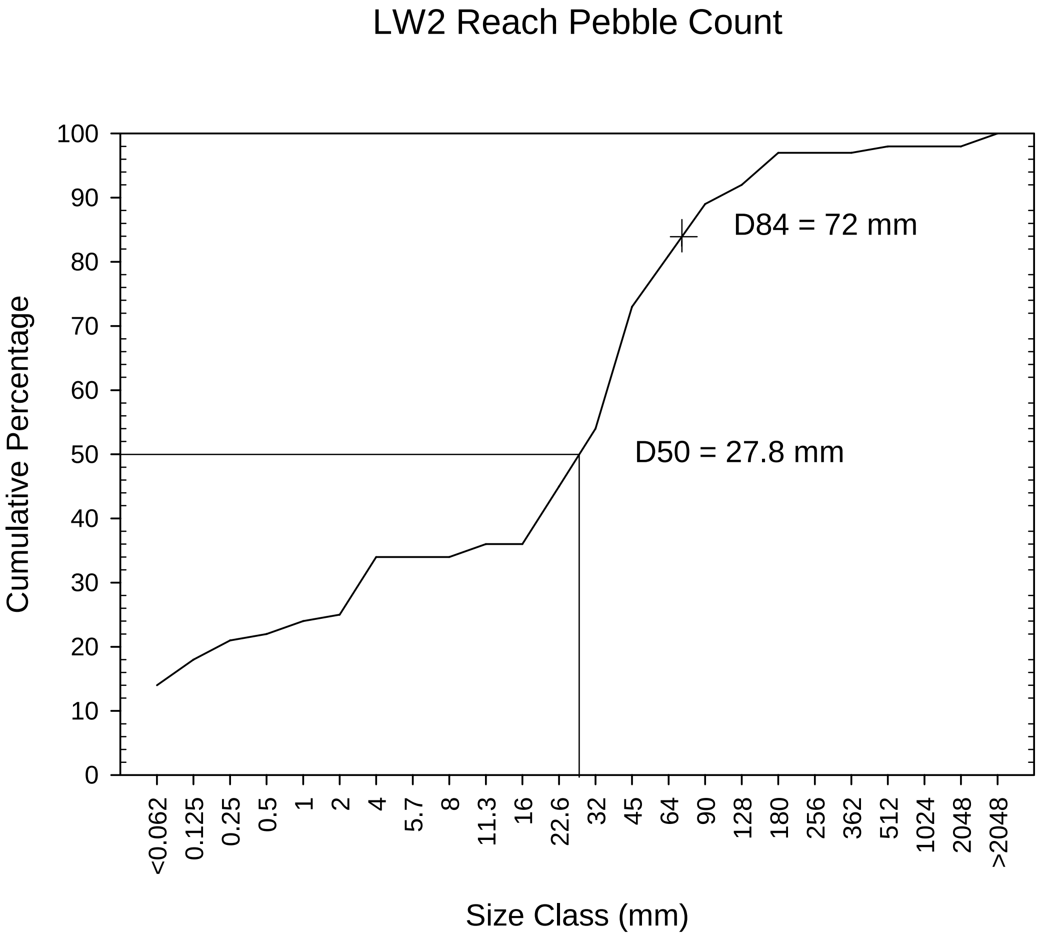

Figure 6: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW2. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

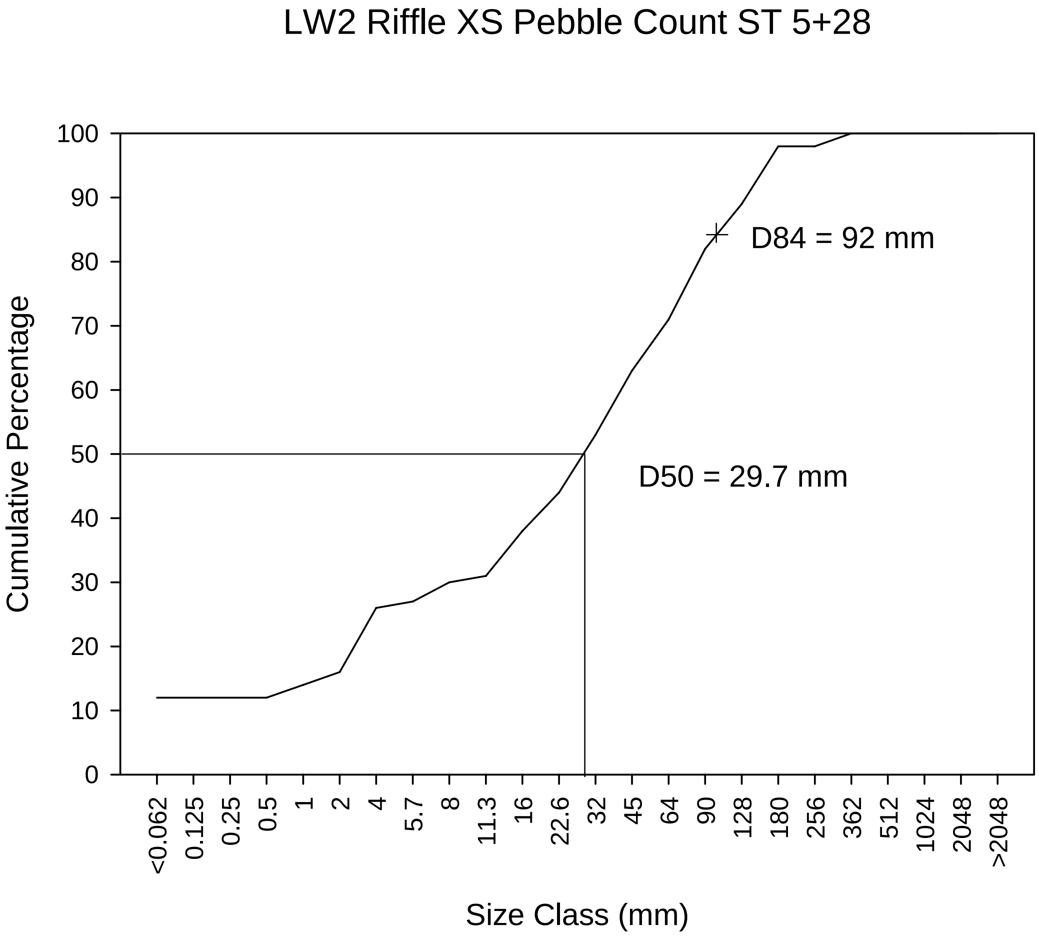

Figure 7: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

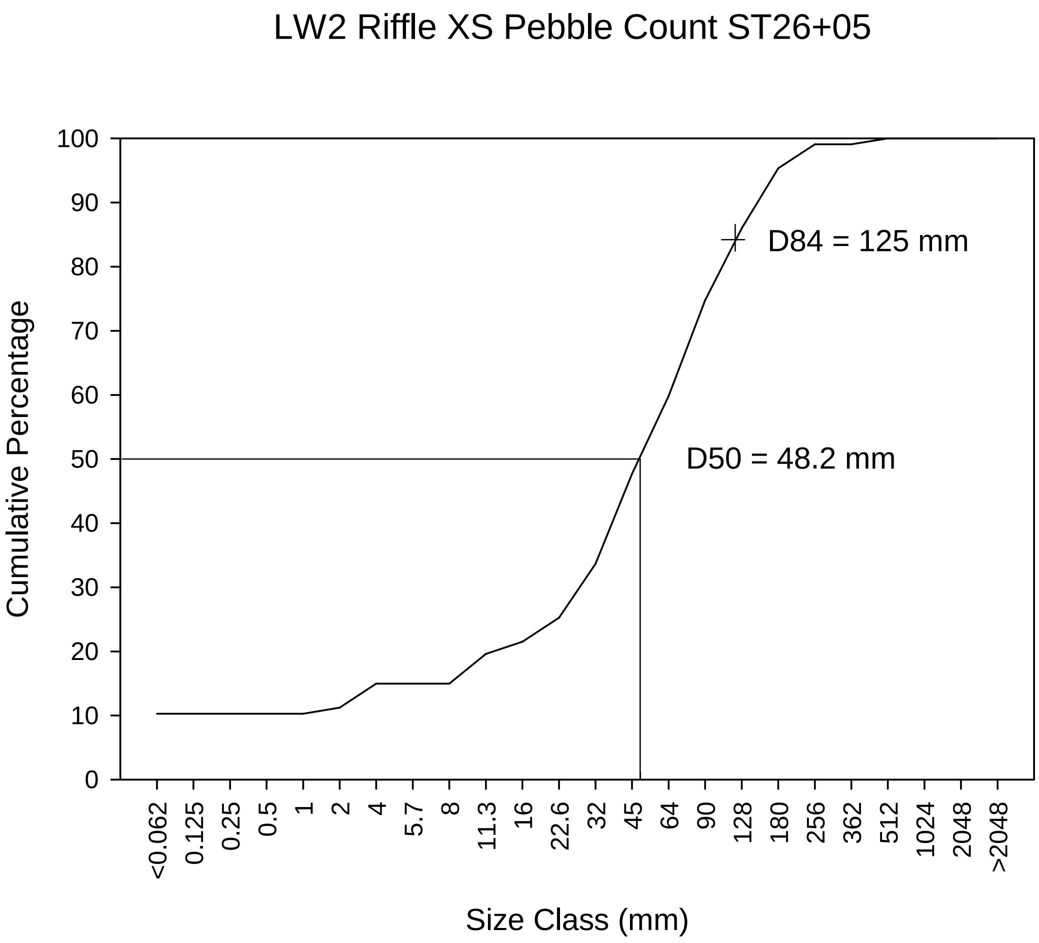

Figure 8: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

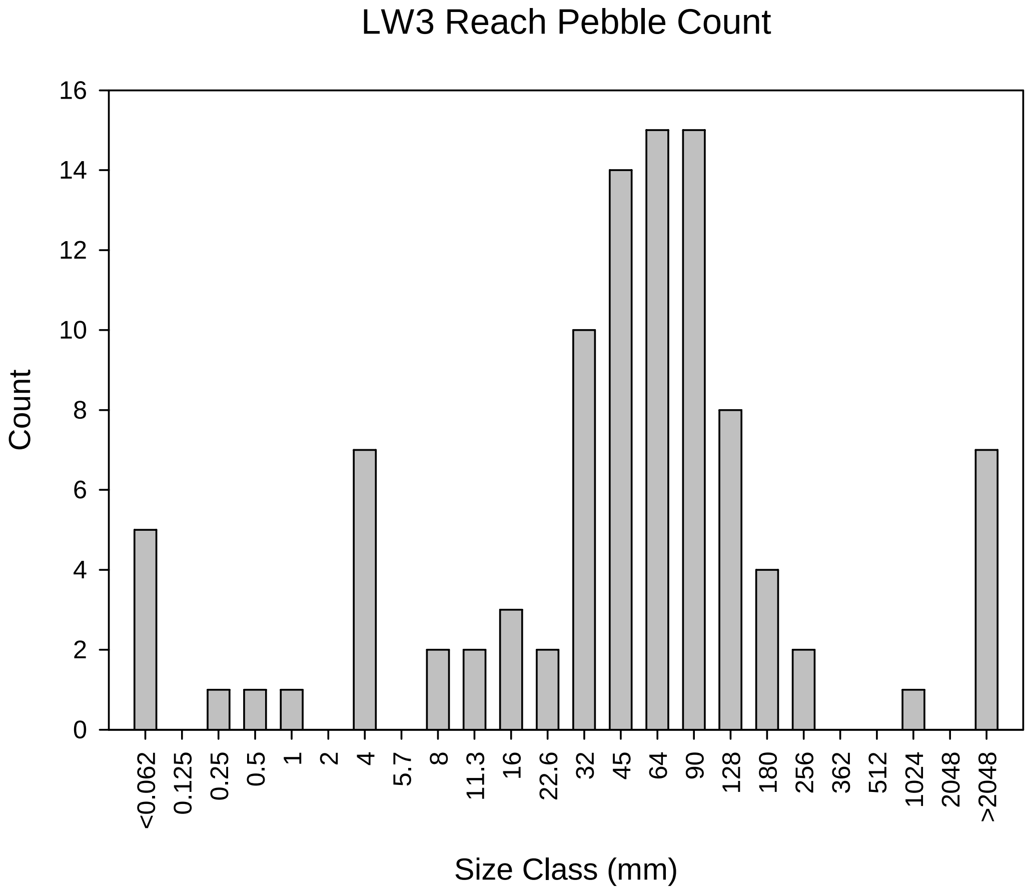

Figure 9: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW3.

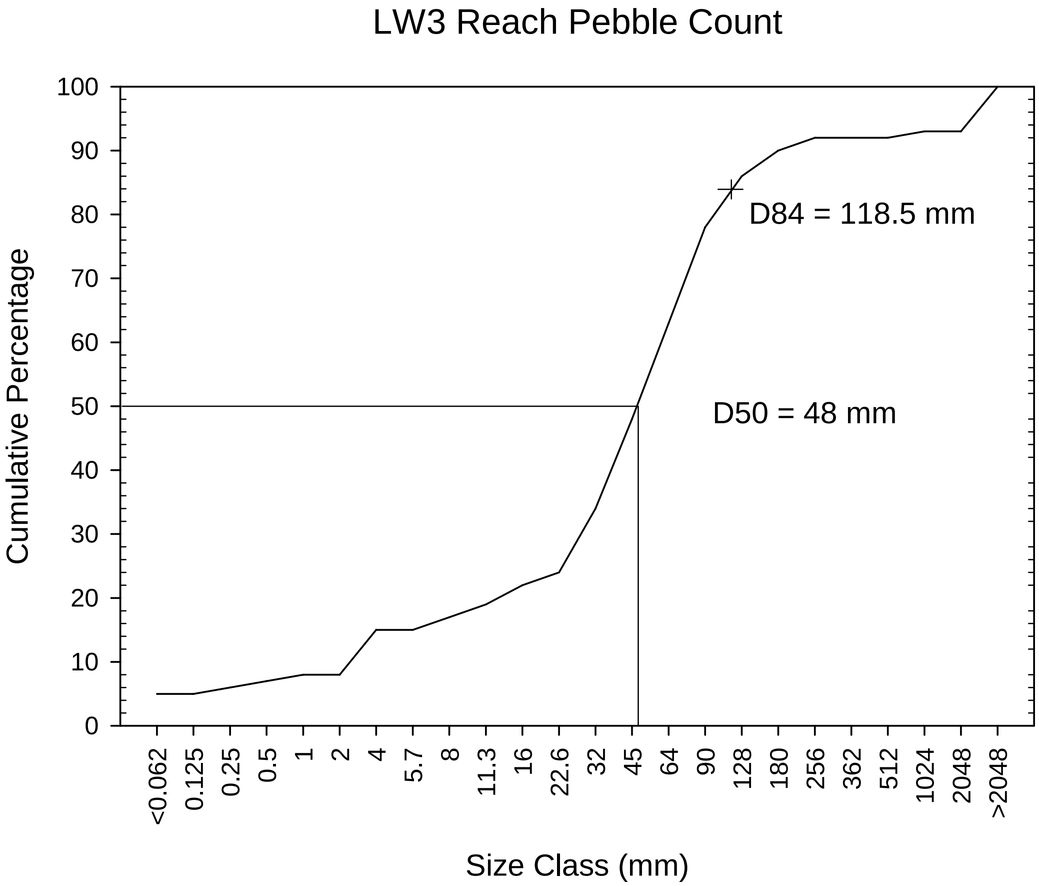

Figure 10: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW3. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

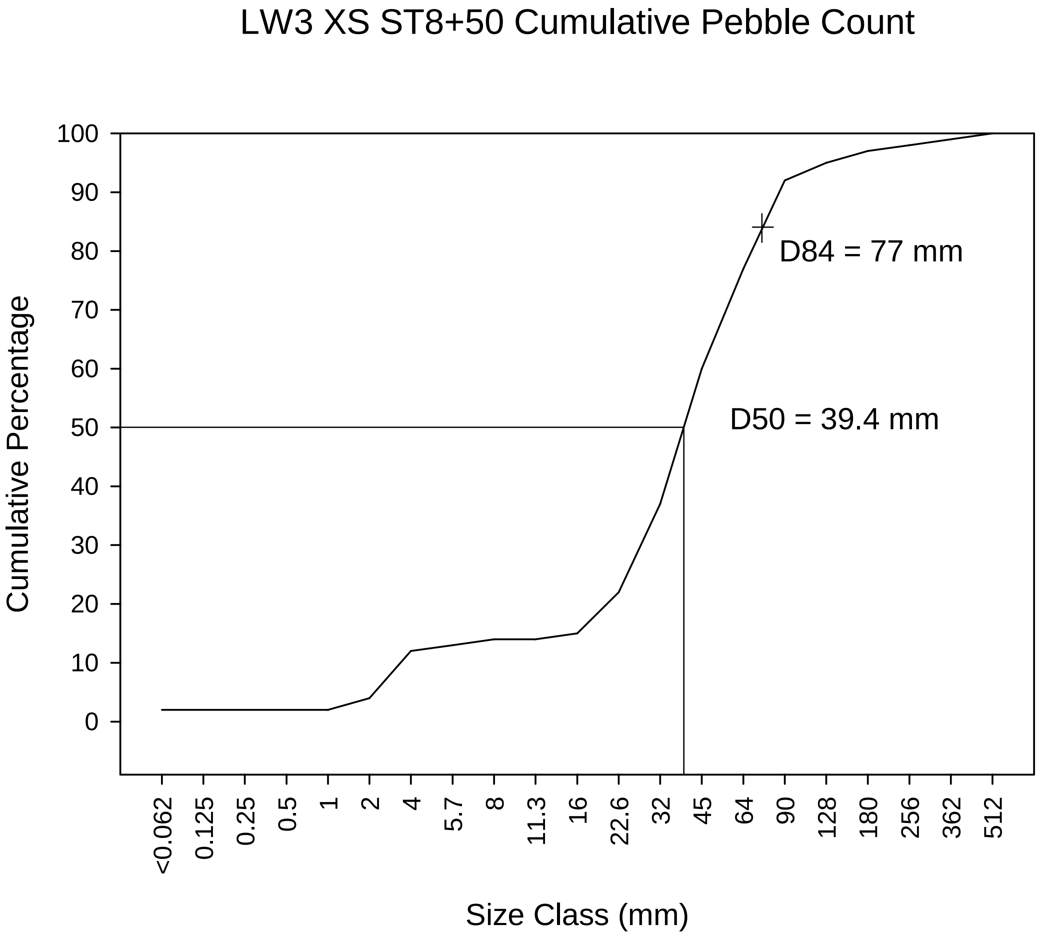

Figure 11: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW3. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

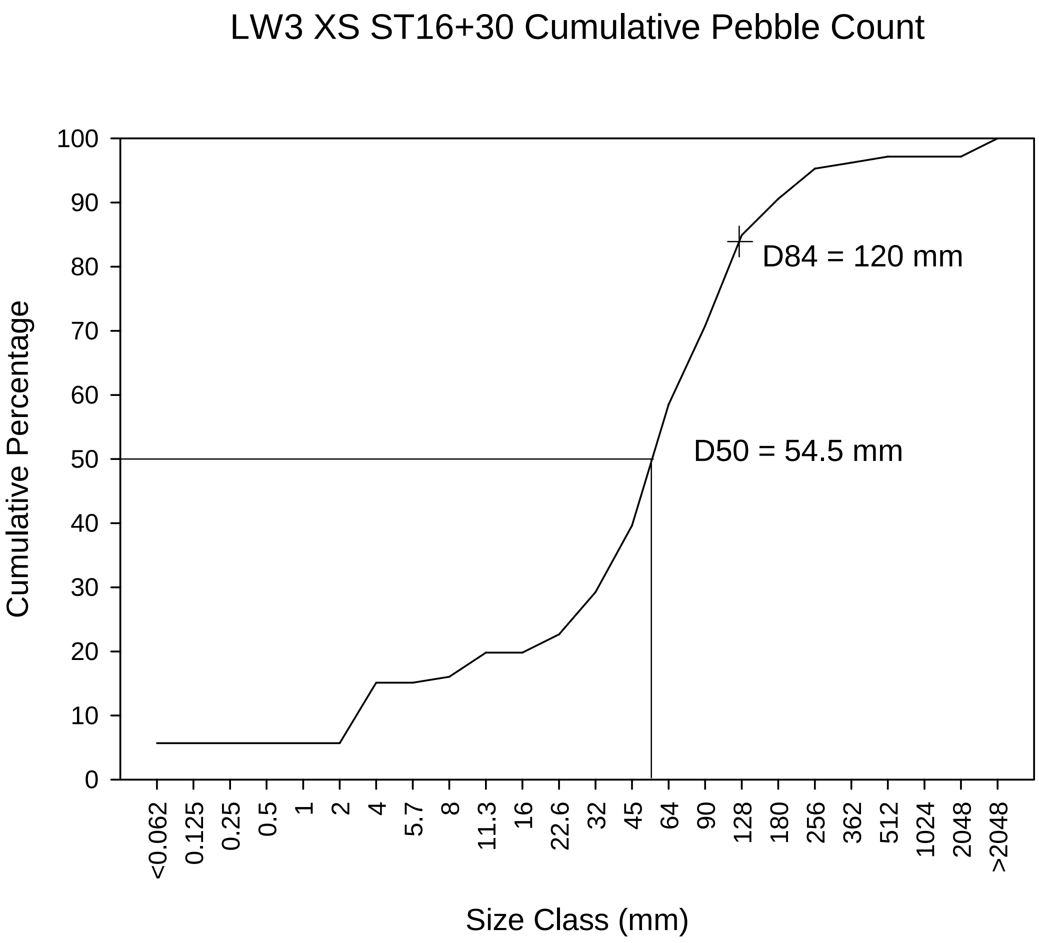

Figure 12: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW3. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

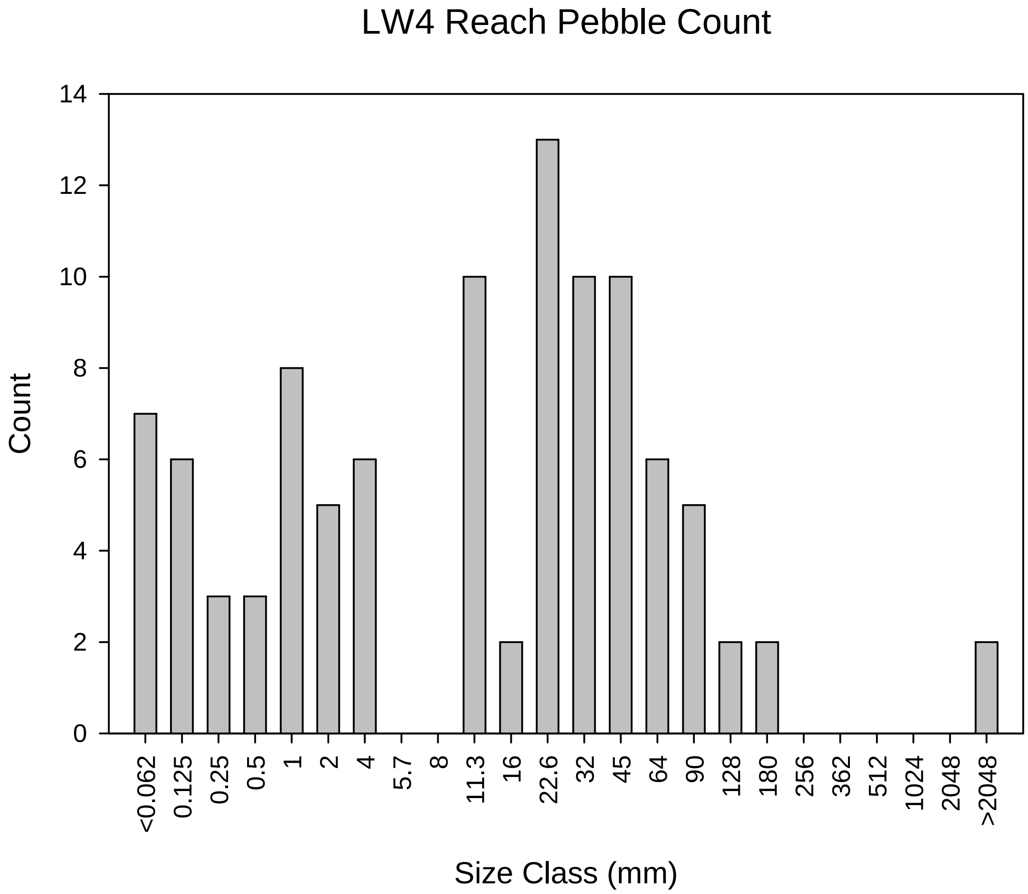

Figure 13: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW4.

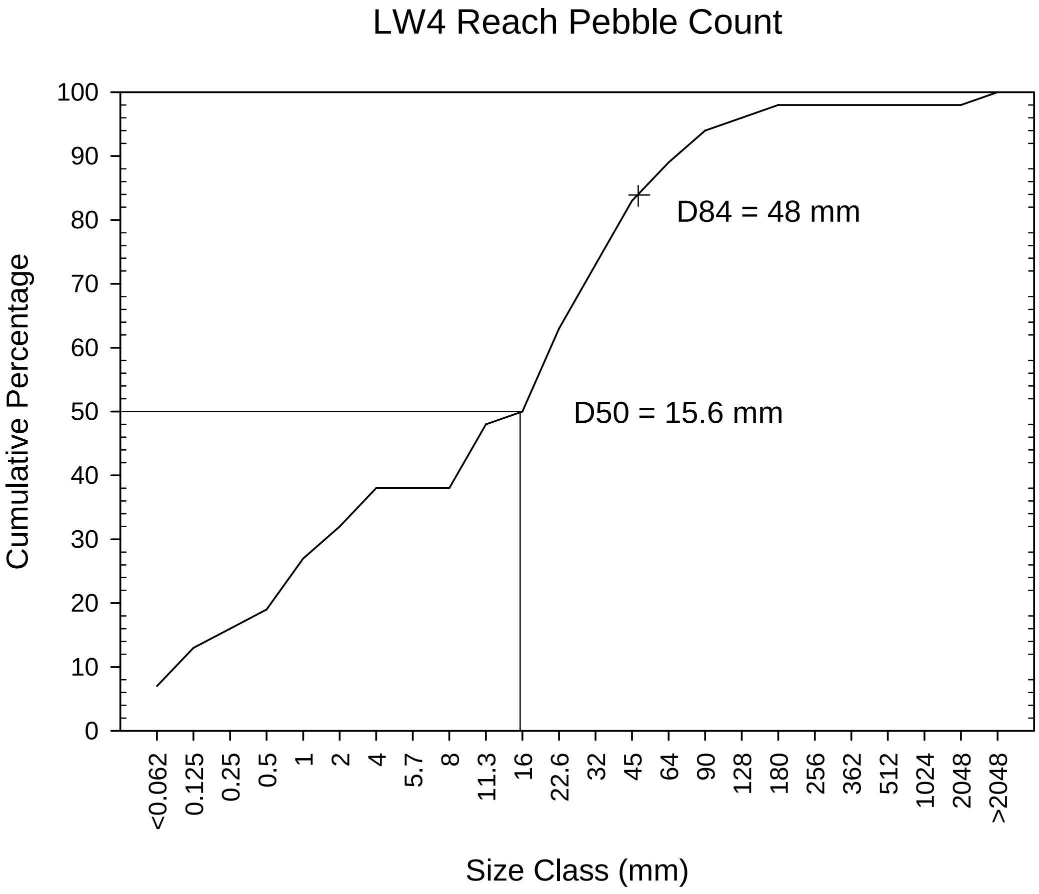

Figure 14: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW4. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

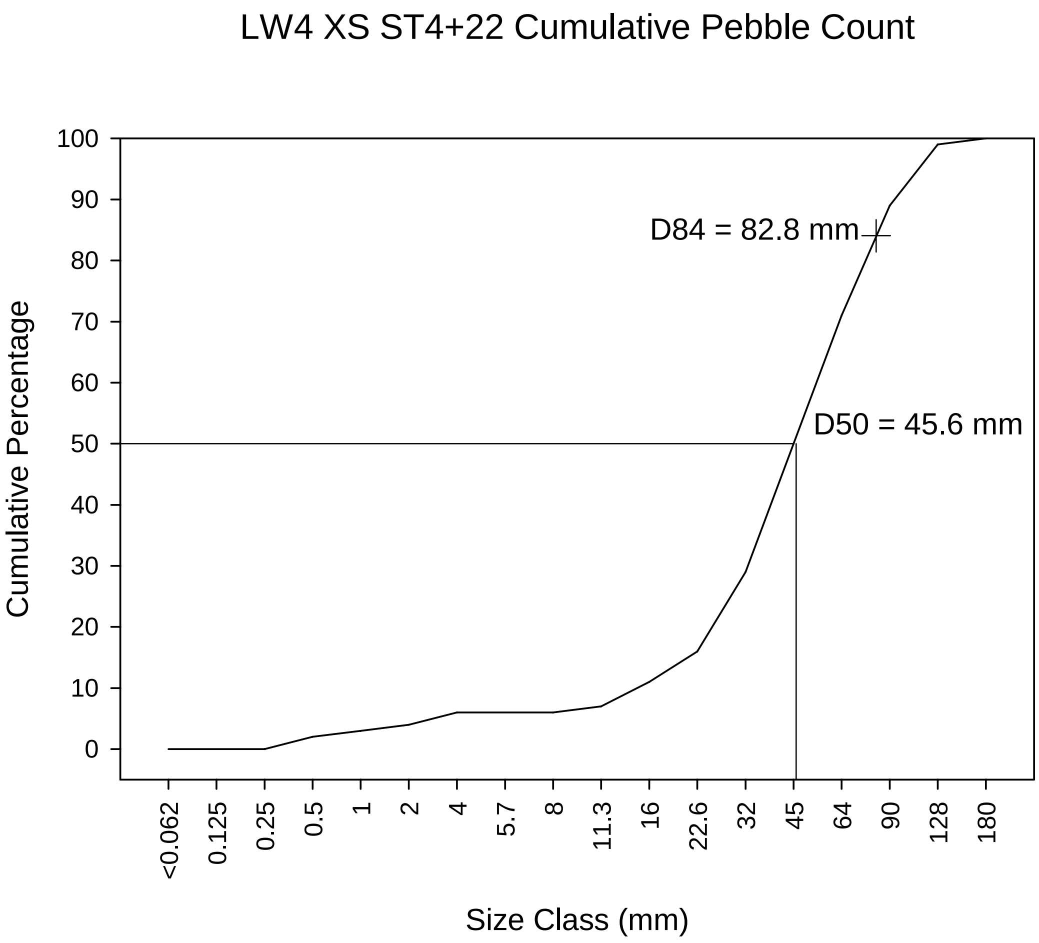

Figure 15: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW4. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

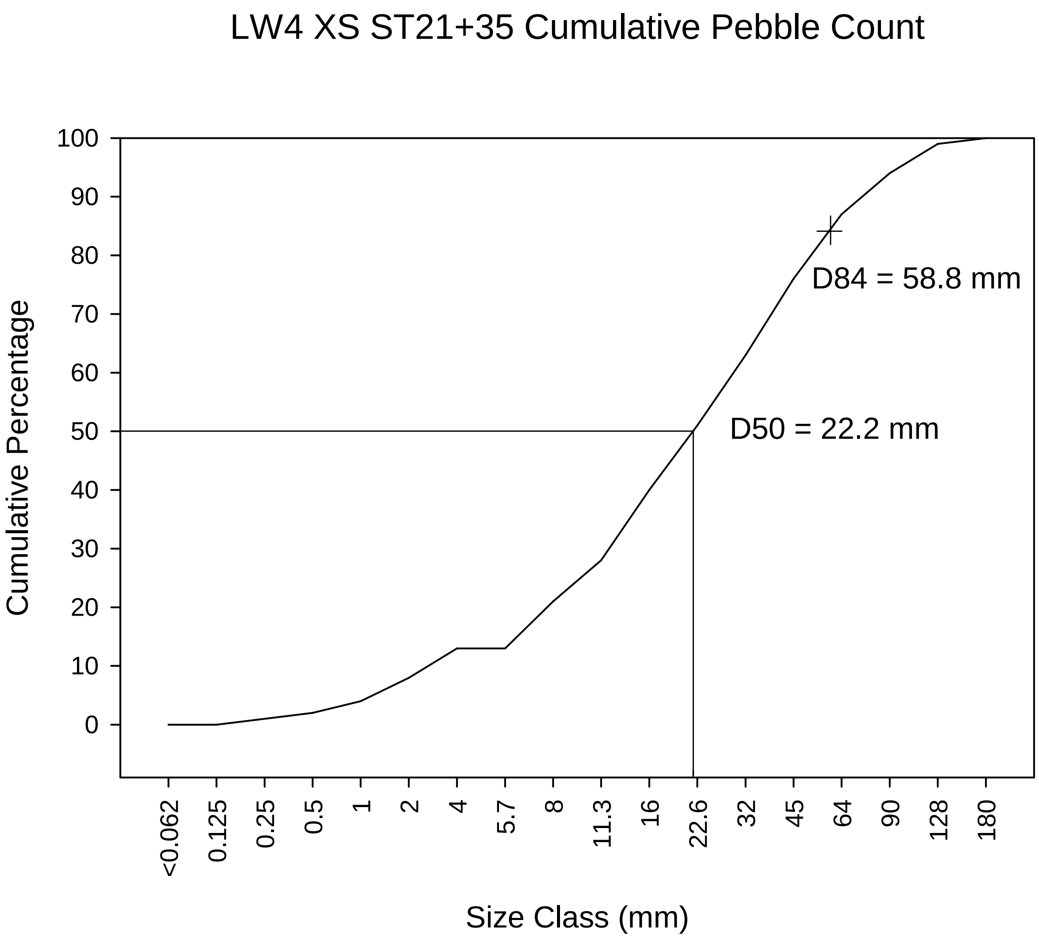

Figure 16: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW4. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

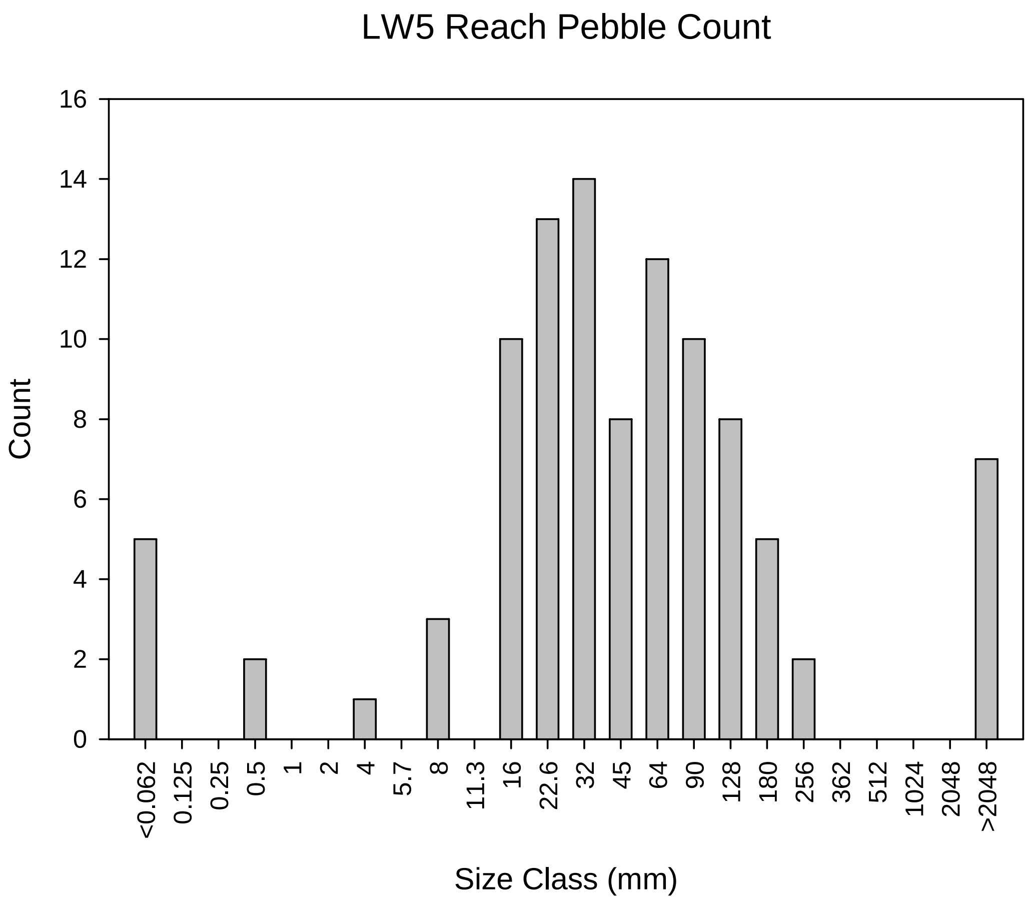

Figure 17: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW5.

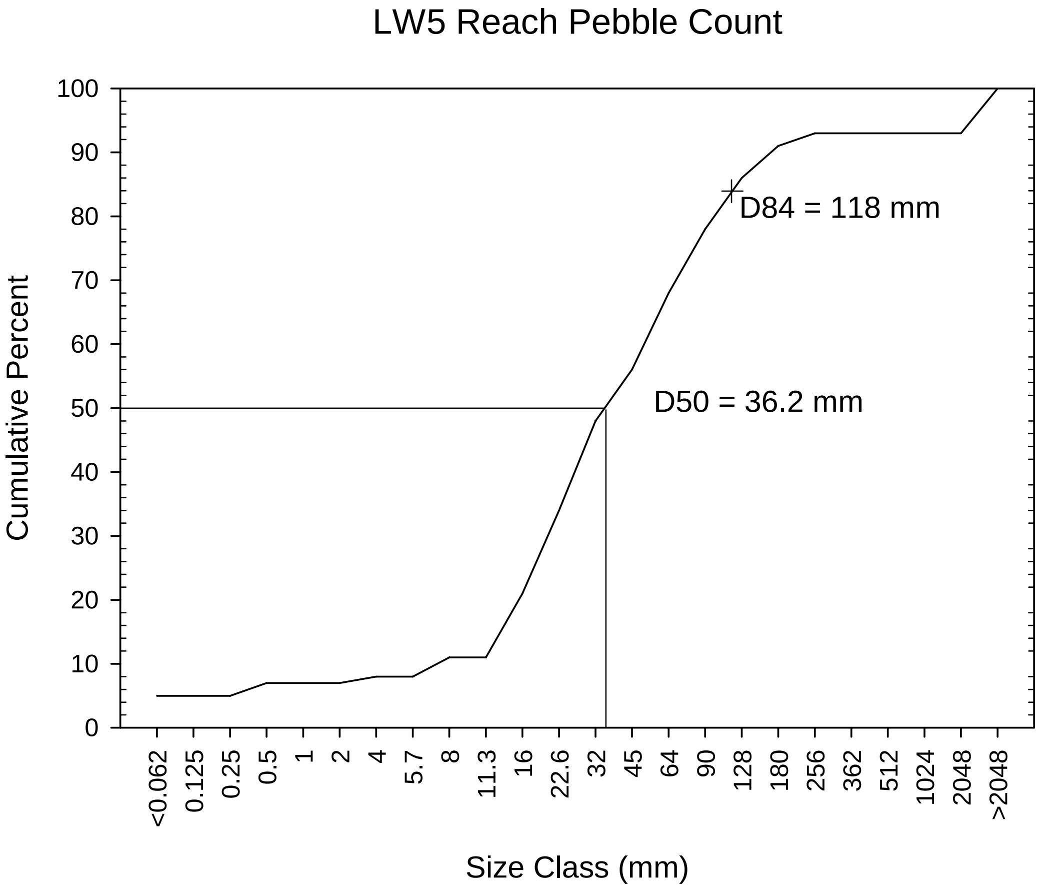

Figure 18: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site LW5. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

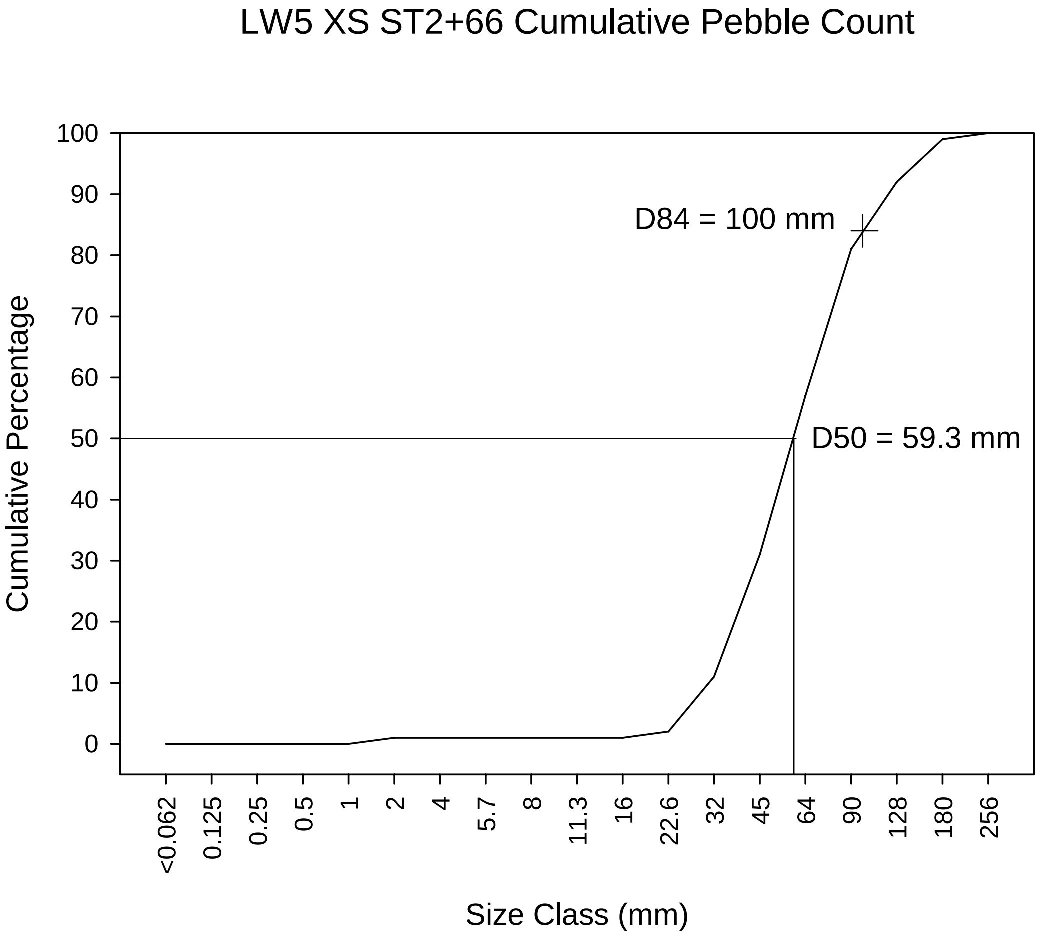

Figure 19: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW5. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

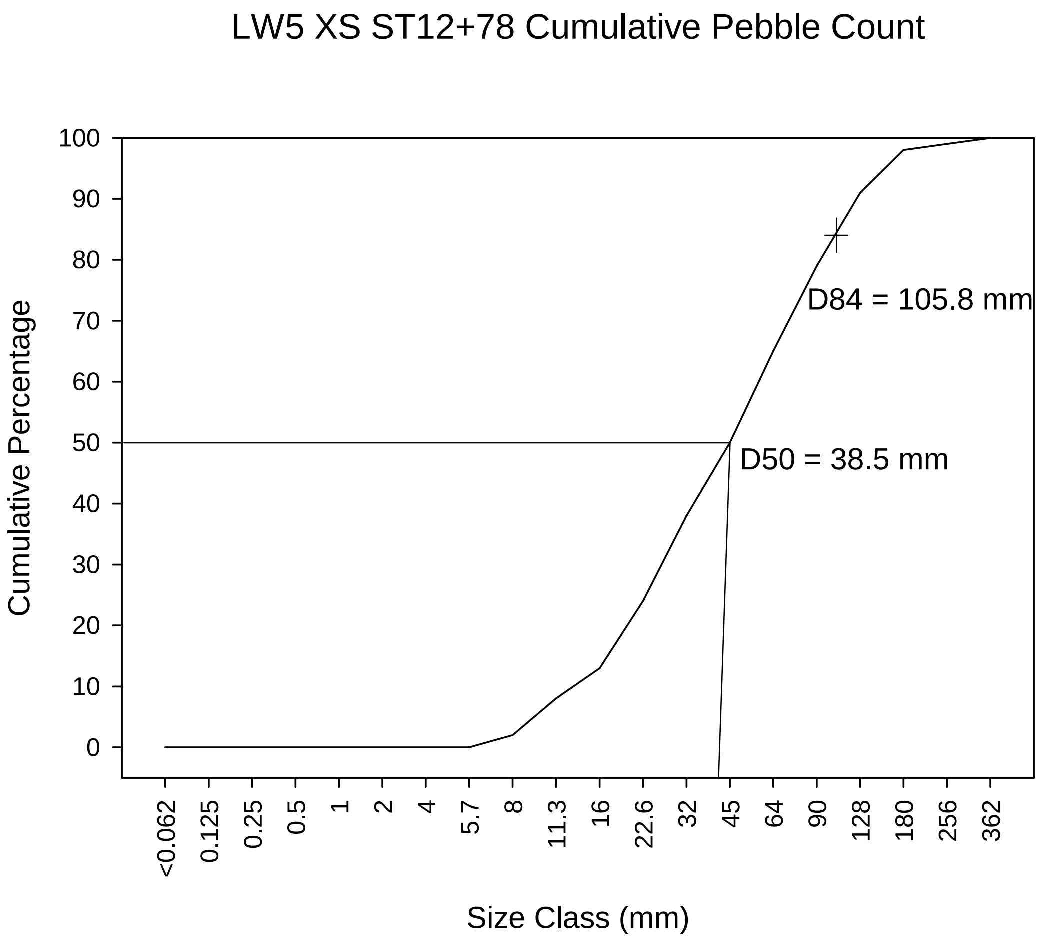

Figure 20: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site LW5. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

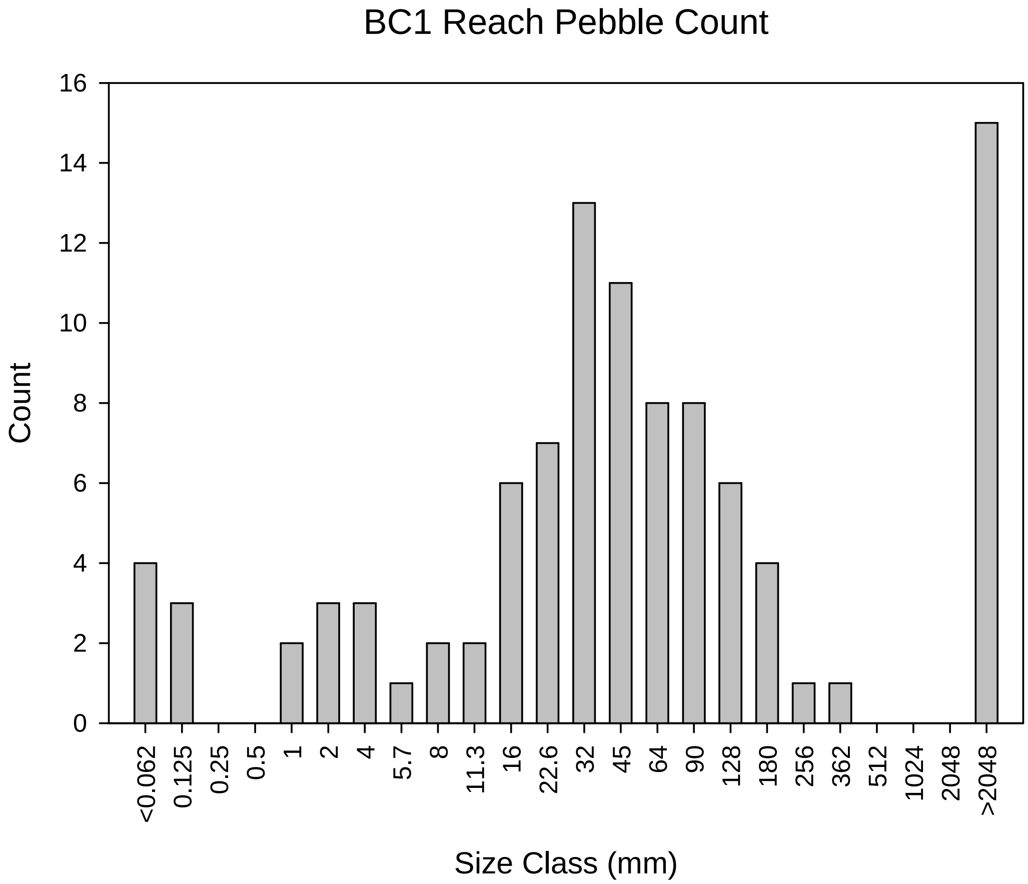

Figure 21: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC1.

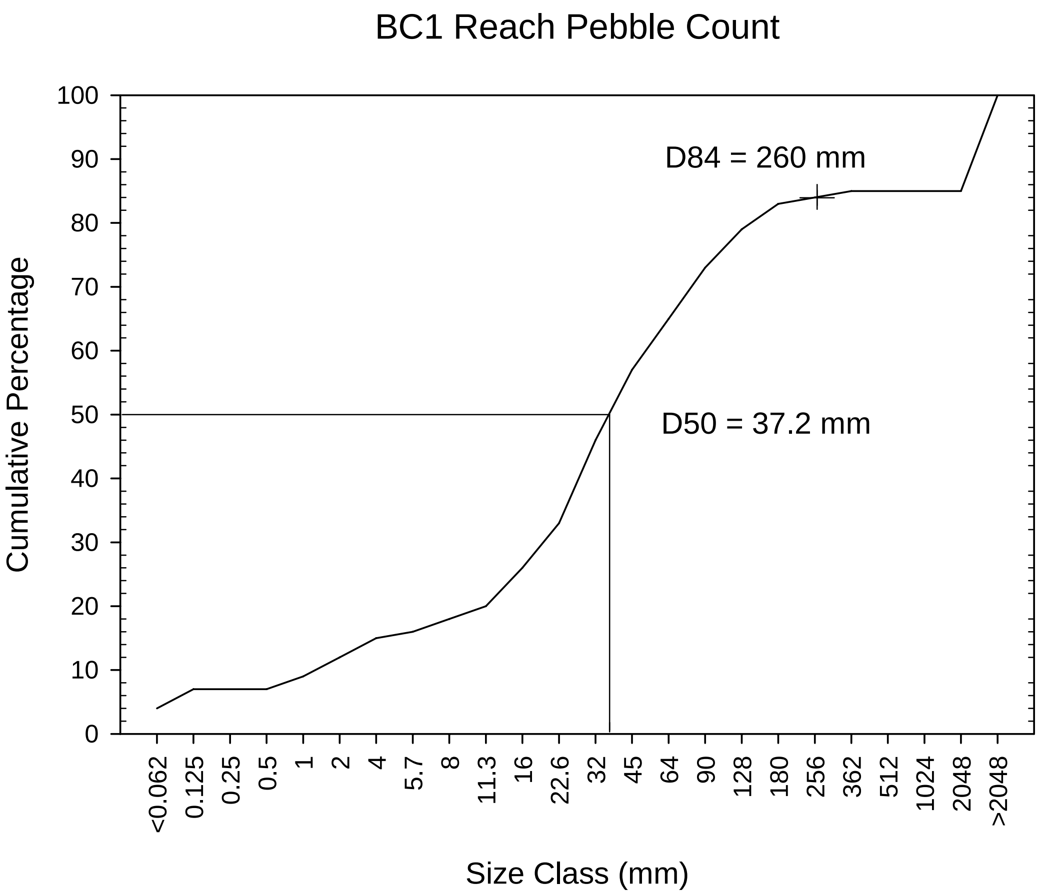

Figure 22: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC1. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

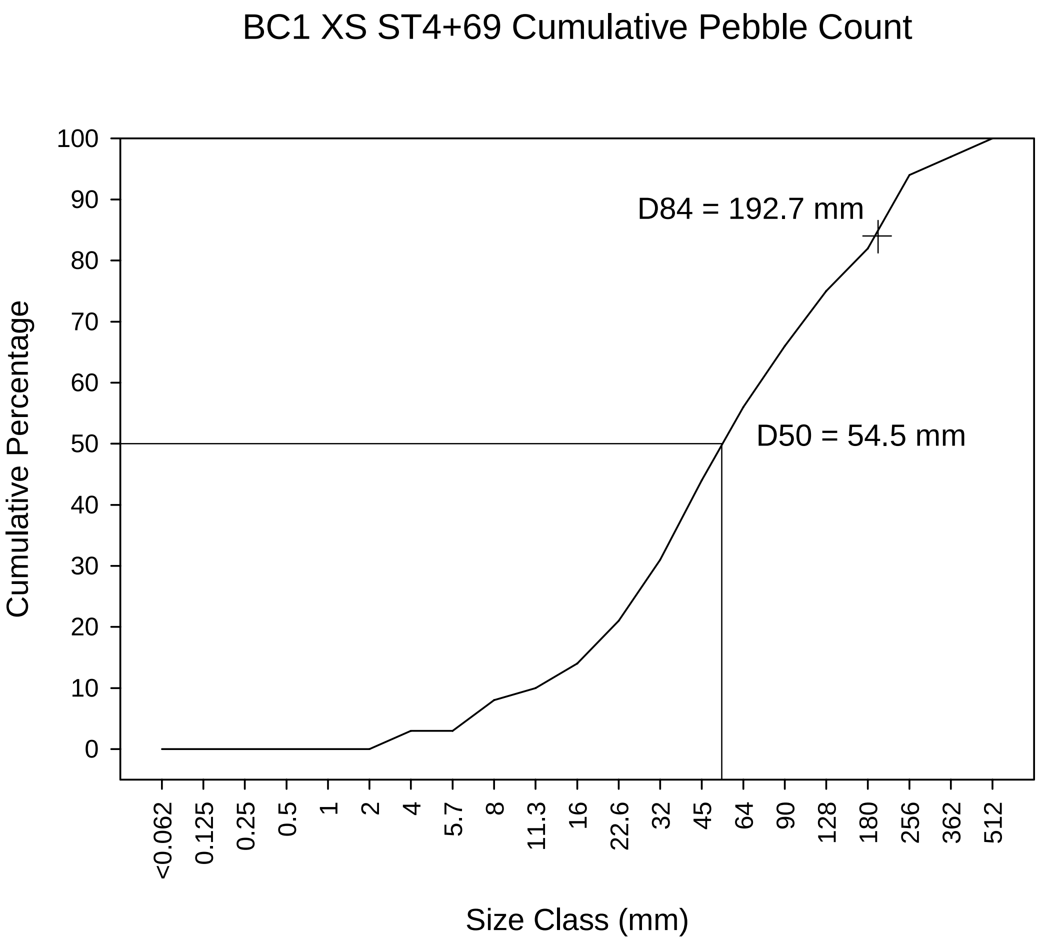

Figure 23: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

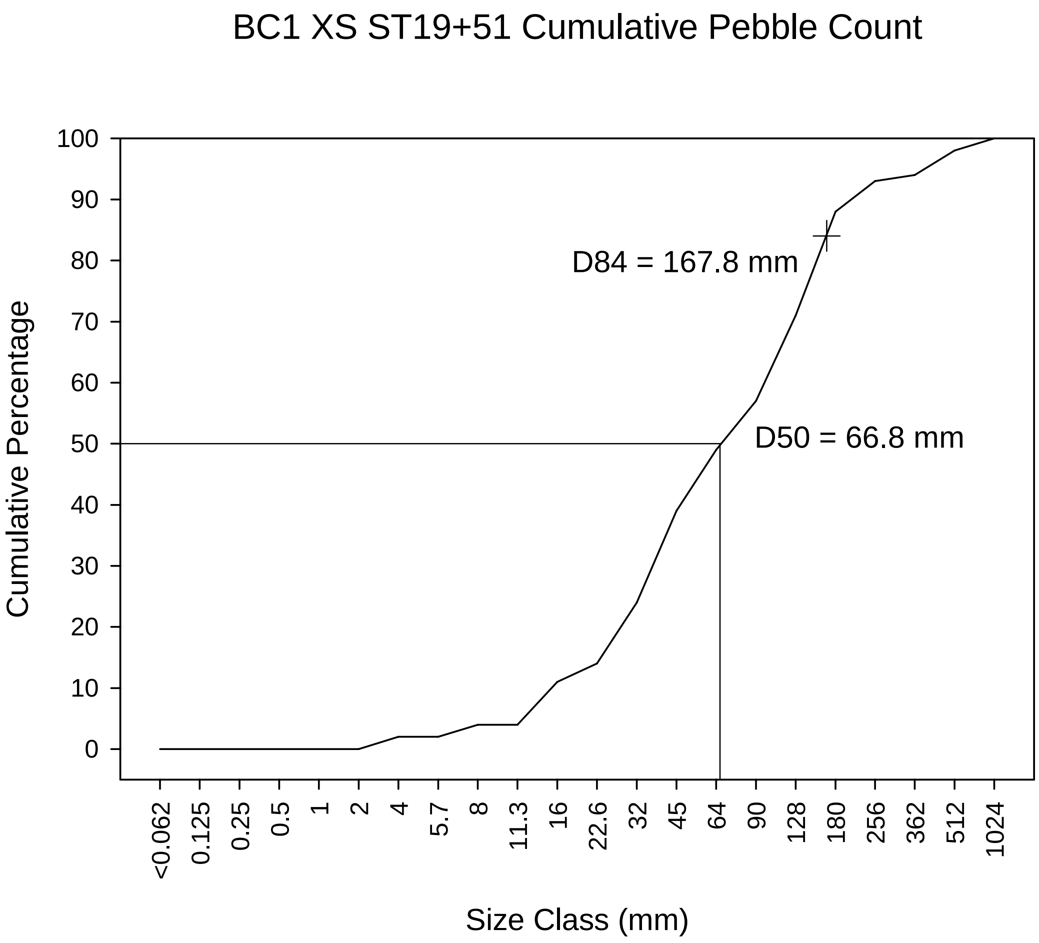

Figure 24: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

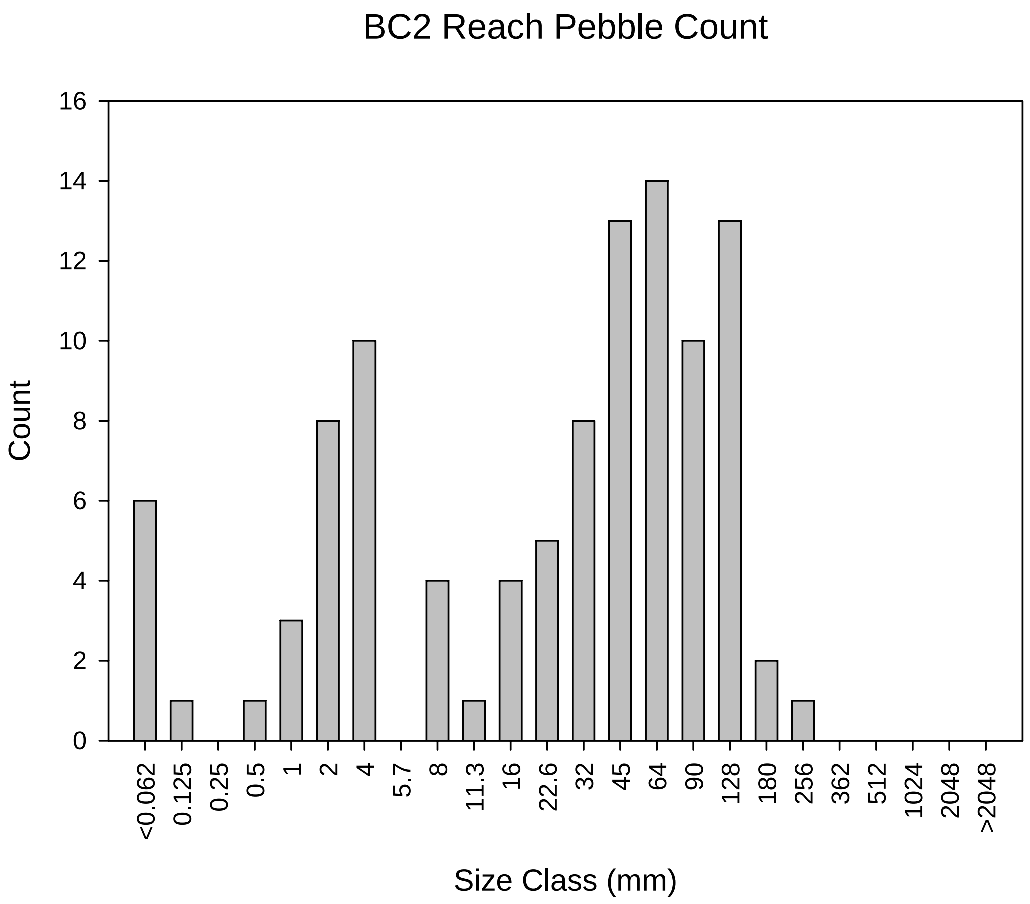

Figure 25: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC2.

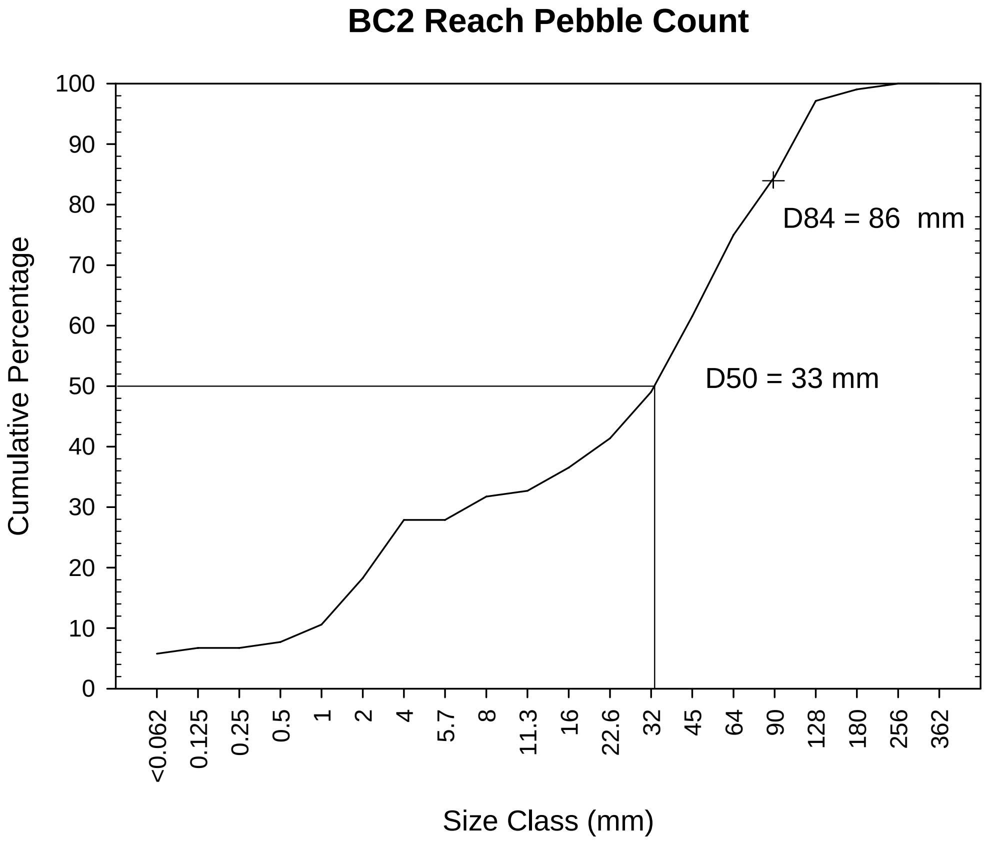

Figure 26: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC2. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

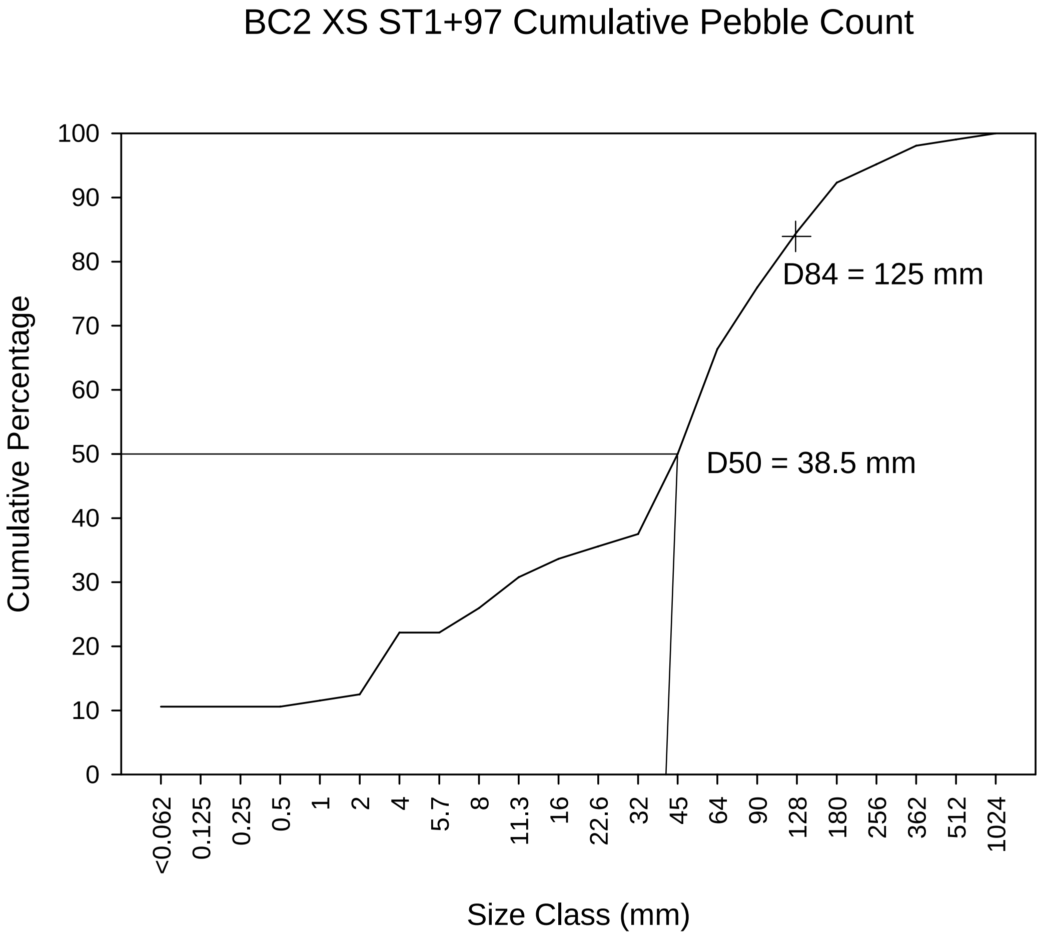

Figure 27: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

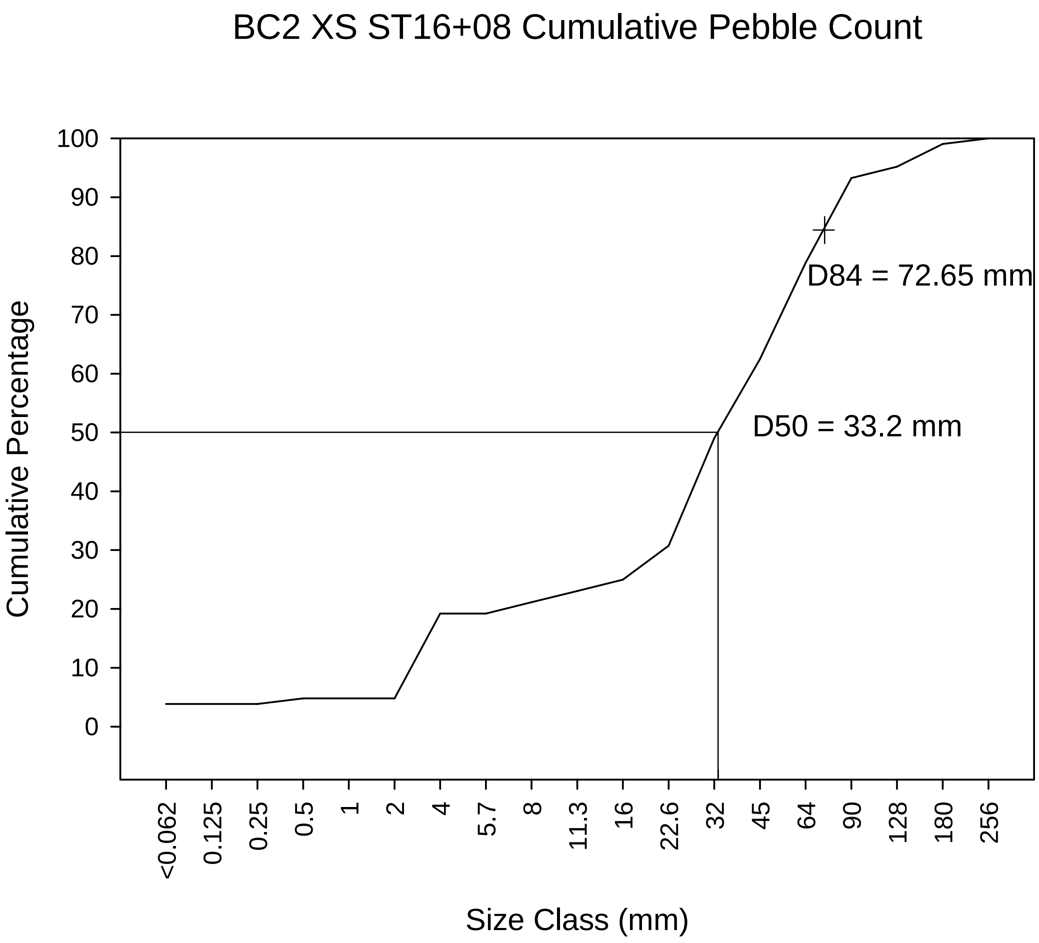

Figure 28: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

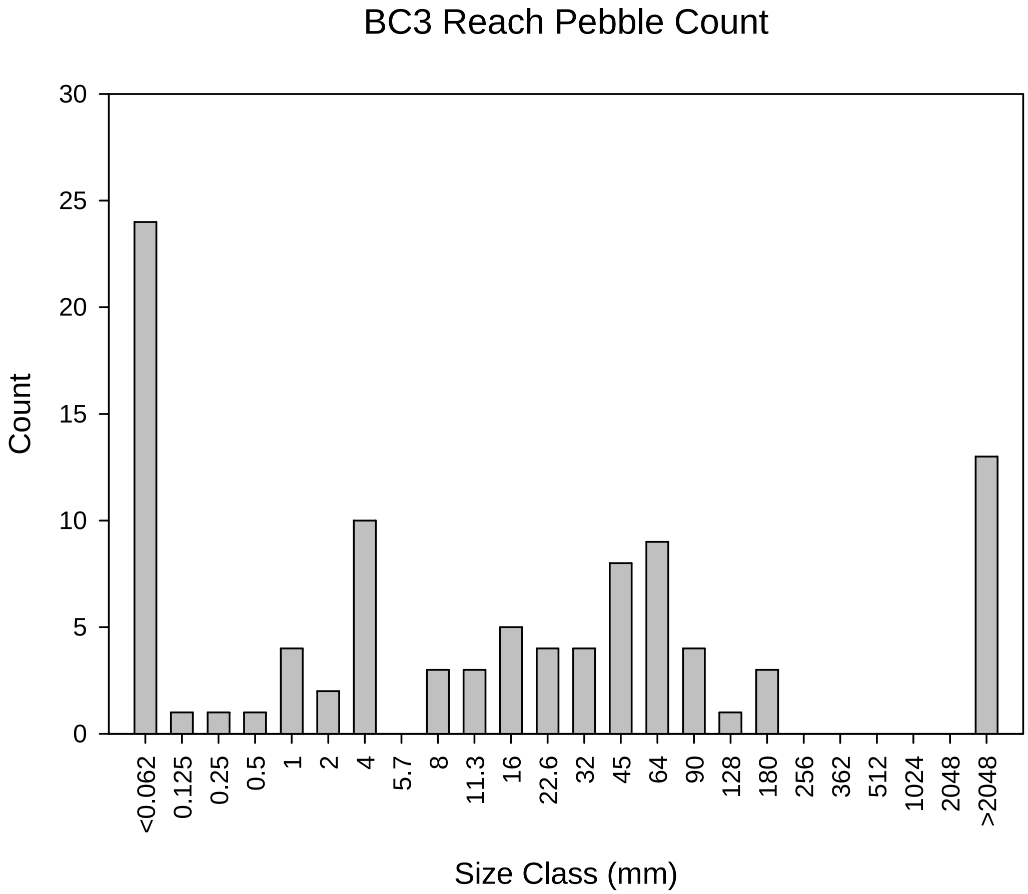

Figure 29: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC3.

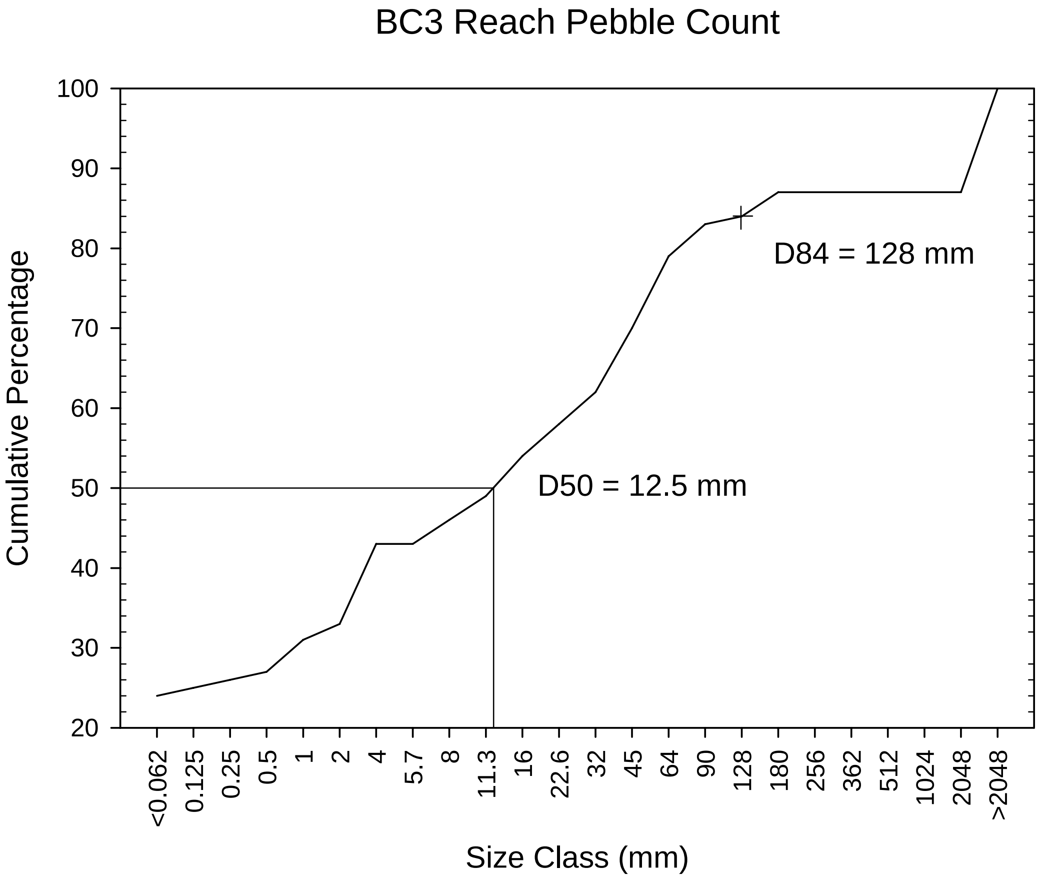

Figure 30: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC3. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

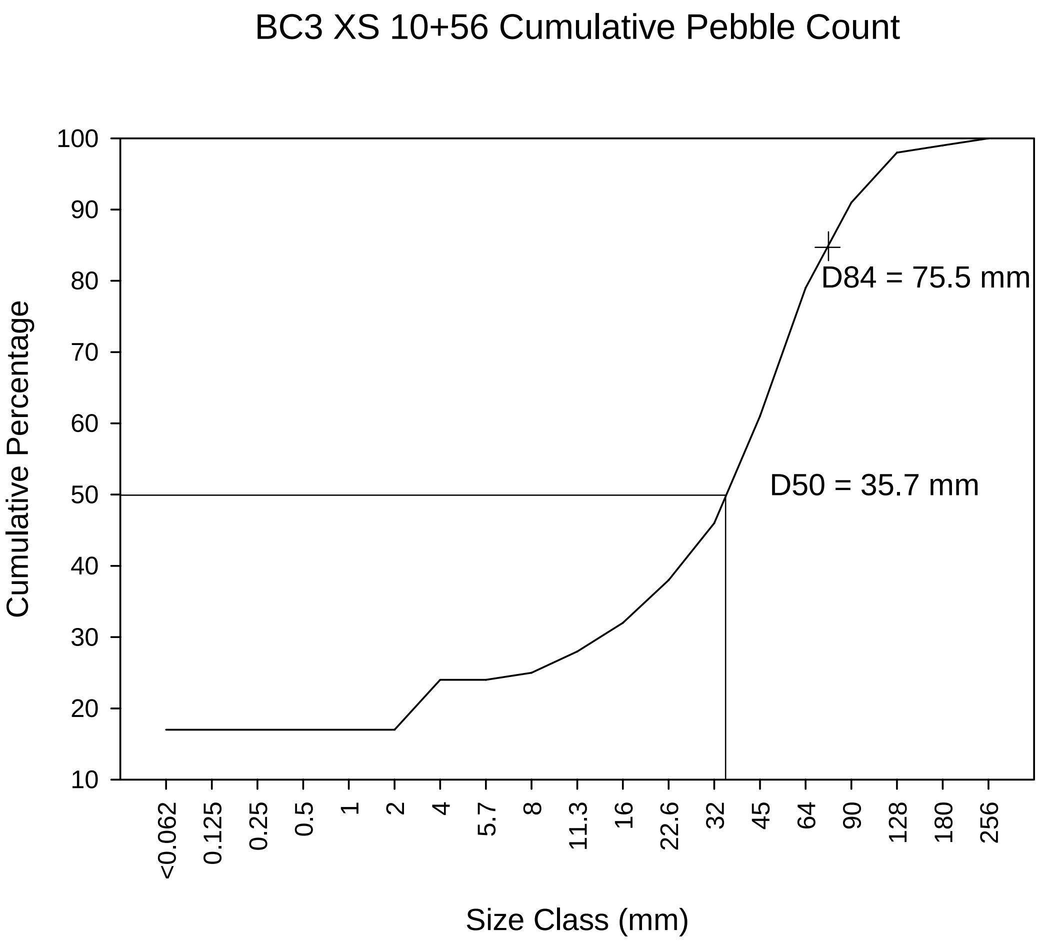

Figure 31: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC3. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

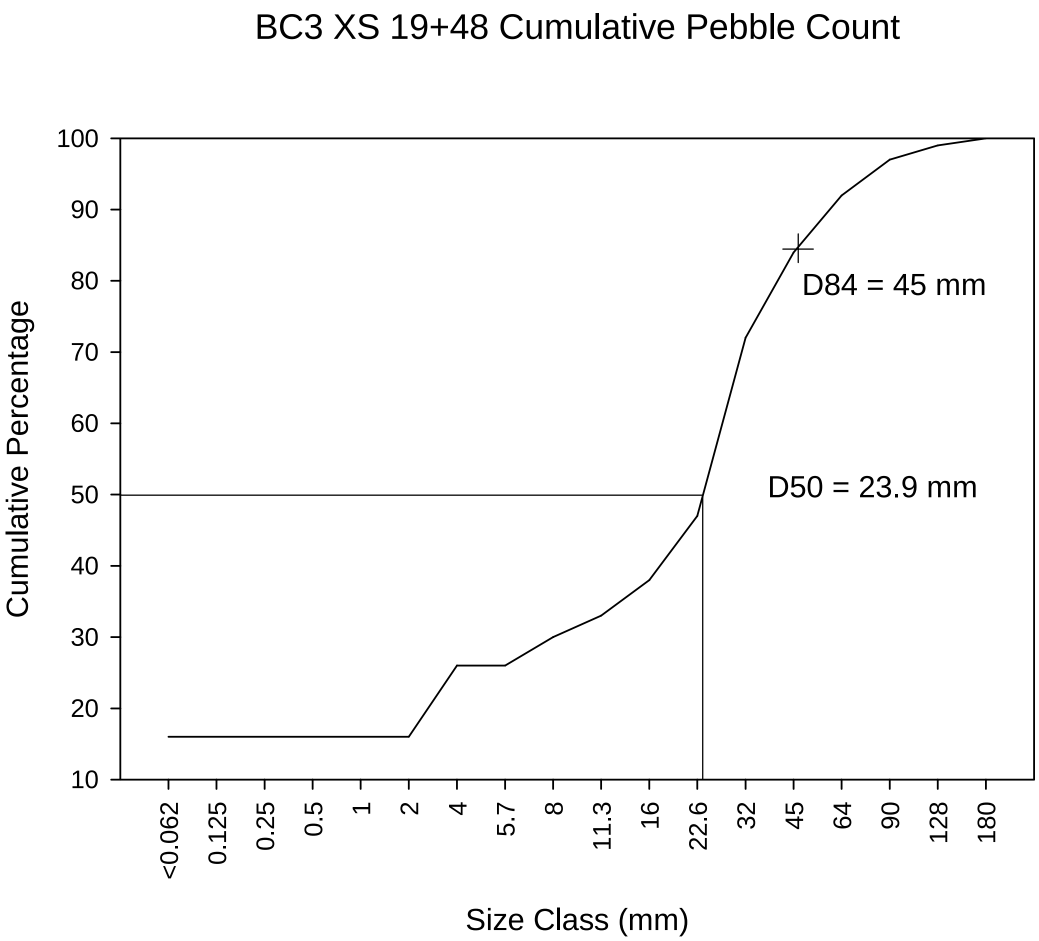

Figure 32: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC3. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

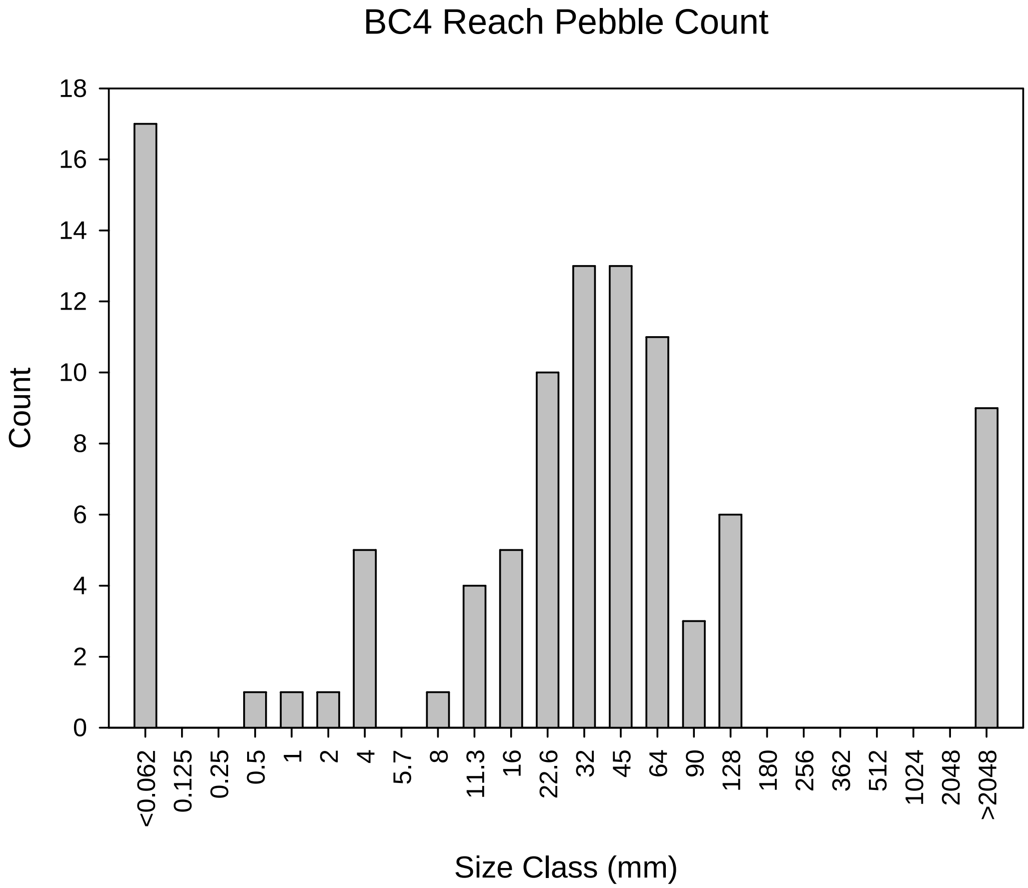

Figure 33: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC4.

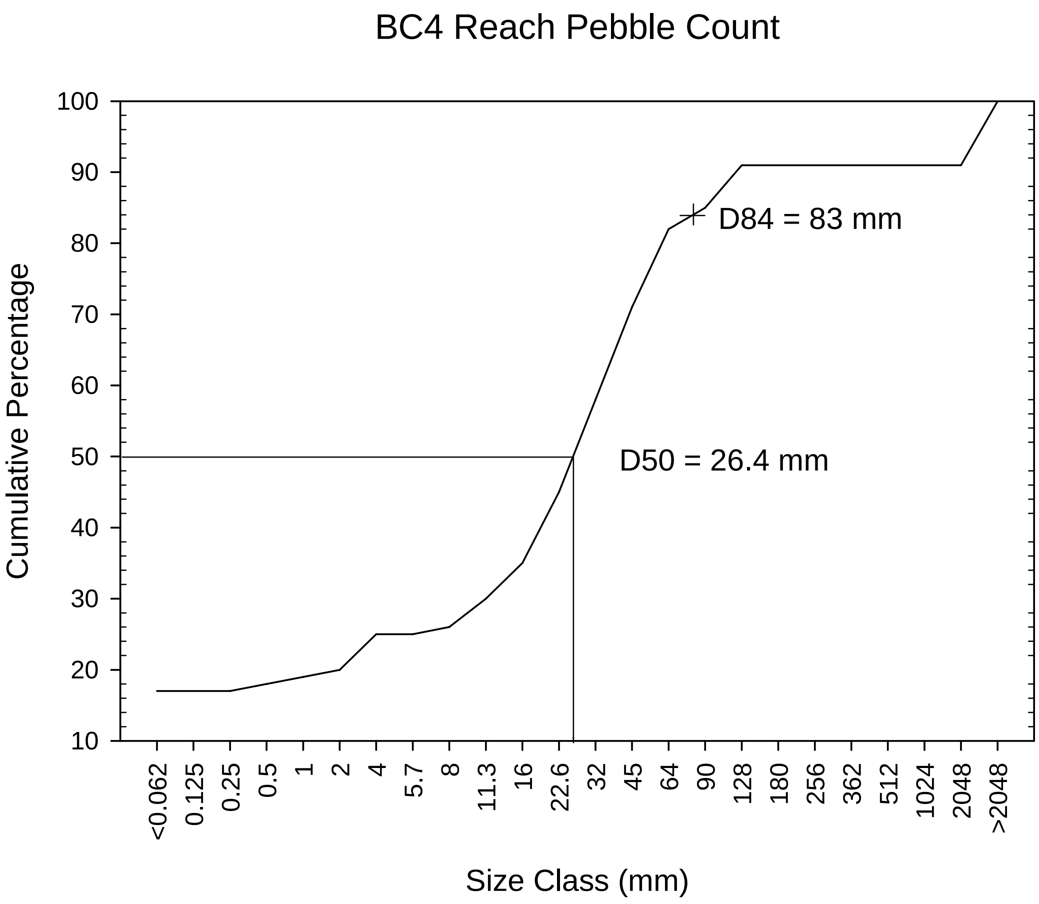

Figure 34: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC4. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

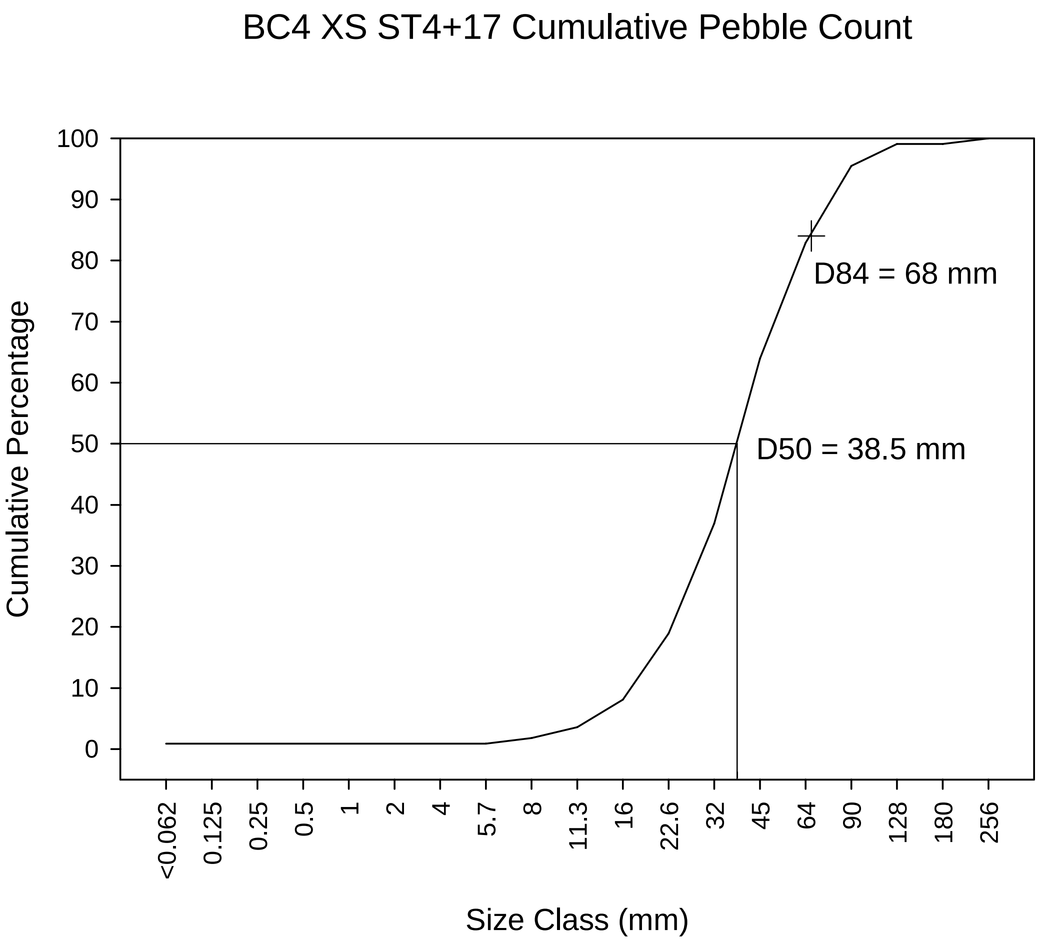

Figure 35: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC4. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

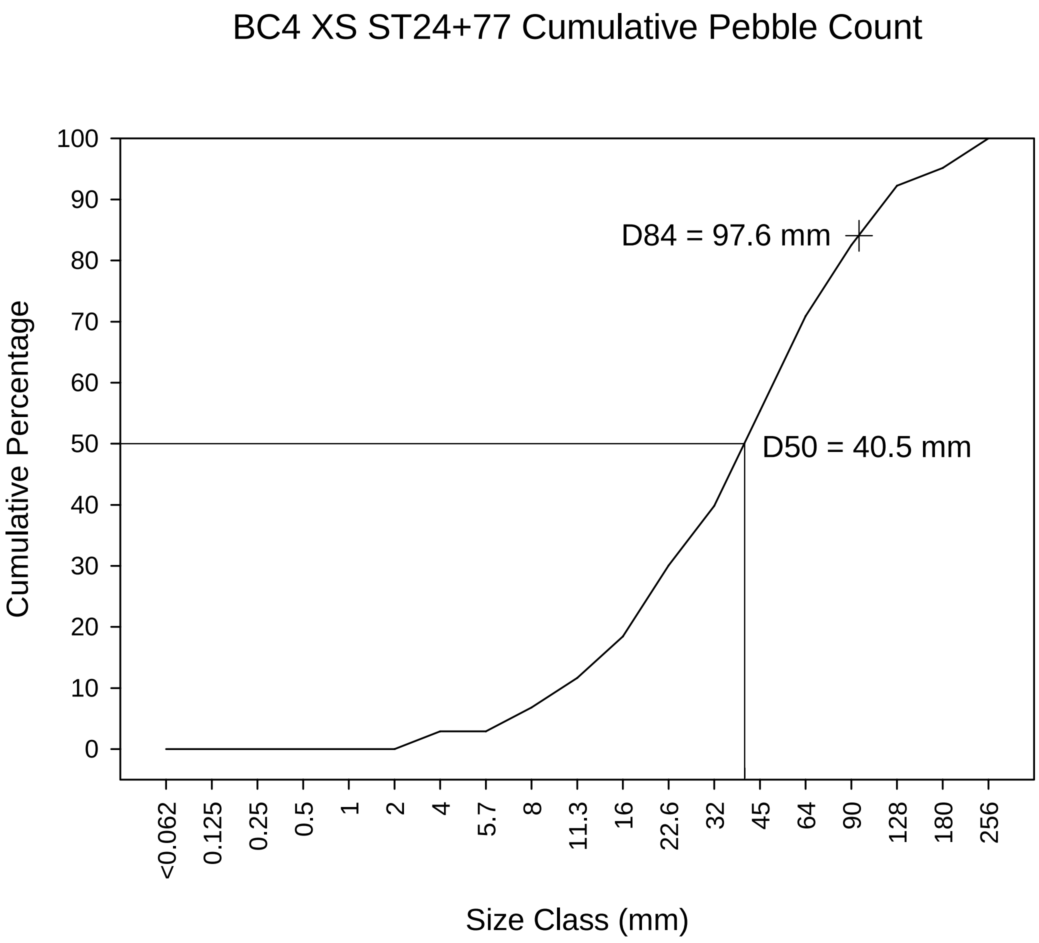

Figure 36: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC4. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

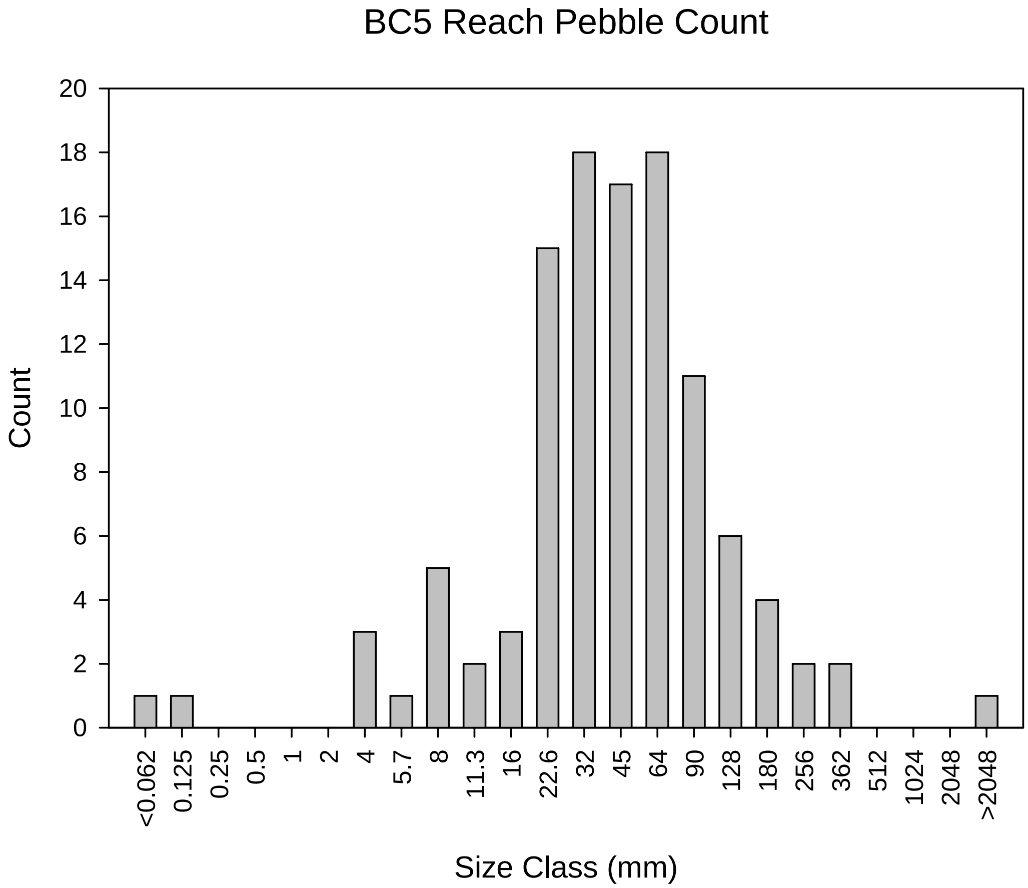

Figure 37: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC5.

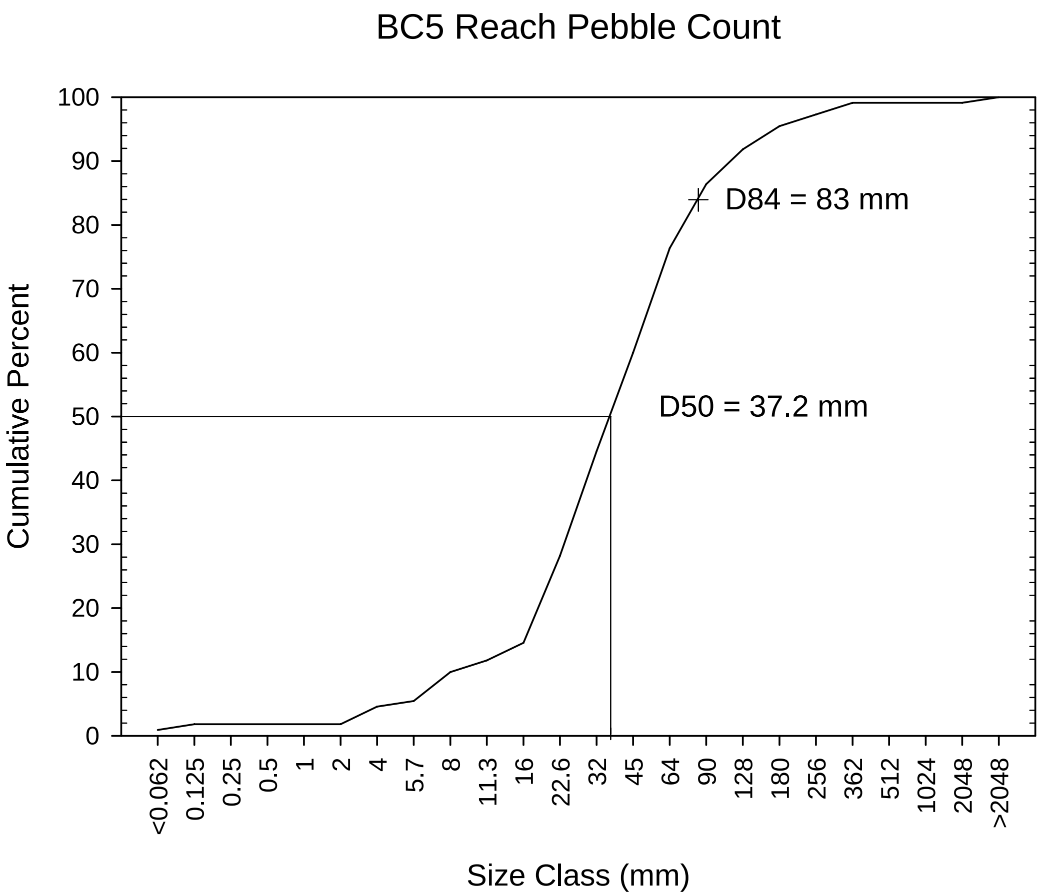

Figure 38: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site BC5. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

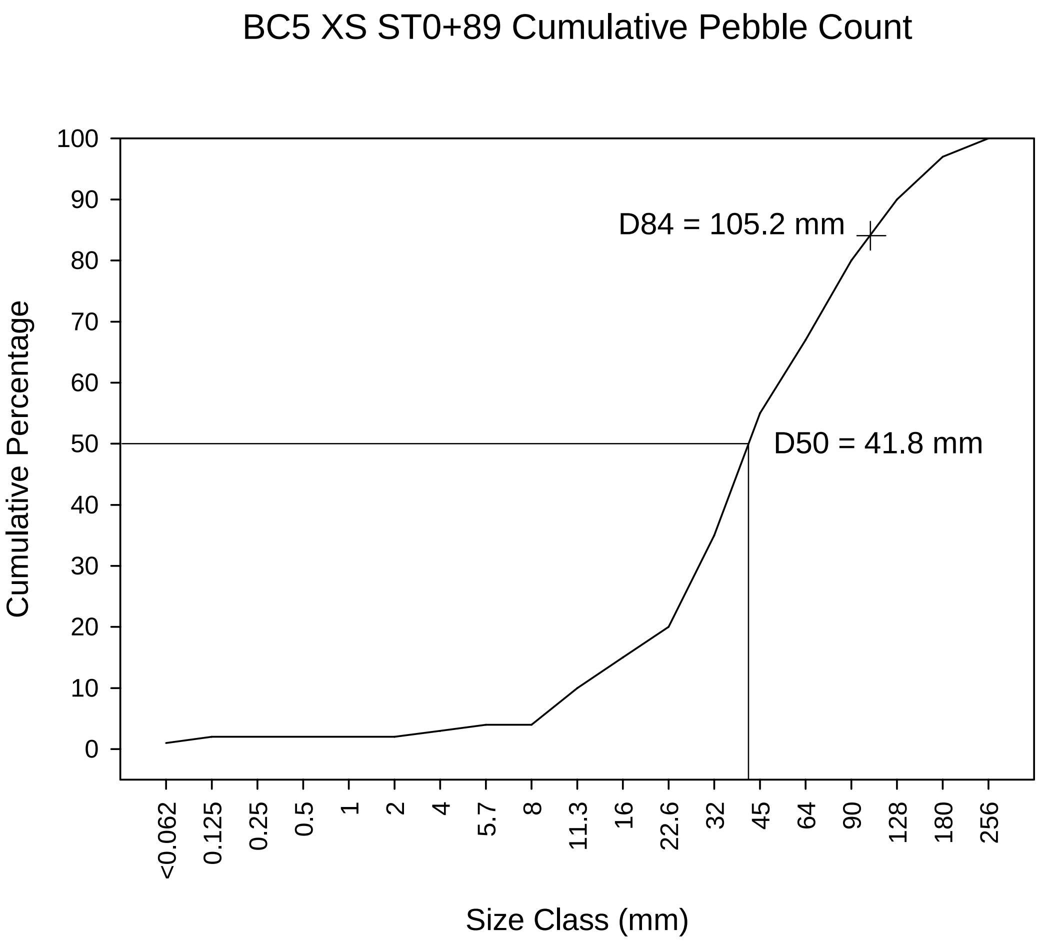

Figure 39: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC5. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

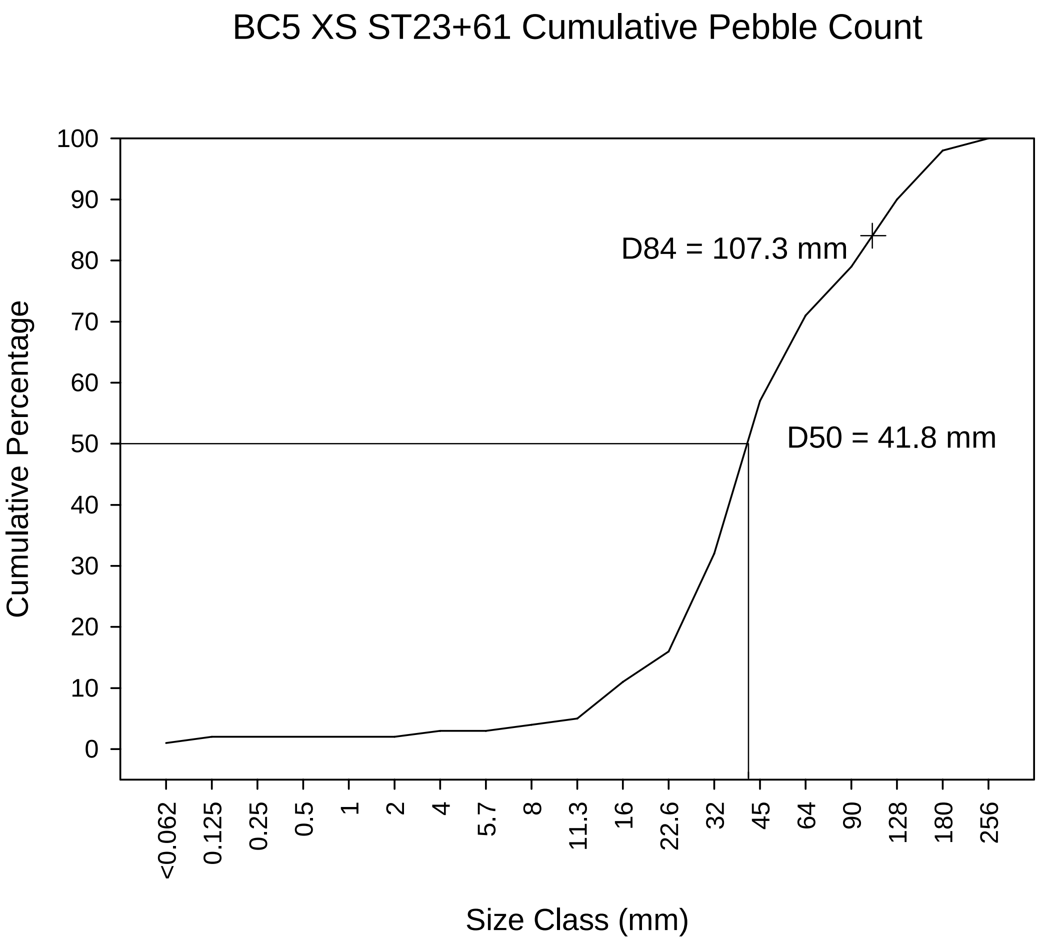

Figure 40: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site BC5. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

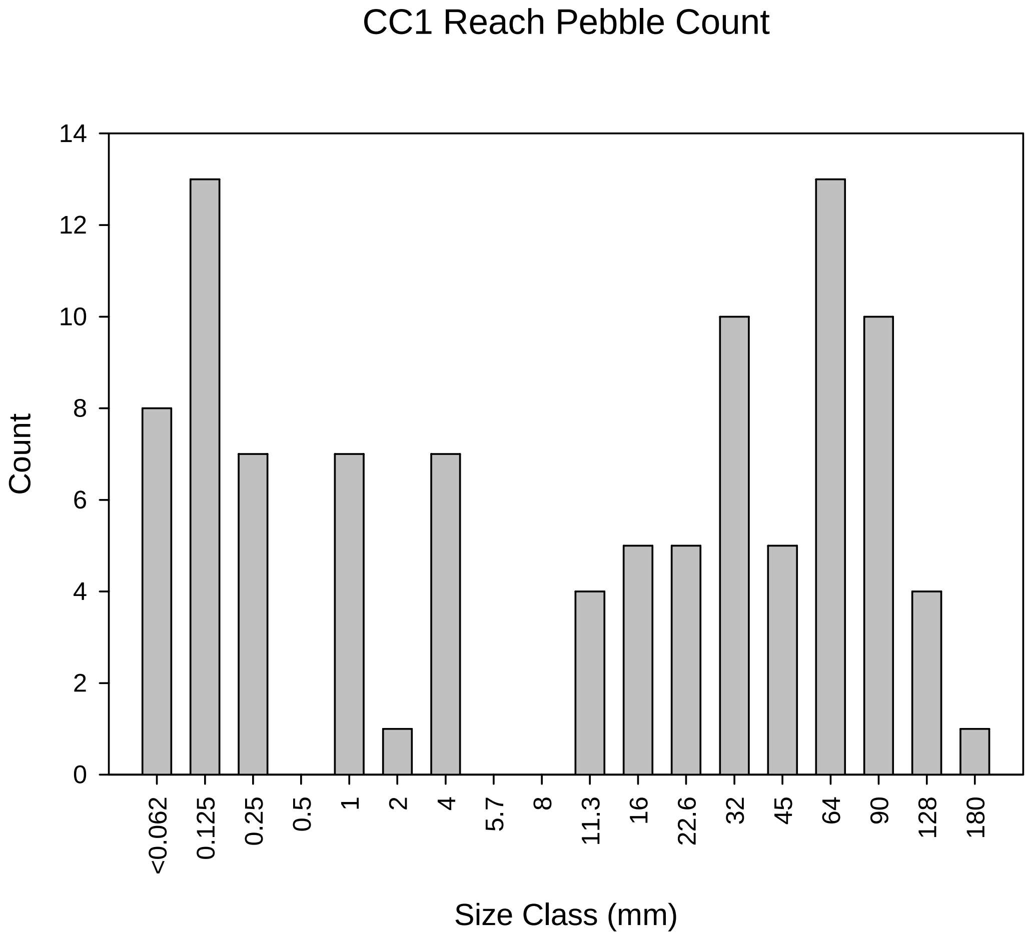

Figure 41: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site CC1.

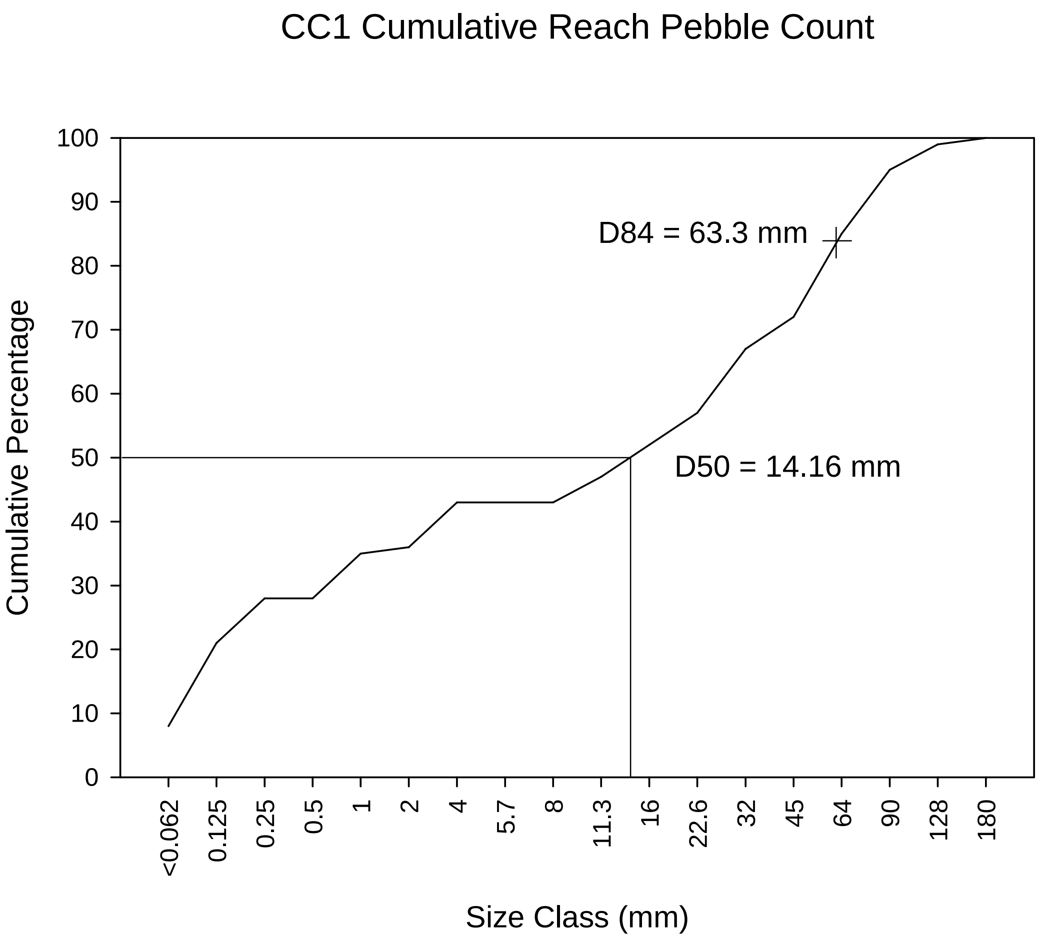

Figure 42: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site CC1. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

CC1 XS ST 7+99 Cumulative Pebble Count

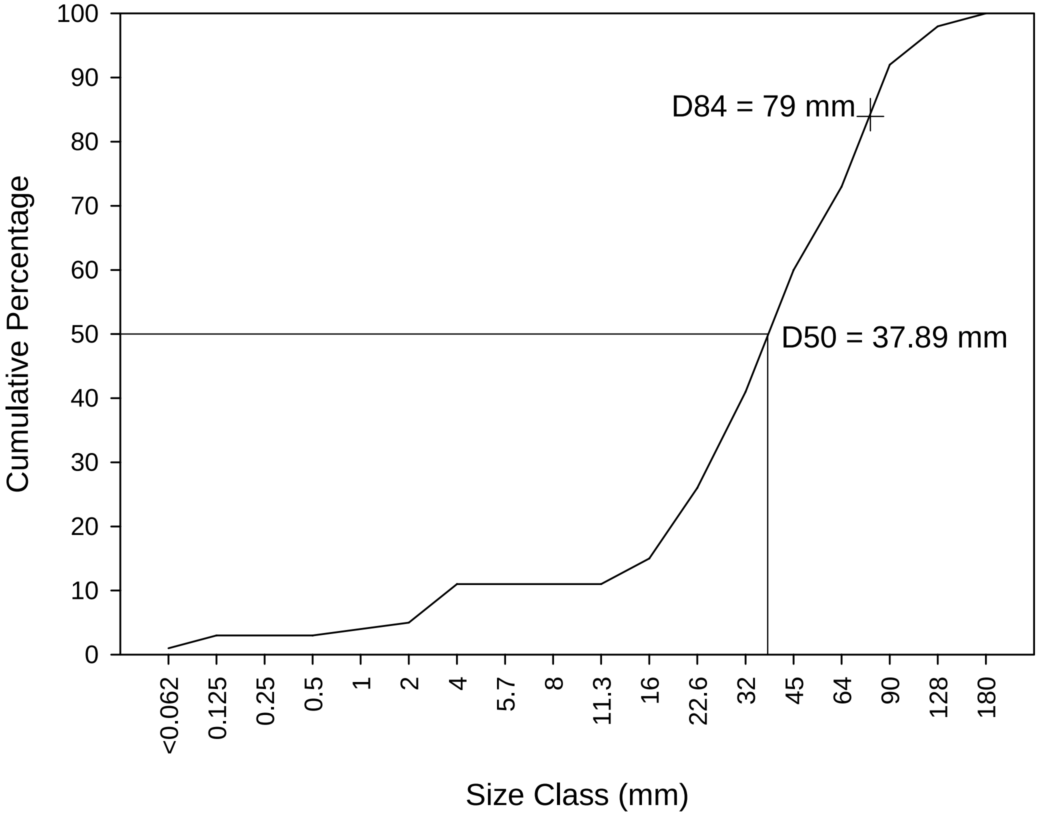

Figure 43: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site CC1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

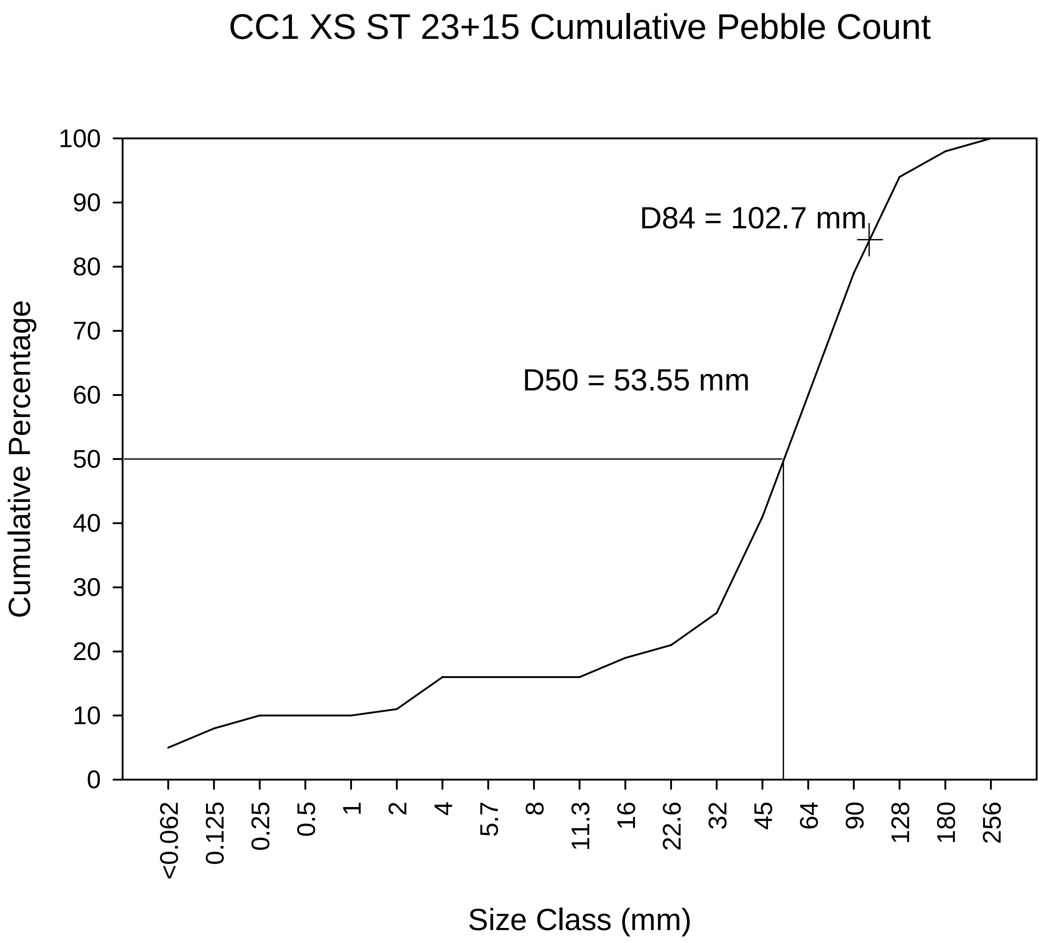

Figure 44: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site CC1. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

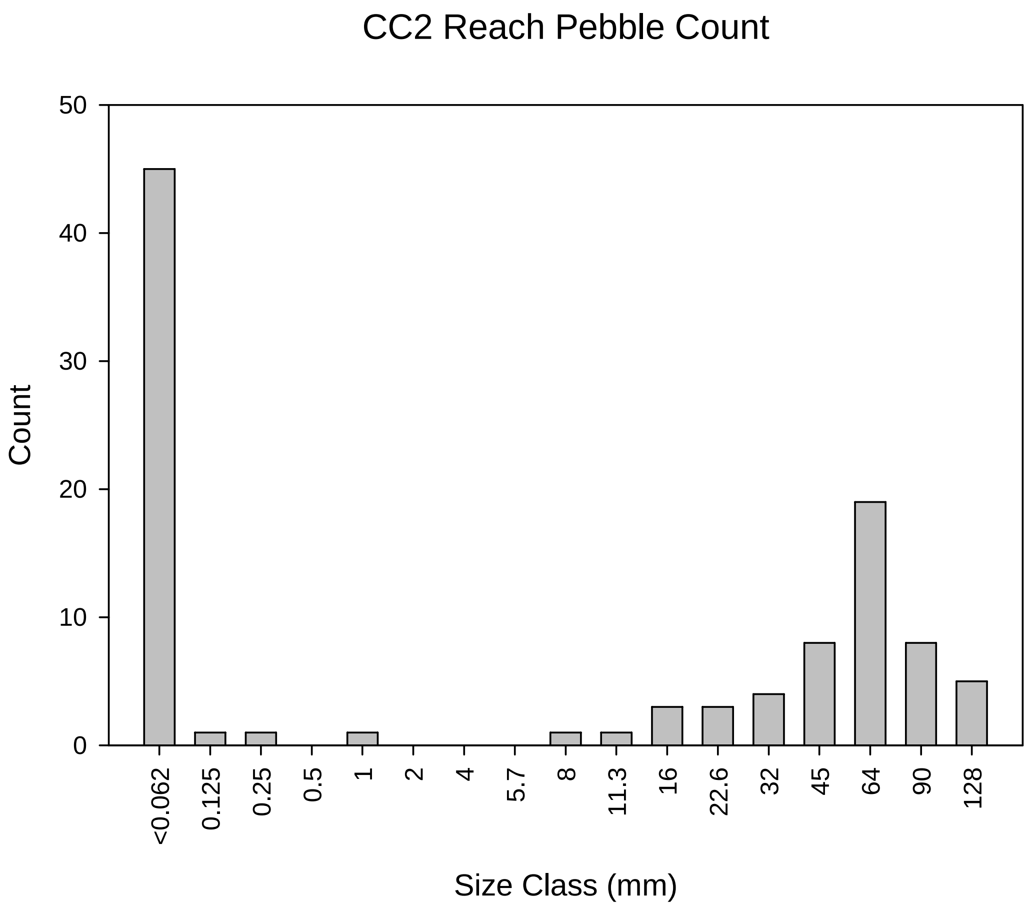

Figure 45: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site CC2.

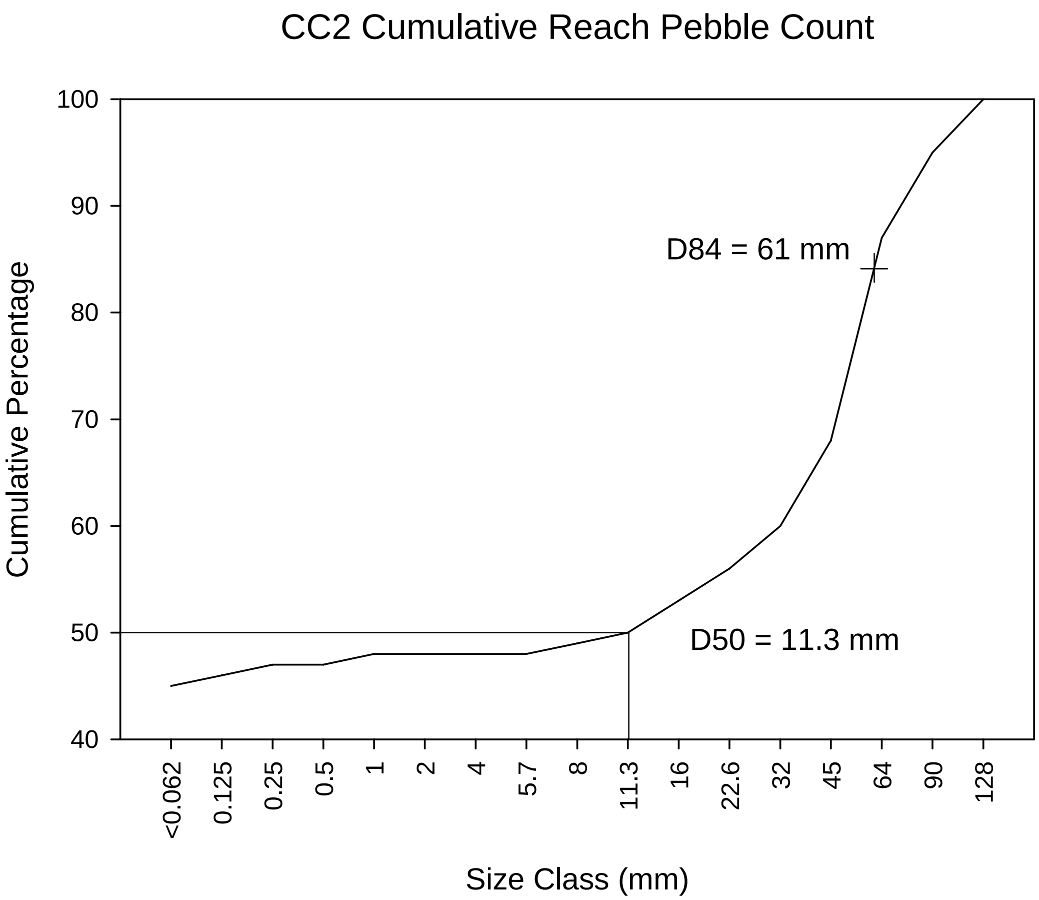

Figure 46: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from pools and riffles over the entire surveyed reach at site CC2. D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

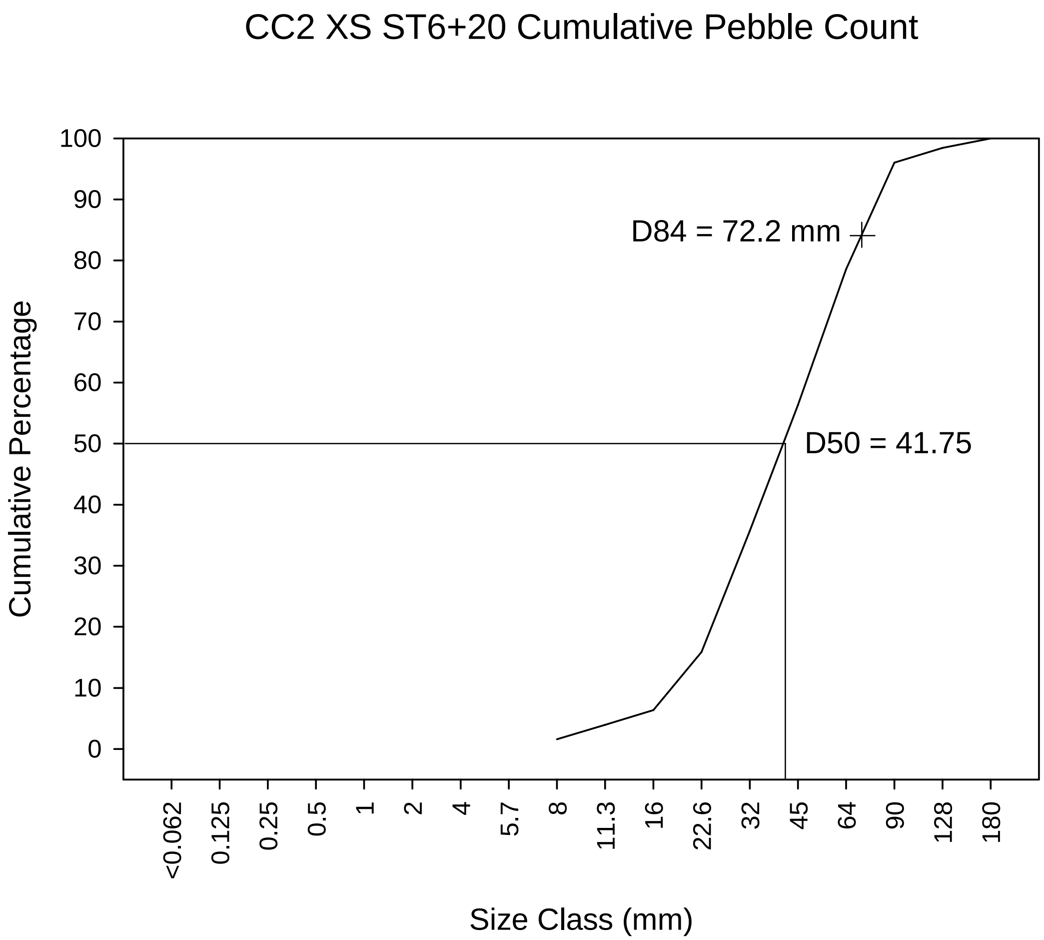

Figure 47: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site CC2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.

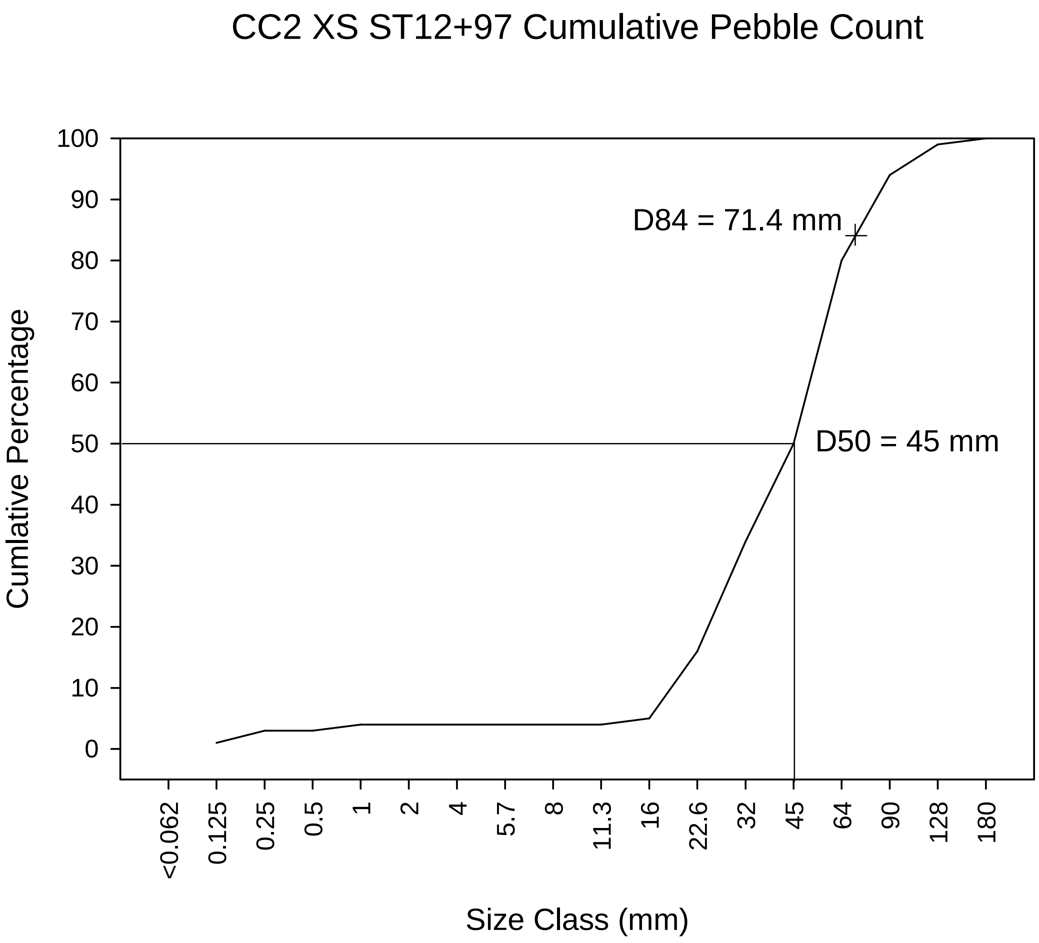

Figure 48: Composition of streambed substrate from modified Wolman pebble counts (Harrelson et al., 1994). Substrate particles were measured on their intermediate axis with 100 random samples from a riffle cross-section at site CC2. XS = cross-section, D50 = median substrate size, at D84, 84% of samples fall below this size, D84 is often the maximum substrate size capable of being transported at bankfull flow.