Final Report

EVALUATION OF STREAM CROSSING CULVERTS TO ASSESS IMPACTS ON STREAM MORPHOLOGY AND AQUATIC PASSAGE-Part II

Prepared by

Daniel E. Line and James D. Blackwell

NC State University
Biological and Agricultural Engineering Dept.
Box 7625, 3110 Faucette Drive
Raleigh, NC 27695

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SUMMARY

Longitudinal profile and cross sectional surveys were performed within 50 ft of 11 culverts at sites mostly in Wilkes, Wake, and Franklin counties during 2013. These data along with other data were collected at each site. These data were compared to similar data collected during 2005 to help assess the stream channel stability near the culverts over period. Comparisons of 2005 and 2013 longitudinal profile data revealed that 3 of 11 upstream channel sections had downcut, 2 had aggraded, 5 had stayed the same, and 1 could not be determined due to suspected survey errors. For the downstream channels, 3 downcut, 2 aggraded and 6 stayed the same. It was impossible to determine if the channel instability at 6 of the sites was caused by embedding the culvert, because none of the culvert inlets or outlets were embedded to the recommended 20% of the culvert diameter. The maximum any invert was embedded was 13% and measures of stream instability did not directly correlate to culverts that were embedded. Thus, it is not clear from these data that embedding the inlet of the culvert causes downcutting in the upstream stream channel, although there is some evidence to suggest it does.

Although the upstream and downstream cross sections for some of the sites could not be compared, where the survey data were comparable it showed that there was no evidence of significant stream bank instability at any of the sites even though BEHI indices were very high at some of the sites. Observation confirmed the bank stability assessment.

Because none of the culverts were embedded to recommended levels, an assessment of aquatic organism passage could not be conducted. Further, the inlet or outlet of 5 of the 11 culverts was perched above the channel bed, which would prohibit two-way passage for most organisms that move in or on the channel substrate. In some cases even when the culvert's inlet or outlet was perched organisms that can swim could conceivably pass the culvert because the discharge provided a continuous water column; however, none of the culverts had a continuous layer of sediment or substrate on the bottom. It is unknown whether the sediment/substrate would have developed if the culverts had been embedded to the recommended depth. From these data the following conclusions were drawn:

- None of the 11 culverts were embedded to the recommended depth suggesting that installation procedures may need to be changed
- There was no consistent trend as to whether embedding the inlet or outlet of the culvert causes the stream channel either upstream or downstream to become unstable as exhibited by significant downcutting or bank failures; however, there was limited evidence that embedding the inlet of the culvert caused downcutting in the upstream stream section.
- There was no significant streambank erosion observed in 2013 even though some of the stream sections had very high BEHI ratings; hence the BEHI ratings were not correlated to observed bank erosion

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INTRODUCTION

Many roads in North Carolina employ small culverts (72-inch diameter or less) for crossing intermittent and small perennial streams. The effects of these culverts on stream channel stability and aquatic habitat are largely unknown. Ideally, stream crossing culverts must be able to carry the design stream discharge while not causing stream channel instability or detracting from aquatic habitat. In many cases, there is a tradeoff between maximizing a culvert's hydraulic capacity and providing optimal habitat and passage for aquatic species such as benthic macroinvertebrates and fish. Fish and benthic passage are enabled in culverts that are buried beneath the stream grade so that they contain substrates and have flow depths and velocities within the culvert similar to the natural stream channel upstream and downstream. The relative difference between flow velocities upstream, within, and downstream of the culvert is a significant performance measure for assessing passage capability of aquatic organisms (Fitch 1995).

Culvert slope is critical in maintaining stream stability as well as aquatic passage. Culverts that are steeper than the streambed slope may result in stream channel scour at the outlet, while those with a slope less than the streambed slope may result in a perched outlet. In some cases, a scour pool may be beneficial for dissipating energy and serving as a resting place for fish before movement through the culvert (Taylor and Love, 2003). Another benefit may be that a culvert can help maintain upstream channel stability by acting as a grade control point (Castro, 2003) that prevents downcutting or incision of the streambed at the location of the invert.

Permit conditions issued by the U.S Army Corps of Engineers and the NC DWQ require burial of culverts a minimum of 12 inches or 20% of the culvert diameter in order to prevent "perched" pipes which could hinder aquatic organisms' passage. The NCDOT Best Management Practices for Construction and Maintenance Activities recommends that 48- to 72-inch culverts be installed 12 inches below average streambed elevation (NC DOT, 2003). Culverts less than 48-inches in diameter shall be embedded/buried a depth equal to 20% of the pipe/culvert diameter; however, the hydraulic conveyance of the culvert should not be compromised (NC DOT, 2003). Robison et al. (1999) recommends that a culvert be embedded into the streambed by 20-25% of its diameter in order to duplicate the flow depths and velocities of the natural stream. The risk is that embedding a culvert below the level of the streambed may release fine sediment previously trapped above a culvert (Castro, 2003). This can cause a short-term increase in sediment transport downstream which will eventually settle, but the location of the deposition will be determined by the stream and not by the culvert. Because culverts provide grade control on some streams, embedding below the streambed may also allow a previously controlled headcut to move upstream above the culvert (Bates, 2003). Hence, embedding the culvert according to recommendation may cause negative consequences to stream stability and even as observation by NCDOT personnel has indicated that burying the culverts resulted in stream instability and headcutting at some NCDOT sites. In addition, embedding the culvert according to recommendations may be difficult in many situations as stream channels are often highly variable in space and time making the determination of the streambed uncertain.

This project was conducted to investigate whether embedding/burying culverts has caused stream channel instability for 11 road culverts, which were installed in 2005. The culvert sites encompassed a variety of topographic and hydraulic conditions, stream channel variations, and locations. While this study was limited in scope to 11 small culverts in the upper Piedmont and foothills, it provides a basis for understanding how culvert design and installation factors may affect stream stability and aquatic passage. Information from this study may be used to direct more comprehensive evaluations of successful culvert design and installation factors.

METHODOLOGY AND PROCEDURES

The project builds on a previous assessment (conducted in 2005) of stream channels up and downstream of newly installed culverts by returning to the same culverts and surveying streams to document differences during the period. Hence, the locations of the culverts are the same as those in the 2005 technical assistance project. Field measurements from the two assessments will be compared to determine if the stream channel was stable during the 7+ years since the previous survey. One of the limitations of the project is that streams are dynamic so that there is no way to know what happened during the period between the surveys.

Field measurements included a longitudinal survey of the stream channel's thalweg beginning 50ft upstream of the culvert and extending to 50ft downstream of the culvert. The survey was conducted using a total station survey instrument with an experienced operator, usually from one set-up location. Considerable effort was made to conduct the whole survey from one set-up position in order to minimize survey error/uncertainty. The longitudinal survey of the stream also included documenting the upstream and downstream ends of the culvert as well as the levels of sediment and water in the culvert. The slope of the upstream and downstream channel sections was determined by using linear regression to compute a best-fit line through the survey data and then reporting the slope of this line as the channel slope. This method attempts to smooth out variability in channel elevations using a statistical method; however, a limitation is that it does not place greater weight on a well-known, fixed point such as that of the culvert invert.

A survey of the cross section of the stream was conducted upstream and downstream of the culvert at the same location of the previous survey, when possible. For several of the sites, particularly those in Wilkes County, locating the cross sections from the 2005 survey was not possible due to poor documentation, loss of physical markers, or survey errors in the 2005 survey. In addition, even if the cross section location was known, the orientation (perpendicular to the channel or not) was not known because it was not documented and there were no physical markers, so the survey points may not match up exactly. The 2013 survey data does provide these points as the total station computes distances as well as direction to each survey point, which would allow users to recreate the exact survey points. Bank Erosion Hazard Index (BEHI) assessments of potential bank erosion were conducted on the channel reach upstream and downstream of the culvert to document the erosion potential of the stream channel. The BEHI assessment was conducted by the same person at every site; however, two different people conducted the assessment in 2005, so comparisons between the years may have some bias. Photos of the stream channel near each culvert were taken to document current conditions and anything unusual. These field measurements were conducted during the spring and summer of 2013 to match the season of collection for initial survey (in 2005). Discharge measurements were made at each culvert to document hydraulic conditions at the time of the survey. Measurements were made using standard equipment and techniques.

Watershed contributing area and land use as of 2006 were obtained from the USGS Stream Stats web page. Changes in land use were assessed using aerial photos. Aerial photographs of the drainage area for each culvert were obtained for 2006 and 2012. Visual analyses of the photographs were conducted to determine if there were significant changes in land use during the period between surveys.

Field assessment of the ease of aquatic organisms' passage through the culvert was made based on each culvert's slope and embeddedness and the depth and velocity of water through the pipe.

RESULTS and DISCUSSION

The results presented in this report include survey data from the 11 culvert sites (figure 1) collected during this project (part II) and the previous phase (part I) of the project. For each longitudinal profile included the downstream invert (elevation rod set at lowest point inside the culvert) of each culvert was set to an elevation of 100 ft, which should provide a relatively easy reference for any additional surveys. As the culvert is fixed this invert should serve as a benchmark for any possible future surveys. Table 1 contains the NCDOT Division for the culvert, the GPS coordinates for the outlet, the drainage area, overall slope, and major land uses determined for 2006. The 2006 land use was the latest available through the USGS Stream Stats data base. As shown, the watersheds encompassed a wide range of areas, slopes, and land uses which should provide a comprehensive test of the effects of imbedding culverts on stream channel stability.

Johnson Pond: The Johnson Pond culvert was located in a residential area of southern Wake County. From observation and an analysis of aerial photographs, the land use in the 179-ac. contributing watershed appears to have changed little from 2006 (2005 or 2013 photos unavailable) to 2012; hence, this should not be a factor in the stream channel stability assessment. From 2006 through 2012 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.66 inches (9/6/08), which was less than the 10-yr, 24-hour rainfall event for Wake County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and culvert at Johnson Pond is shown in figure 2. The slope of the culvert was considerably less than that of the upstream channel section and slightly greater than the downstream channel section (Table 2). Comparing the 2005 and 2013 survey data shows that the first 20-30ft of the stream channel upstream of the culvert has downcut ~0.5-1.0ft during the period. A possible reason for the downcutting is that there was a log across the channel ~10ft upstream of the culvert which would cause an overflow and scour hole dynamic during higher flows (figure 3). The scouring worked long enough to undermine the log and then the stream channel eroded to below the log (figure 3). This situation may have been started or helped by lowering the invert of the new culvert as in order to install a larger diameter culvert (from 36 to 66 in.) the invert was lowered ~1.5ft. Evidence for this is that the channel was over the top of the log in a 2004 photo, but in the 2005 photo after the new culvert was installed, the log was almost totally exposed. The downcutting appears to have migrated upstream ~30ft over the 8 years, but it is unknown when this occurred, if it would have occurred in the absence of the upstream log, or if it will continue upstream. Downstream of the culvert, there were only minor, perhaps survey method related, differences between the 2005 and 2013 survey data indicating that the channel was stable during the period.

Survey data of the upstream cross sections are shown in figure 4. As shown, the 2013 survey data indicates the channel has downcut about 1ft since 2005. The fact that there were many roots, fallen tree limbs across the channel, roots, and detritus in the channel (figure 3) may indicate that changes in the stream channel survey could have been caused by decay and/or movement of these stream stabilizing factors. Survey data from the downstream cross section (figure 5) document little change from 2005 to 2013 thereby confirming the longitudinal data, which also showed little change. The small differences in the surveys are likely the result of uncertainty in survey measurements.

The inlet and outlet of the culvert were 0.33 and 2.74 ft higher than the stream channel immediately adjacent to the culvert (Table 2); hence, the culvert was not embedded at either end. The water surface was 4-6 inches above the elevation of the upstream invert. The downstream end of the culvert was 8-10 inches above the water surface in the channel (figure 2) which would obviously prevent movement of aquatic organisms upstream even at higher discharges.

The BEHI rating of the stream channel upstream remained basically unchanged from the moderate rating in 2005. Downstream the rating improved from very high in 2005 to moderate mostly because of an increase in root density and surface protection indices. Discharge at the time of the survey was measured at 0.02cfs, which is not unusual for springtime baseflow for Piedmont streams of this size.

Herbert Akins1: The Herbert Akins1 culvert was located in a combination agricultural and residential area of southern Wake County. From observation and an analysis of aerial photographs, considerable build-out has occurred in the 160-acre watershed from 2006 (don't have 2005 or 2013 photo) to 2012. At least 1 subdivision near the culvert has been started and is about one-third built; however, a pond between the subdivision and the culvert likely mitigated much of the impact of the buildout; thus, it is unclear how the buildout affected stream channel stability. From 2006 through 2012 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.66 inches (9/6/08), which was less than the 10-yr, 24-hour rainfall event for Wake County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and the culvert is shown in figure 6. Although the inlet of the culvert could not be surveyed due to the beaverdam, it appears from the figure that the slope of the culvert is greater than that of the stream channel, which suggests an embedded culvert outlet and in fact this was the case (figure 7). Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert has downcut ~0.2-0.5ft during the period. It is difficult to explain why a stream with a low slope would downcut to a level 0.5-0.8 ft below the elevation of the culvert invert. A possible explanation for this is that there was an error in one of the surveys or that prior to the beaverdam (figure 7) vegetation increased the elevation of the channel and after the vegetation died due to standing water the channel material consolidated thereby dropping the elevation of the channel. Soft depositional material was observed in the upstream channel, which makes determining an accurate channel height difficult. The invert of the larger culvert installed in 2005 (72 vs 60 in.) was likely at a lower elevation than the previous one, but the upstream invert was still at a higher elevation than the bottom of the channel; thus the culvert should have provided grade control. Downstream of the culvert, the stream channel also downcut ~0.5ft over the last 30ft of the profile. This downcutting may not have been a natural occurrence as it appears that a combination of soil and #57 stone were dumped along one bank at some point during the period and there was rip rap observed in the channel in 2005. In addition, a large tree fell across the channel which likely changed the hydraulics of flow in the surveyed reach. The fact that the survey indicates that the stream channel upstream and downstream downcut would seem to provide strong evidence of stream instability caused by the new culvert, but there are so many confounding factors including the build-out in the watershed changing peak discharge that this cannot be stated with a high degree of confidence.

Survey data of the upstream cross sections are shown in figure 8. The 2013 survey was conducted about 4ft upstream from the 2005 survey. As shown, the 2013 survey data indicates the channel has downcut and widened about 0.5-0.7ft since 2005, but this may be explained by the difference in longitudinal location. It was often difficult to repeat the 2005 survey as it was not well-documented. Survey data from the downstream cross section (figure 9) could not be obtained at the same location because of a fallen tree, so it was conducted 8ft downstream; however, the cross sections from 2005 and 2013 are similar indicating little change.

The upstream invert of the culvert appeared to be imbedded slightly, although waterflow over the invert and the beaverdam made this difficult to determine. The downstream invert was embedded 0.25 ft; thus, it would not be a detriment to the movement of aquatic organisms (Table 2). The slope of the culvert appeared to be low enough that even though there was little to no substrate in the culvert aquatic organisms would likely have little trouble moving upstream through the culvert at nonstorm discharge. Discharge at the time of the survey was estimated at 0.10 cfs, which is typical of springtime baseflow for Piedmont streams of this size.

The BEHI rating of the upstream channel in 2013 remained basically unchanged from the moderate rating in 2005. The downstream channel improved from very high in 2005 to high, mostly because of increases in root depth and density and surface protection.

Herbert Akins2: The Herbert Akins2 (HA2) culvert was located in a combination agricultural and residential area of southern Wake County. From observation and an analysis of aerial photographs, much of the land use changed from agricultural to residential in the 128-acre watershed from 2006 to 2012. Several roads were built and houses constructed during the period. Increases in peak discharge from the build-out could, in itself, contribute to instability of the stream channel. From 2006 through 2012 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.66 inches (9/6/08), which was less than the 10-yr, 24-hour rainfall event for Wake County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and culvert is shown in figure 10. The slope of the culvert (longer than shown in figure 10 to fit better) was about the same as the upstream stream section, but was much less than the downstream section (Table 2). Survey data from 2005 showed that the outlet was embedded which was indicated on the profile by the stream channel being higher than the downstream invert of the culvert. Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert remained about the same during the period. Downstream of the culvert, the stream channel has downcut ~0.5 to 1ft. This downcutting may not have been a natural occurrence as it appears that there was a considerable amount of relatively new sediment deposition in the channel at the time of the 2005 survey (figure 11), which was removed by the time of the 2013 survey (figure 11). Excess sediment originating from the development in the contributing watershed likely raised the streambed in 2005 and then was removed via normal stream sediment dynamics by 2013. The build-out in the watershed could have been the reason for the channel downcutting more than 50ft downstream from the culvert also. Increased peak flows following build-out has been shown to cause instability/downcutting of stream channels.

Survey data of the upstream cross sections are shown in figure 12. The 2013 survey was conducted about 30ft downstream (as best we can determine) from the 2005 survey; thus, the comparison is likely inexact, but as shown the elevation of the bottom of the channel is similar for both years. It was often difficult to repeat the 2005 survey as it was not well-documented. Like the longitudinal profile, survey data from the downstream cross section (figure 13) showed that the stream had downcut from 2005 to 2103. However, it appears that significant widening did not occur.

Neither the inlet nor the outlet of the culvert was embedded in 2013 whereas the outlet was embedded 0.69 ft in 2005 (Table 2). The downstream channel section downcut from 2005 to 2013, which is why the outlet was no longer embedded. Whether embedding the culvert caused the downcutting downstream cannot be determined since other factors such as the development/build-out upstream changed the natural stream dynamics. There was little water flowing at the time of the survey, but it appeared that at moderate flows the culvert inverts both upstream and downstream would not be a detriment to the movement of aquatic organisms. Discharge at the time of the survey was measured at 0.05 cfs, which is typical of springtime baseflow for Piedmont streams of this size.

The BEHI rating of the upstream channel segment remained basically unchanged from the 2005 rating of moderate. The downstream rating of very high also remained the same as 2005. Even with the very high rating, there was no observed evidence of significant, active streambank erosion in the downstream section

Heatherstone: The Heatherstone culvert was located under SR 3978 in a combination wooded and residential area of southern Wake County. From observation and an analysis of aerial photographs, land use has not changed from 2006 to 2012 in the 61-acre watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through 2012 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.66 inches (9/6/08), which was less than the 10-yr, 24-hour rainfall event for Wake County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and culvert is shown in figure 14. The slope of the culvert (shortened in figure 14 to fit better) was slightly less than half both the upstream and downstream stream channel sections (Table 2). Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert eroded/downcut during the period; however, there were likely problems with the 2005 survey. The very steep section of channel from station 60 to 70 seems very unlikely for such a small stream unless there was a rock outcrop and this was not found in 2013. Downstream of the culvert, the stream channel was similar during the period, except for some filling-in of the scour hole at the end of the culvert and minor stream dynamics or survey uncertainty. These data indicated a stable channel.

Survey data of the upstream cross sections are shown in figure 15. Comparison between survey data is not possible due to the likely problems with the 2005 survey. In 2005 the downstream cross section survey was conducted ~147ft downstream of the culvert, which was likely outside the influence of the culvert. In 2013 the cross section survey was conducted 55ft from the culvert. As shown in figure 16 the surveys are still similar indicating, like the longitudinal profile survey, that there was little change in the stream channel from 2005 to 2103.

Both the inlet and outlet inverts of the culvert were perched slightly higher than the stream channel. The outlet invert was less perched than it had been in 2005. There was no discharge at the time of the survey, which is not uncommon for Piedmont streams of this size during periods of dry weather. While there was no flow at the time of the survey, it appeared that at moderate flows the culvert inverts both upstream and downstream would not be a detriment to the movement of aquatic organisms.

The BEHI rating of the upstream channel remained basically unchanged from the low rating of 2005. Downstream the rating changed from high to very high mostly because of a decrease in the surface protection index and the presence of sand on the channel bed. Even with this high rating, there no evidence of significant bank erosion in either stream section.

Walter Collins: The Walter Collins culvert was located under SR 1468 in a combination wooded and agricultural area of eastern Franklin County. Land use in the contributing watershed in 2006 was 62% forest and 28% cultivated (Table 1). From observation and an analysis of aerial photographs, the land use did not changed from 2006 to 2012 in the 83-acre contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through 2012 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.66 inches (9/6/08), which was less than the 10-yr, 24-hour rainfall event for Wake County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and culvert is shown in figure 17. The slope of the culvert (shortened in figure 17 to fit better) was slightly greater than the upstream stream section and much greater than the downstream section (Table 2). Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert downcut during the period; however, the raw data from the 2005 survey (not in figure 17) were not consistent with known points and the 2013 survey was made difficult due to the dense vegetation (figure 18) and soft material in the channel. These factors combine to make comparisons between the data suspect. If the tops of the 2013 survey data are used the downcutting is relatively small (<0.25 ft) for most of the upstream section. Downstream of the culvert, the stream channel was similar for the first 20 ft then the data shows that a hole was filled in sometime between 2005 and 2013. Runoff from a side channel entered the stream near here which likely carried the sediment that filled in the hole.

Survey data of the upstream cross section are shown in figure 19. The 2013 survey data shows that the channel narrowed from 2005 to 2013, which often happens as the channel becomes more densely vegetated. For the downstream cross section, the 2013 data shows that the thalweg aggraded slightly but for the most part the stream channel was not significantly different (figure 20).

The culvert inlet invert was embedded and the outlet was just at the stream channel level (Table 2). There was very low flow at the time of the survey; however, both the inlet and outlet inverts were under water so even at this low flow it appeared that the culvert would not be a detriment to the movement of aquatic organisms (figure 18 right). Discharge at the time of the survey was too low to measure.

The BEHI rating of the upstream streambanks improved from moderate to low from 2005 to 2013 mainly due to increased root density and depth. The rating for the downstream banks improved from high to moderate also mainly due to increased root density and depth. No bank erosion of significance was observed in the upstream or downstream sections.

Pine Mountain: The Pine Mountain culvert was located under SR 1575 at the outlet of an almost totally wooded 173-ac. watershed in northern Wilkes County. From observation and an analysis of aerial photographs, the land use did not change significantly from 2006 to 2012 in the 173-acre contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 21. The slope of the culvert (shortened in figure 21 to fit better) was geater than the upstream stream channel and slightly less than the downstream channel section (Table 2). Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert has aggraded and downcut in several places, but nothing to indicate that the channel was not stable. From 5 to 15 ft downstream of the culvert the channel downcut about 0.5 ft, whereas from 20-30 ft it aggraded about 0.5 ft. These relatively small changes are typical of natural stream dynamics; thus, the channel appeared to be stable.

About 50 ft upstream from culvert there was a 5ft section of streambank failure. The landscaping and foot traffic from the adjacent homeowner has negatively affected the streambank in several locations upstream of the culvert. The location of the upstream survey in 2005 was not be duplicated in 2013, so this cross section is not shown. The downstream cross section survey data are shown in figure 22. The channel appears to have filled-in along the right bank, but otherwise the channel has not changed significantly, thereby indicating stable stream banks.

The culvert inlet was embedded, but the outlet was perched 0.14 ft above the channel. Discharge at the time of the survey was measured at 0.93 cfs. Both the inlet and outlet were under water (figure 23) so it appeared that the culvert would not be a detriment to the movement of swimming aquatic organisms, but those that moved on the channel bed would likely have difficulty getting upstream.

The BEHI rating of the stream channel upstream (high) and downstream (moderate) remained basically unchanged from the 2005 value. The upstream channel was rated higher than the downstream mainly because of lower root depth and density. There was some significant bank erosion observed in the upstream section; however, it appeared to be caused by human activity. Other than this no bank erosion of note was observed.

UT Buckwheat Branch: The unnamed tributary (UT) to Buckwheat Branch culvert was located under SR 1575 at the outlet of an almost totally wooded 43-ac watershed in northern Wilkes County. From observation and an analysis of aerial photographs, the land use did not change significantly from 2006 to 2012 in the contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 24. The slope of the culvert (shortened to fit better) was greater than the stream channel upstream, but less than the channel downstream (Table 2). Comparing the 2005 and 2013 survey data shows that the stream channel upstream and downstream of the culvert have remained basically the same, with the exception of a few relatively small differences that appear to be associated with natural stream dynamics. Thus, the channel appeared to be stable during the period. This was not surprising given that the most of the channel was on bedrock or coble.

The 2005 and 2013 surveys of the upstream cross section are shown in figure 25. As shown, the cross sections are similar indicating a stable channel. Comparing the downstream cross section survey data (figure 26) similarly shows little change indicating a stable cross section. The relatively small differences were likely caused by survey uncertainty and/or differences in cross section location or orientation (whether perpendicular to the channel or not).

The inlet of the channel was at the stream channel and the outlet was embedded by 0.12 ft, which was greater than the 2005 embeddedness (Table 2). Neither the inlet nor outlet inverts were perched and both were underwater so it appeared that the culvert would not be a detriment to the movement of aquatic organisms. Discharge at the time of the survey was measured at 0.82 cfs.

The BEHI rating of the stream channel remained basically unchanged from the 2005 value with both the upstream and downstream section being rated low. No significant bank erosion was observed in the upstream or downstream stream sections.

Buckwheat Branch: The two Buckwheat Branch culverts were located under SR 1575 at the outlet of an almost totally wooded 493-ac watershed in northern Wilkes County. From observation and an analysis of aerial photographs, the land use did not change significantly from 2006 to 2012 in the contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 27. The slope of the two culverts (shortened to fit better) was less than the stream channel upstream, but was about equal to the downstream (Table 2). Comparing the 2005 and 2013 survey data shows that while the stream channel upstream of the culvert remained basically the same, it appears that the downstream channel has downcut ~1.5 ft over the whole length of the survey. After reviewing photos from 2005 and 2013 and the embedded data (0.0ft) from 2005, it can reasonably be concluded that there was an error in the 2005 longitudinal survey of the downstream section. Thus, the stability of the channel downstream of the culvert cannot be determined from the survey data, but visual evidence suggests that the channel has remained stable.

The 2005 and 2013 surveys of the upstream cross section are shown in figure 28. As shown, the cross sections are similar indicating a stable channel. The relatively small differences were likely caused by survey uncertainty and/or differences in cross section location or orientation (whether perpendicular to the channel or not). The downstream cross section could not be compared due to an error in the 2005 data.

Both the inlet and outlet inverts of the culverts were embedded (Table 2) and underwater so it appeared that the culvert would not be a detriment to the movement of aquatic organisms (figure 29). However, like all of the culverts there was no sediment or bed material over the length of much of the culvert to allow organisms that move in or on the substrate to navigate through the culvert. Discharge at the time of the survey was measured at 2.65 cfs.

The BEHI rating of the upstream channel (moderate) remained basically unchanged from the 2005 value, but the downstream increased from low to moderate. The increase was mainly the result of decreased root depth and density. No significant bank erosion was observed in the upstream or downstream stream sections.

UT Pine Mountain: The UT Pine Mountain culvert was located under SR 1575 at the outlet of an almost totally wooded watershed in northern Wilkes County. From observation and an analysis of aerial photographs, the land use did not change significantly from 2006 to 2012 in the 102-acre contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County. While not definitive, this, and the fact that there was no evidence of water overtopping the road, indicated that an extreme channel stressing event did not occur during this period.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 30. The slope of the culvert (shortened in figure 20 to fit better) was less than the upstream and downstream stream channel indicating albeit only slightly less than the downstream section. Comparing the 2005 and 2013 survey data shows that the stream channel upstream of the culvert and downstream are basically the same thereby indicating a stable channel.

The 2013 surveys of the upstream and downstream cross sections were similar to those conducted in 2005, so only the downstream section is shown (figure 31).

The inlet invert of the culvert was at the stream level while the outlet was embedded by 0.14 ft (Table 2). Both the inlet and outlet of the culvert were under water so it appeared that the culvert would not be a detriment to the movement of aquatic organisms at this discharge. However, much of the culvert was clear of substrate so organisms that move on or through the substrate would likely have a hard time moving through the culvert, especially at higher discharges. Discharge at the time of the survey was measured at 0.45 cfs.

The BEHI rating of the stream channel upstream (moderate) and downstream (low) remained basically unchanged from 2005 to 2013. No significant bank erosion was observed in the upstream or downstream stream sections.

UT Bee Tree Branch: The UT Bee Tree Branch culvert was located under SR 1715 at the outlet of a 122-ac watershed in northern Wilkes County. In 2006, about 35% of the land in the watershed was cultivated, 49% forested, and 5.5% developed. From observation and an analysis of aerial photographs land use changed little from 2006 to 2012 in the contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County. Residents in the area observed that water frequently overtops the road. From observation at the time of the survey, this was likely due to a log jam at the upstream end of the culvert and not to an undersized culvert.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 32. The slope of the culvert (shortened to fit better) was slightly greater than both the upstream and downstream stream channel sections (Table 2). Comparing the 2005 and 2013 survey data shows that stream channel upstream of the culvert aggraded 0.5-0.8 ft. This was likely due to the log across the upstream end of the culvert creating backwater in the upstream channel area which caused sediment deposition. Downstream of the culvert the channel downcut to create a pool from about the 84 to 100 ft station. The reason for the pool created in this section was unknown, but may be related to the deposition of sediment upstream, which would create water with an artificially low amount of suspended sediment compared to the water's sediment transport capacity. Thus, it is unclear if the channel has been stable during the period due to the changing stream dynamics caused by the log across the culvert inlet.

The survey of the upstream cross section is not shown due to the backwater from the log creating sediment deposition, which was atypical for culverts. The 2005 and 2013 surveys of the downstream cross section are shown in figure 33. As shown, the cross sections are similar indicating a stable channel. The relatively small differences were likely caused by survey uncertainty and/or differences in cross section location or orientation (whether perpendicular to the channel or not).

The log across the inlet to the culvert prevented a determination of how much the inlet was embedded. The outlet was embedded by 0.09 ft. Both the upstream and downstream inverts were under water, so it appeared that the culvert would not be a detriment to the movement of aquatic organisms, but it was difficult to determine what the upstream end would be like without the log across the culvert. Discharge at the time of the survey was measured at 1.37 cfs.

The BEHI rating of the upstream channel improved from very high to moderate due to a number of factors including an increase in root density, root depth, and surface protection. The rating for the downstream section remained basically unchanged from the 2005 (high) value. No significant, active bank erosion was observed in either the upstream or downstream channel sections.

UT Little Warrier Creek: The UT of Little Warrier Creek culvert was located under High Rock Road at the outlet of a 90-ac watershed in southern Wilkes County. In 2006, about 2.3% of the land in the watershed was cultivated, 83.2% forested, and 2.3% developed. From observation and an analysis of aerial photographs land use changed little from 2006 to 2012 in the contributing watershed; thus, land use changes should not be a factor in the stream stability assessment. From 2006 through May, 2013 the maximum one-day rainfall accumulation (estimated from NC DOT and State Climate Office website) was 4.7 inches (8/27/08), which was less than the 10-yr, 24-hour rainfall event for Wilkes County.

The longitudinal profile for the thalweg of the stream channel and the road culvert is shown in figure 34. The slope of the culvert (shortened to fit better) was slightly greater than the upstream channel and much greater than the downstream stream channel (Table 2). The ‘v’ just upstream of the culvert inlet was due to the roadside drainage ditch. Comparing the 2005 and 2013 survey data it first appears that the stream channel upstream of the culvert aggraded 0.2-0.4 ft; however, the difference in elevation of the upstream culvert invert was about 0.2ft, which was likely the result of a survey error in the 2005 data as it is unlikely the culvert moved upward. If the elevation of the stream was decreased 0.2ft, then the channel aggraded only slightly in a few places. Downstream of the culvert the channel also aggraded from about 0.2 to 0.5 ft, except for one small section where the data showed that the channel appeared to erode a highpoint. The downstream channel was relatively flat, which would facilitate sediment deposition if excess sediment was transported from upstream. The channel bed appeared to have a significant amount of relatively fine sediment in it (figure 35) thereby indicating an aggrading channel. Thus, the channel has been aggrading during the period, but this does not appear to be related to the culvert.

The survey of the upstream cross section is not shown due to the likely error in the 2005 survey data. The 2005 and 2013 surveys of the downstream cross section are shown in figure 36. As shown, the cross sections are similar indicating a stable channel. The relatively small differences were likely caused by survey uncertainty and/or differences in cross section location or orientation (whether perpendicular to the channel or not).

Both the inlet and outlet inverts were perched above the channel by more than 0.5 ft making passage by organisms that move on or in the channel bottom impossible. Both the upstream and downstream inverts were under water, so it appeared that the culvert would not be a detriment to the movement of aquatic organisms that swim. Discharge at the time of the survey was measured at 0.19 cfs, which does not seem to be atypical for streams of this size.

The BEHI rating of the upstream and downstream channels in 2013 was the same (high) as it was in 2005. However, no significant, active bank erosion was observed either upstream or downstream.

Embedding and culvert slope assessment: Comparisons of 2005 and 2013 longitudinal profile data revealed that 3 of 11 upstream channel sections had downcut, while 2 of 11 aggraded, although one of these was due to a log across the culvert and the other was likely due to errors in the 2005 survey data (Table 3). Five of the 11 upstream channels stayed the same with 2 of these, namely the Buckwheat Branch and UT Buckwheat Branch sites, being mostly on bedrock and one upstream channel was unknown due to a beaverdam across the culvert inlet. For the downstream channels, 3 of 11 downcut, while 2 aggraded and 6 stayed the same. It was impossible to determine if the channel instability at 6 of the sites was caused by embedding the culvert, because none of the culvert inlets or outlets were embedded the recommended 20% of the culvert diameter. The maximum any invert was embedded was 13%, which was upstream at the Walter Collins road site. Because the upstream stream section at this site downcut, although the 2005 survey data appears suspect, the indication is that embedding results in downcutting upstream; however, only 1 (Johnson Pond in 2005) of the other 2 upstream channels that downcut had embedded inlets in 2005 and neither was embedded by 2013. Thus, it is not clear from these data that embedding the inlet of the culvert causes downcutting in the upstream stream channel, although there is some evidence to suggest it does.

Although the upstream and downstream cross sections for some of the sites could not be compared, where the survey data were comparable, it showed that there was no evidence significant stream bank instability at any of the sites even though BEHI indices were high at some of the sites. Observation confirmed the bank stability assessment. Most of the banks surveyed had permanent vegetation on and along the banks, which helped maintain stability.

The outlets of several culverts were embedded with the maximum being 4.2% at the Herbert Akins I site. The downstream stream section at this site did downcut, but it started more than 20ft from the end of the culvert and could have been caused by build-out in the upstream watershed. For the other two sites (Herbert Akins2 and UT Bee Tree Branch) that downcut, the outlet was nearly at the channel level. The next greatest embeddedness of an outlet (2.8%) was at the UT Pine Mountain Branch site where the downstream channel was stable from 2005 to 2013. Thus, the data was inconclusive because culverts were not embedded to recommended depth and downstream stream stability was mixed for culverts that had outlets slightly embedded.

The slope of the culvert in relation to channel slope may also affect channel stability. The culvert and channel slopes at 7 of the 11 sites were determined and related to channel instability measurements. Four of the sites (Herbert Akins I, UT Bee Tree Branch, Buckwheat Branch, and UT Buckwheat Branch) were not used because the channel was either bedrock, a beaverdam was present, or the 2005 survey data was considered suspect. Of the 4 sites where culvert slope was less than the upstream channel slope, two downcut and two stayed the same (Tables 2 and 3). For the other 3, one downcut, one stayed the same, and one had suspect 2005 survey data. Of the 5 culverts with slopes greater than the downstream channel, 3 stayed the same and 2 aggraded. For the other 2, one stayed the same and one downcut. Thus, no consistent trend can be concluded from these data. It could be that the slope of the culvert must differ by a threshold amount before consistent trends become evident or other confounding factors change the relationship.

Because none of the culverts were embedded to recommended levels, an assessment of aquatic organism passage could not be conducted. Further, the inlet or outlet of 5 of the 11 culverts was perched above the channel bed, which would prohibit two-way passage for most organisms that move in or on the channel substrate. In some cases even when the culvert’s inlet or outlet was perched organisms that can swim could conceivably pass the culvert because the discharge provided a continuous water column; however, none of the culverts had a continuous layer of sediment or substrate on the bottom. It is unknown whether the sediment/substrate would have developed if the culverts had been embedded to the recommended depth.

Research needs: It is apparent from this project that in order to obtain meaningful results culvert sites must be selected with great care to provide at least one replication of each condition. Ideally, a series of similar-sized culverts with a stable upstream watershed would have the stream channel surveyed 2-4 years prior to being replaced with culverts embedded to the recommended depth/level. Then the stream channels would be surveyed shortly after culvert replacement and every 2-3 years for a sufficient time to assess channel stability (5-7 years). The surveyed reach should be at least 50-75ft upstream and downstream of the culvert to encompass the length of stream that is likely to be influenced by the culvert. A sufficient number of thalweg and cross section points should be surveyed to adequately characterize the stream channel and, above all else, the survey methods and instrumentation (preferably a total station with an experienced operator set up at one location for the entire survey) should be such that the survey is accurate and repeatable. If possible, survey pins should be hammered into the ground to mark cross section locations (although these could also be determined via the stake-out feature of the total station) and at least one set-up location. Other measurements should be made to help characterize stream dynamics. Because of the variability and distance between sites, it may be more efficient to conduct the study outlined above at a field laboratory where conditions could be controlled.

SUMMARY AND CONCLUSIONS

Longitudinal profile and cross sectional surveys were performed within 50 ft of 11 road culverts at sites mostly in Wilkes, Wake, and Franklin counties during 2013. The sites corresponded to those surveyed in 2005. These data along with other data such as the embeddedness of the inlet and outlet, BEHI rating, and stream discharge were collected at each site. These data were compared to similar data collected during 2005 to help assess the stream channel stability near the culverts over the 8 years. From these data the following conclusions can be drawn:

- None of the 11 culverts were embedded to the recommended depth in 2013 (also the case in 2005) suggesting that installation procedures may need to be changed
- There was no consistent trend as to whether embedding the inlet or outlet of the culvert caused the stream channel either upstream or downstream to become unstable as exhibited by significant downcutting and/or bank failures; however, there was limited evidence that embedding of the culvert inlet resulted in downcutting in the upstream stream section. This could not be confirmed due to the uncertainty of the 2005 survey data at some sites and the limited number of sites overall.
- There was no significant streambank erosion observed in 2013 even though some of the stream sections had very high BEHI ratings; hence the BEHI ratings were not correlated to observed bank erosion
- There was no consistent trend as to whether a culvert slope that was greater or less than the channel slope affected stream stability either upstream or downstream of the culverts.
- Additional research involving carefully selected culverts using current survey instrumentation to provide accurate data is needed to document the effects of embedding culverts on stream channel stability.

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Table 1. Locations and Characteristics of Watersheds to Culverts.

Culvert/Site Name	DOT Div.	Lat	Long	Drain area[1] (acres)	Watershed Slope[1] (%)	Forest 2006[1] (%)	Cultivated 2006[1] (%)	Developed 2006[1] (%)
Johnson Pond	5	35.626	78.746	179	4.8	32.2	22.1	28.8
Herbert Akins1	5	35.623	78.802	160	3.5	8.0	34.7	38.0
Herbert Akins2	5	35.623	78.797	128	3.1	12.4	40.9	31.2
Heatherstone Drive	5	35.701	78.751	61	4.8	14.3	9.3	76.4
Walter Collins	5	36.116	78.149	83	4.8	61.6	28.3	10.1
Pine Mountain	11	36.330	81.240	173	43.8	99.1	0.2	0.7
UT Buckwheat	11	36.323	81.253	43	29.1	64.1	17.4	7.4
Buckwheat Branch	11	36.319	81.257	493	35.0	87.5	6.4	1.7
UT Pine Mountain	11	36.328	81.244	102	36.2	95.1	2.6	0.1
UT Bee Tree Branch	11	36.270	81.161	122	17.7	49.4	34.6	5.5
UT Little Warrior Creek	11	36.051	81.319	90	20.2	83.2	2.3	2.3

[1] From USGS StreamStats website (http://streamstatsags.cr.usgs.gov/nc_ss). Land use was based on 2006 data.

Table 2. Culvert Characteristics and Embeddedness.

Site Name	Culvert Diam. feet	Upstream slope[1]	Culvert slope	Down-stream slope[1]	Inlet Embed 2005[2] feet	Inlet Embed 2013[3] feet	Outlet Embed 2005 feet	Outlet Embed 2013[3] feet
Johnson Pond	6.0	0.049	0.010	0.006	0.20	-0.33	-0.69	-2.74
Herbert Akins1	6.0	0.012	na[4]	0.016	0.14	na[4]	0.45	0.25
Herbert Akins2	6.0	0.019	0.019	0.037	-0.22	-0.16	0.69	-0.01
Heatherstone Dr.	6.0	0.037	0.017	0.041	-0.3	-0.22	-0.60	-0.03
Walter Collins	6.0	0.022	0.029	0.007	0.18	0.80	0.30	0.00
Pine Mountain	3.0	0.084	0.065	0.053	0.1	0.27	0	-0.14
Buckwheat Branch	2@5.0	0.045	0.028, 0.031	0.031	0	0.24, 0.02	0	0.03 & 0.15
UT Buckwheat	5.5	0.023	0.055	0.086	0	0.00	0	0.12
UT Pine Mountain	5.0	0.063	0.038	0.043	0	0.00	0.68	0.14
UT Bee Tree Branch	3.0	0.003	0.011	0.000	0.01	N/A	0.10	0.09
UT Little Warrior Cr.	3.0	0.023	0.033	0.002	0	-0.53	0.02	-1.88

[1] Computed using linear regression on survey data for the section.
[2] From report by Shaffer and Jennings, 2005.
[3] Difference between channel (at invert) and culvert invert elevation (negative indicates invert higher than channel)
[4] Beaverdam at upstream culvert invert prevented this measurement.

Table 3. Summary of Steam Channel Stability.

Site Name	Upstream channel[1]	Comment	Downstream channel[1]	Comment
Johnson Pond	downcut	none	same	none
Herbert Akins1	na	beaverdam	downcut	none
Herbert Akins2	same	none	downcut	none
Heatherstone Dr.	downcut	none	same	none
Walter Collins	possible downcut	dense vegetation, 2005 survey error?	aggraded	none
Pine Mountain	same	none	same	none
Buckwheat Branch	same	bedrock	same	bedrock
UT Buckwheat	same	bedrock	same	bedrock
UT Pine Mountain	same	none	same	none
UT Bee Tree Branch	aggraded	log at inlet	downcut	none
UT Little Warrior Cr.	aggraded	2005 survey error?	aggraded	none

[1] Difference in overall channel thalweg based on comparing 2005 and 2013 survey data.

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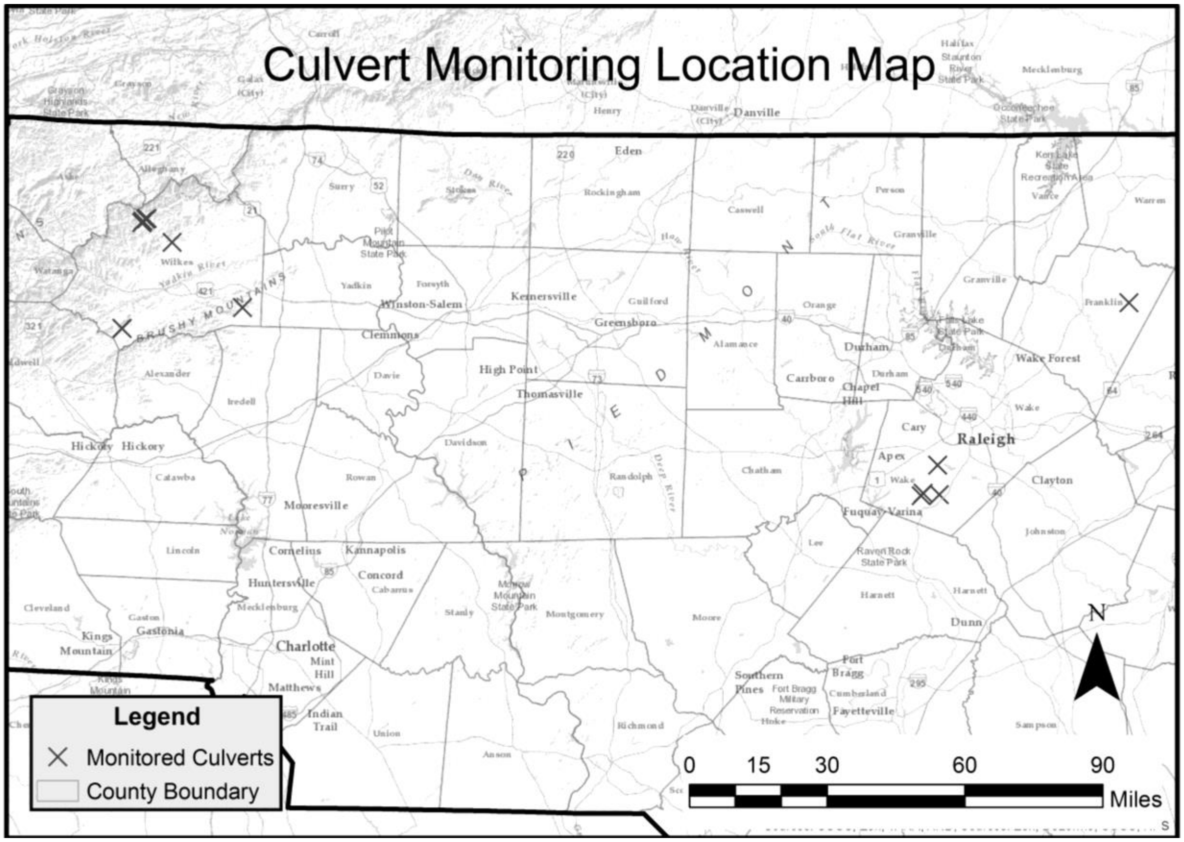

Figure 1. Locations (indicated by X) of culvert sites.

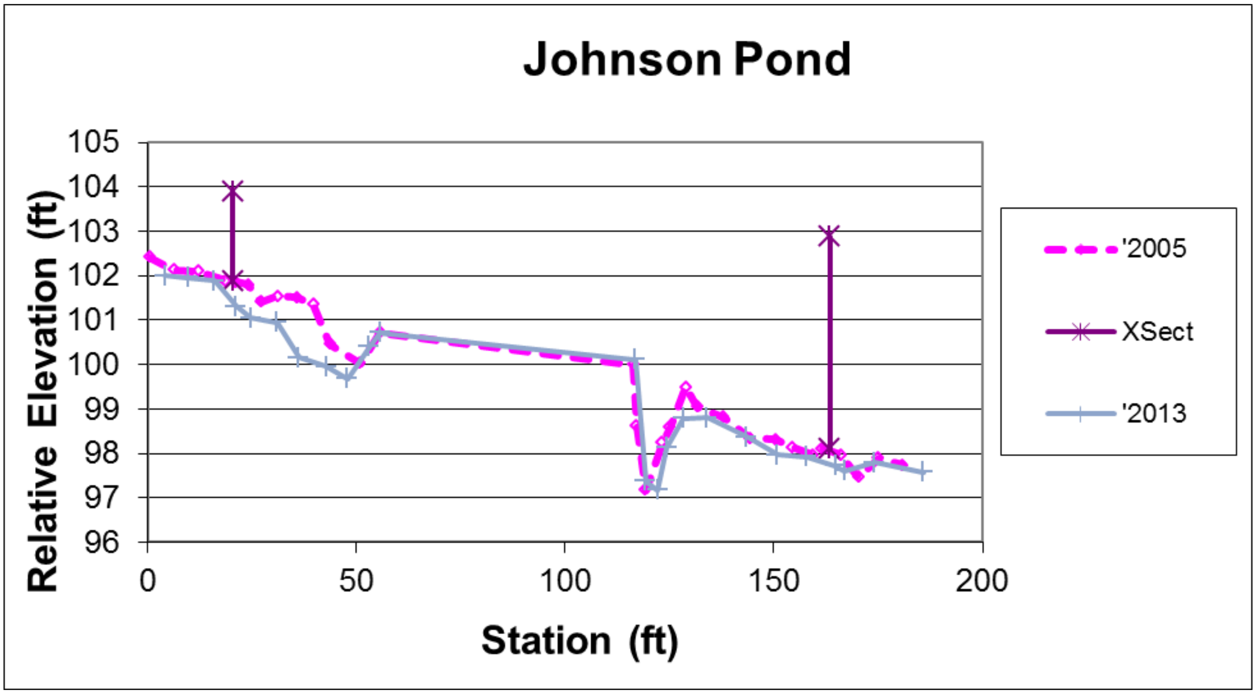

Figure 2. Longitudinal survey data for the Johnson Pond culvert.


Figure 3. Downstream end of pipe (left) and upstream channel (right) at Johnson Pond culvert.

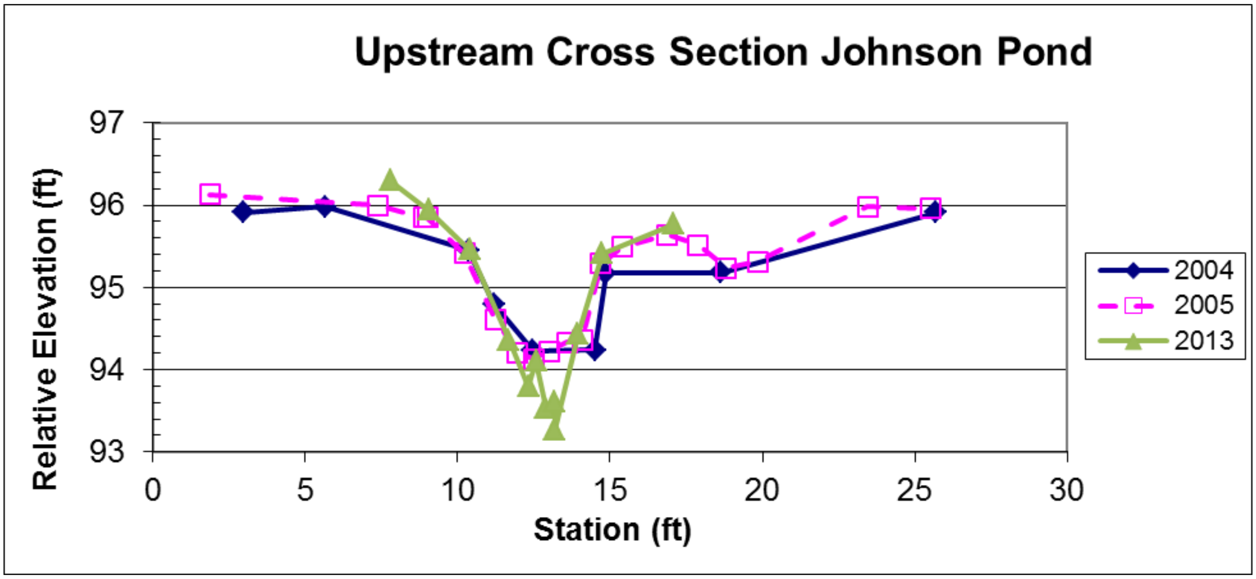

Figure 4. Upstream cross section for Johnson Pond.

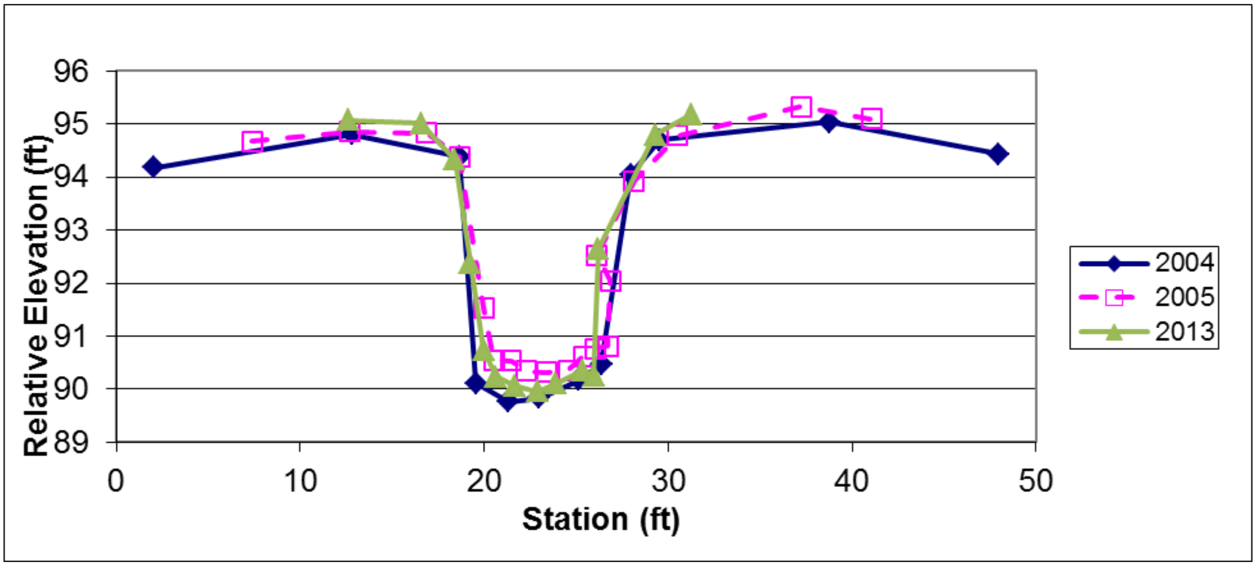

Figure 5. Downstream cross section at Johnson Pond.

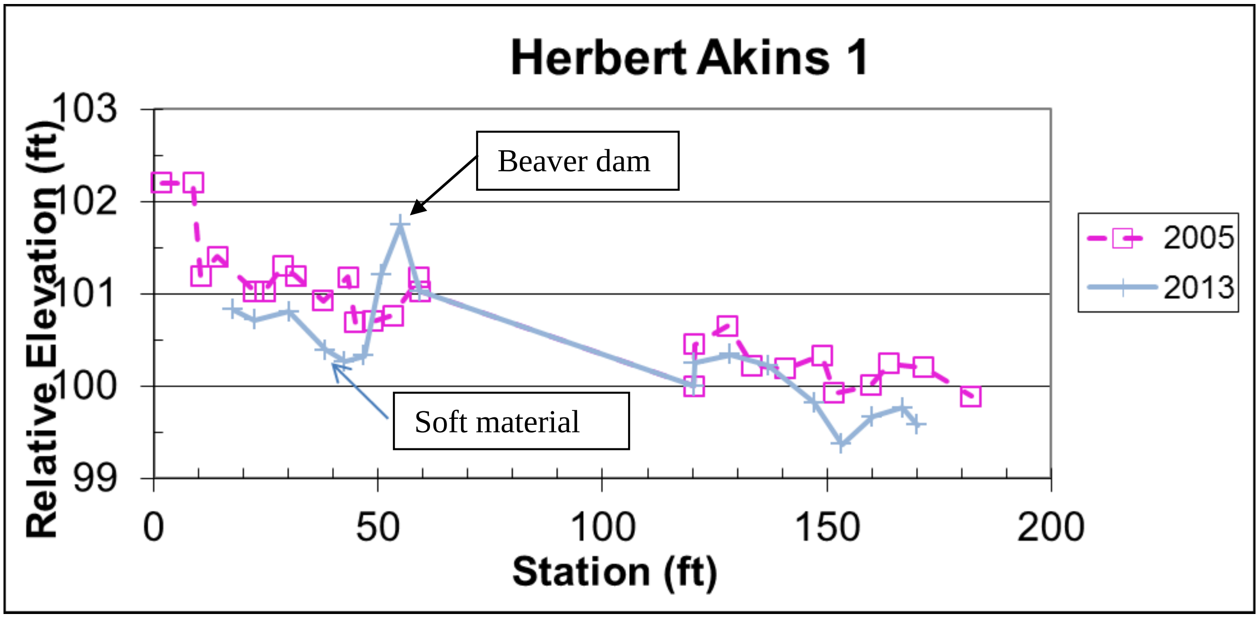

Figure 6. Longitudinal survey data for the Herbert Akins1 stream and culvert.


Figure 7. Photo of downstream (left) and upstream (right) ends of the HA1 culvert.

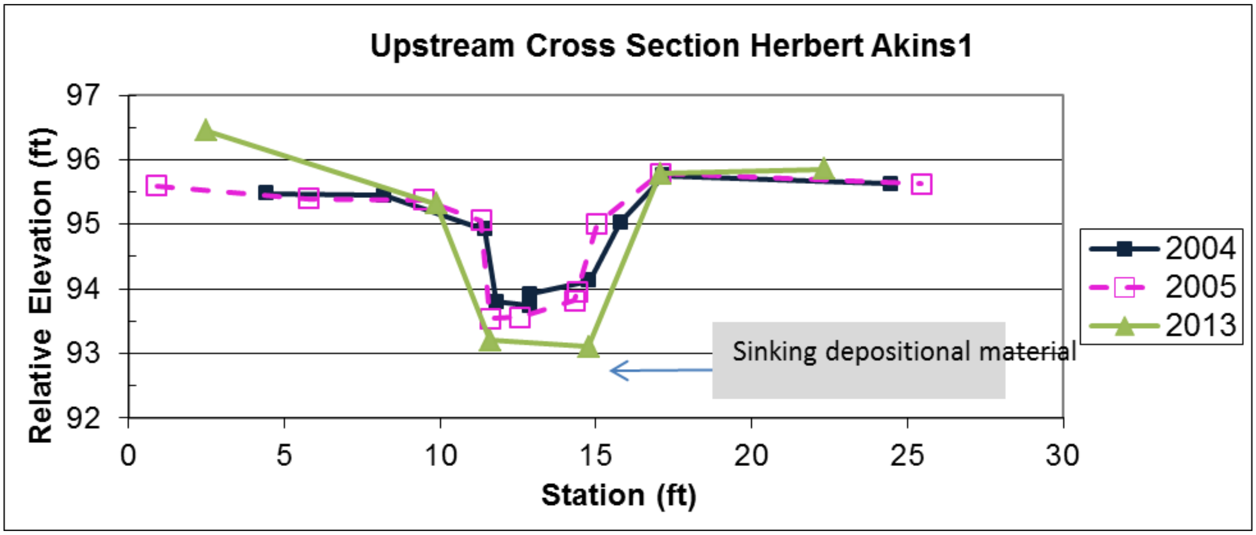

Figure 8. Upstream cross section at Herbert Akins1.

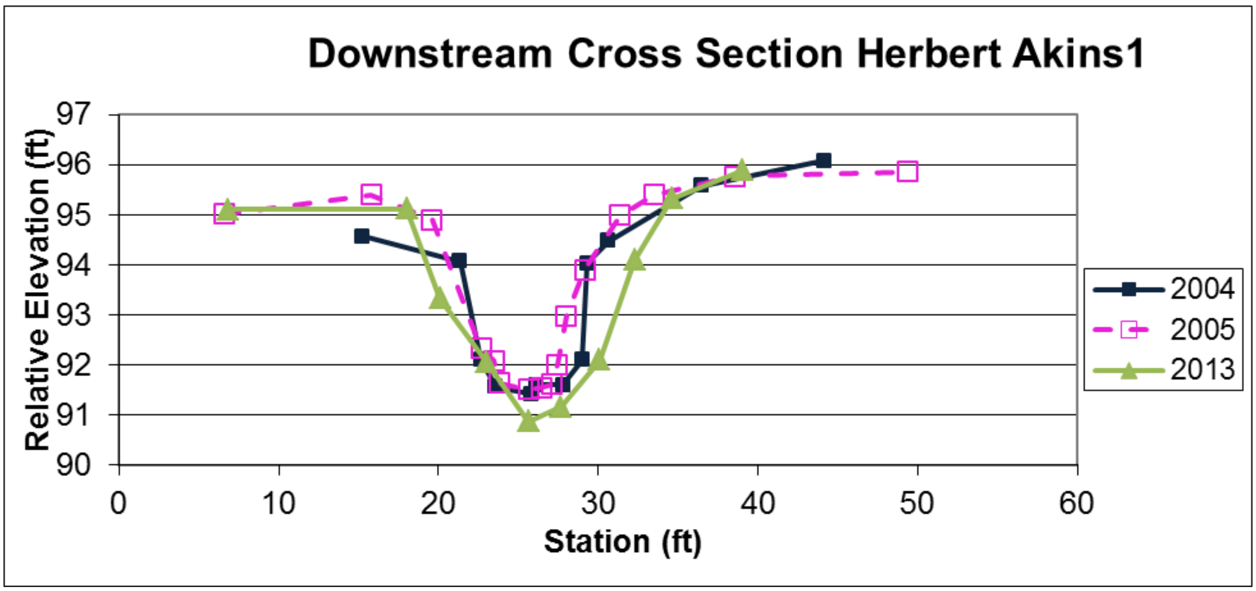

Figure 9. Downstream cross section at Herbert Akins1.

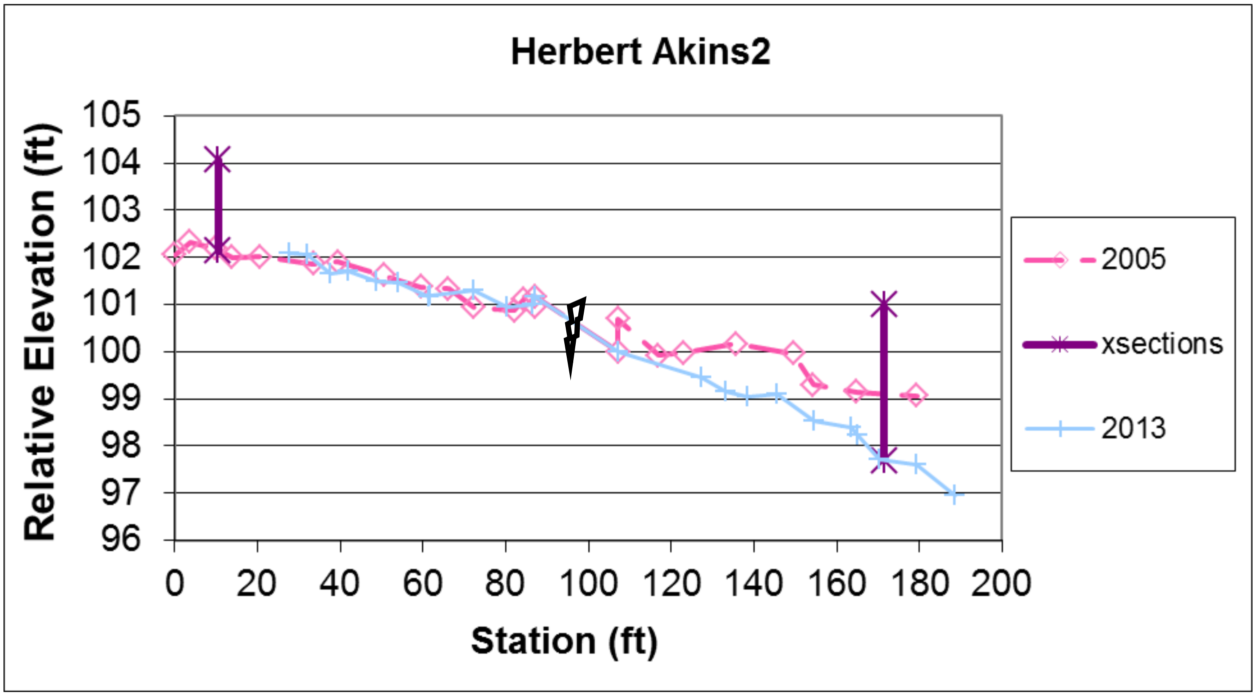

Figure 10. Longitudinal survey data for the Herbert Akins2 stream and culvert.


Figure 11. Channel downstream of culvert in 2005 (left) and 2012 (right) at Herbert Akins2.

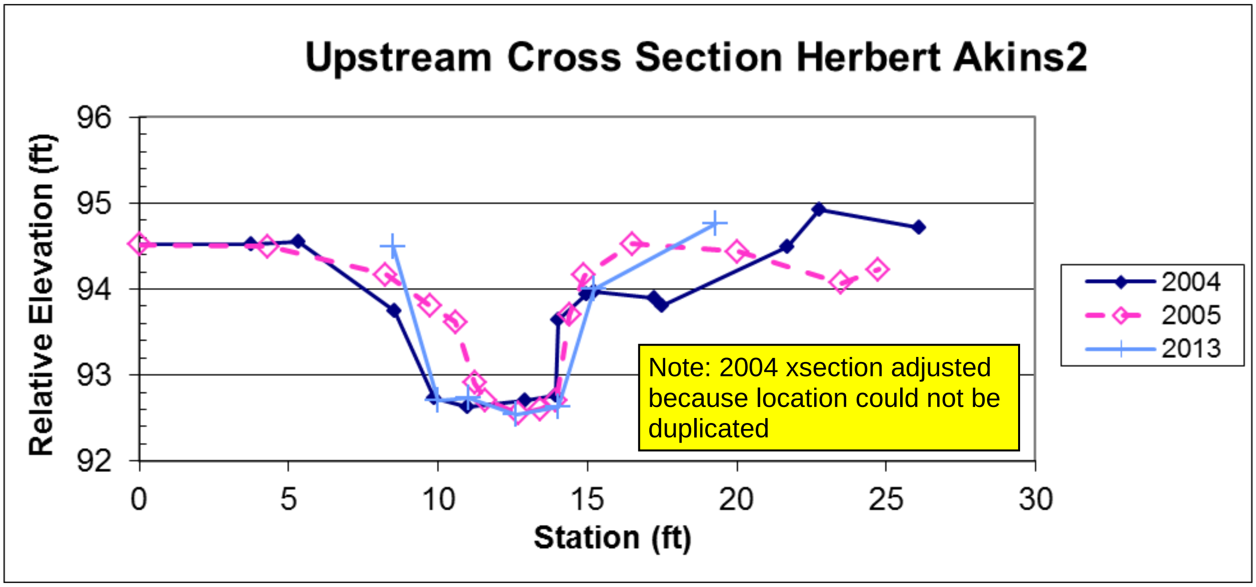

Figure 12. Upstream cross section at Herbert Akins2.

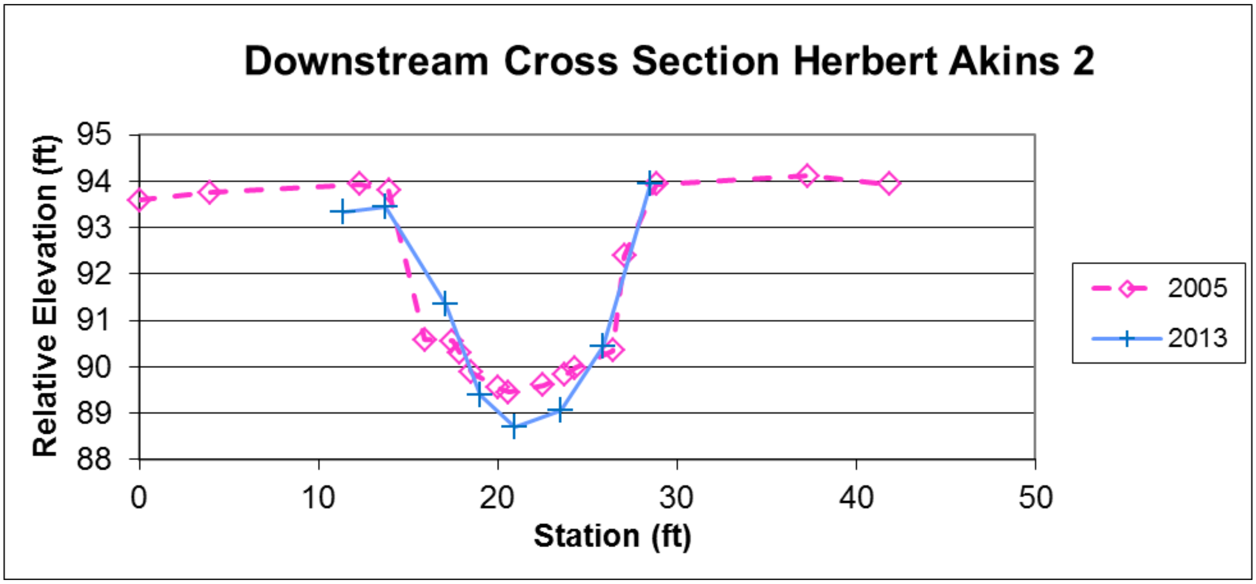

Figure 13. Downstream cross section at Herbert Akins2 site.

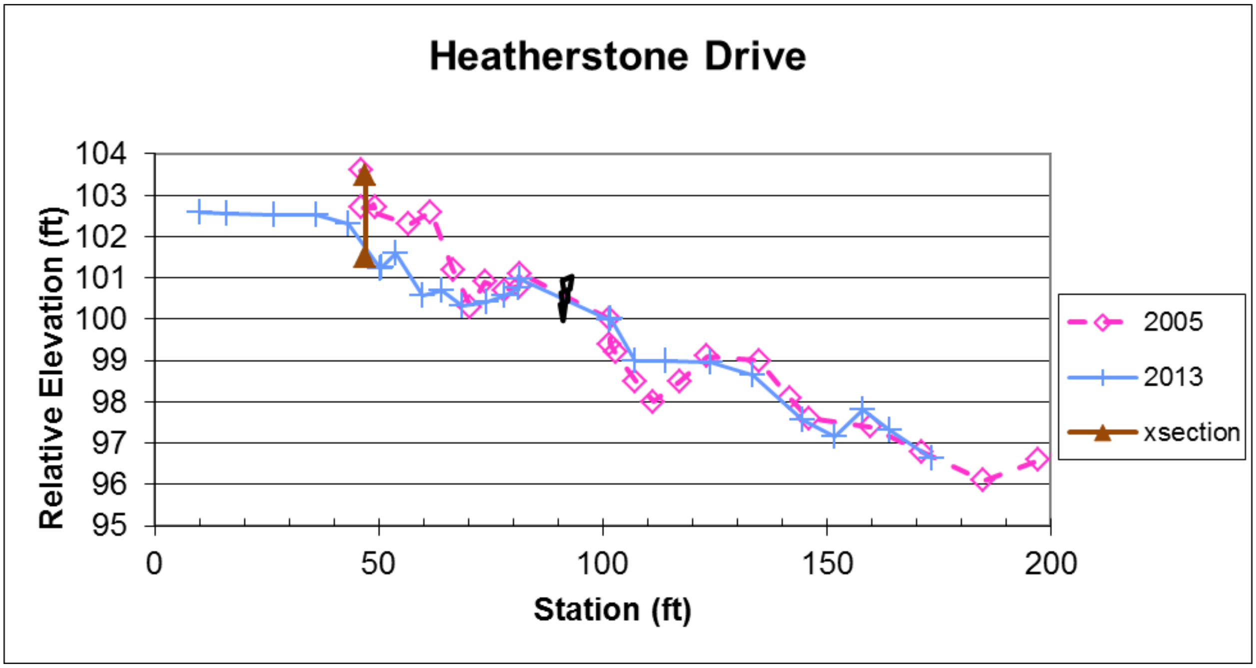

Figure 14. Longitudinal profile of stream at Heatherstone.

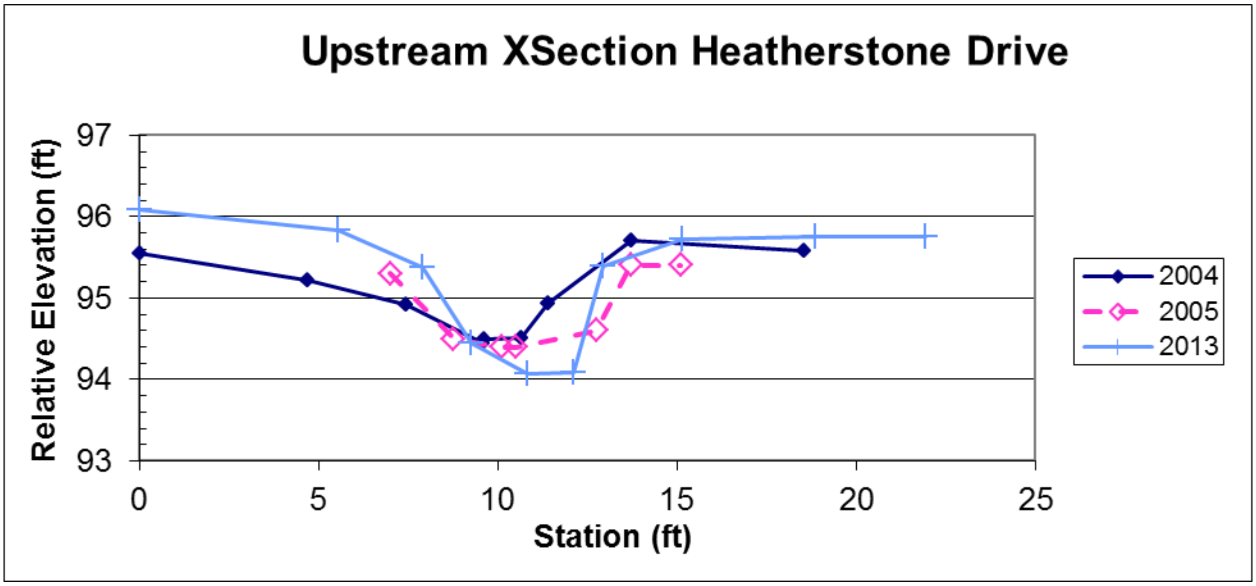

Figure 15. Upstream cross section data at Heatherstone site.

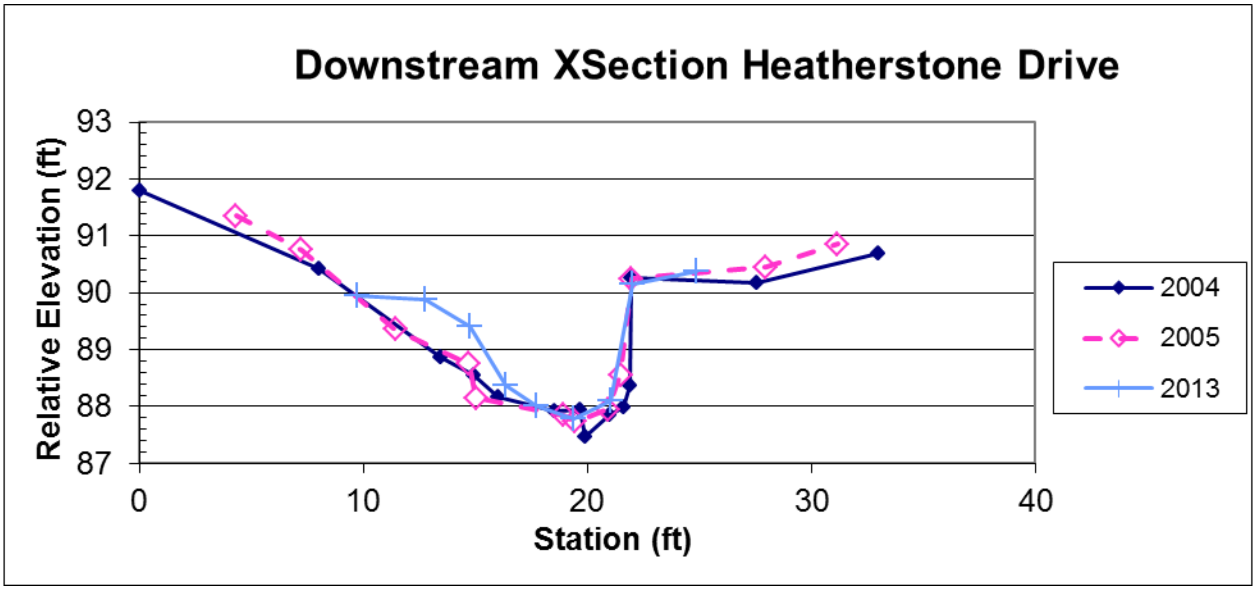

Figure 16. Downstream cross section data at Heatherstone site.

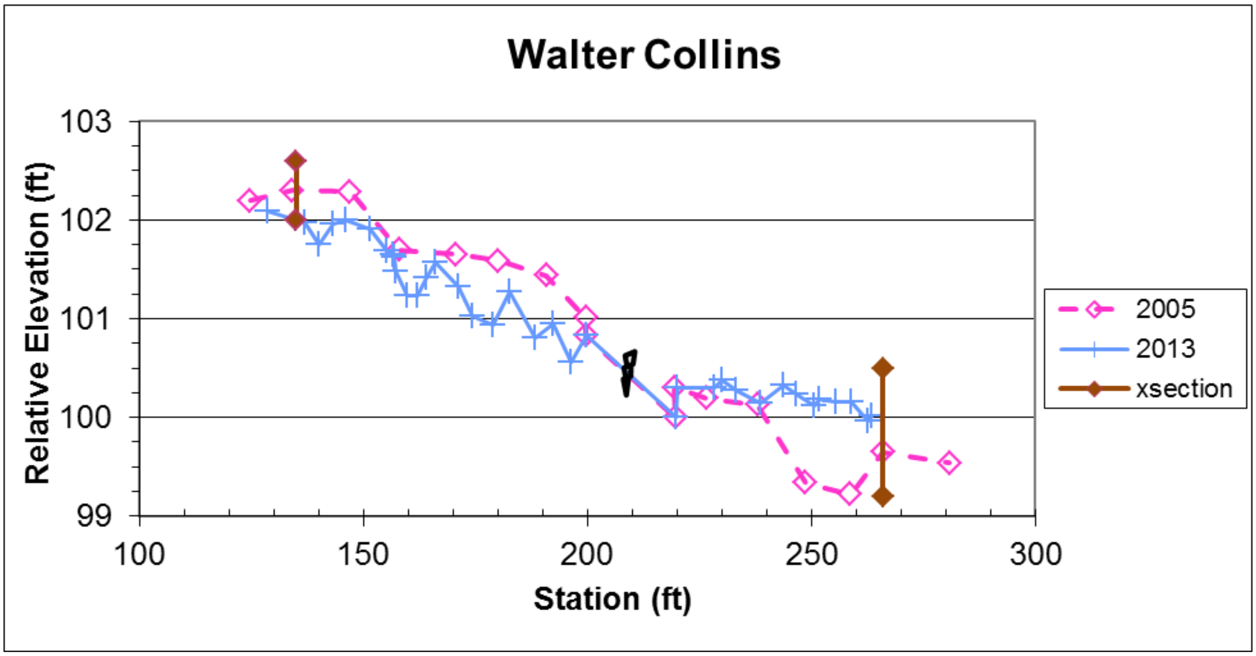

Figure 17. Longitudinal profile of stream at Walter Collins site.

Figure 18. Channel upstream of culvert (left) and downstream (right) at Walter Collins site.

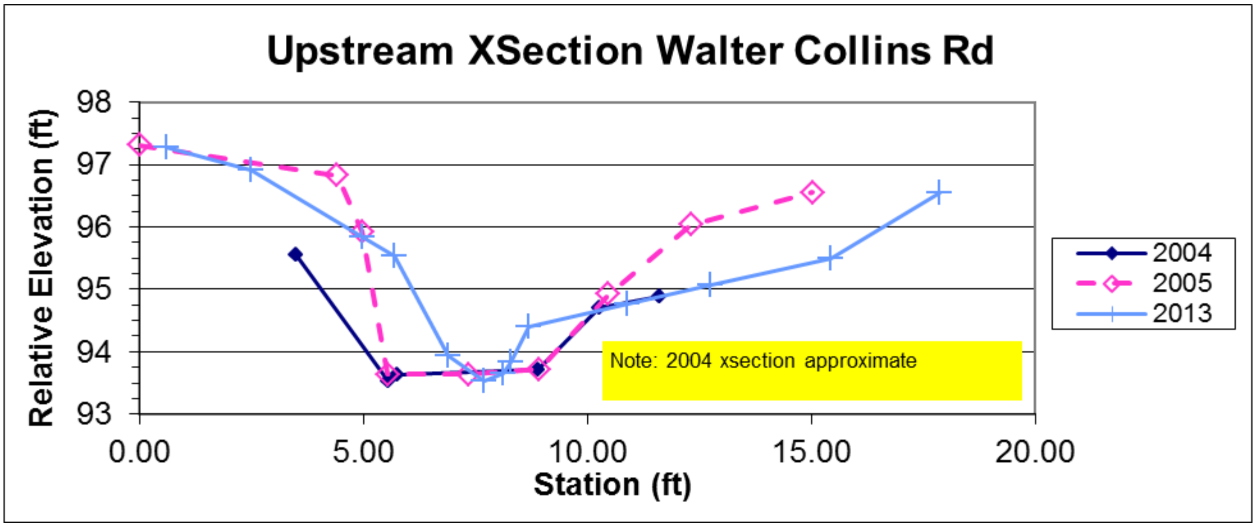

Figure 19. Upstream cross section of stream at Walter Collins site.

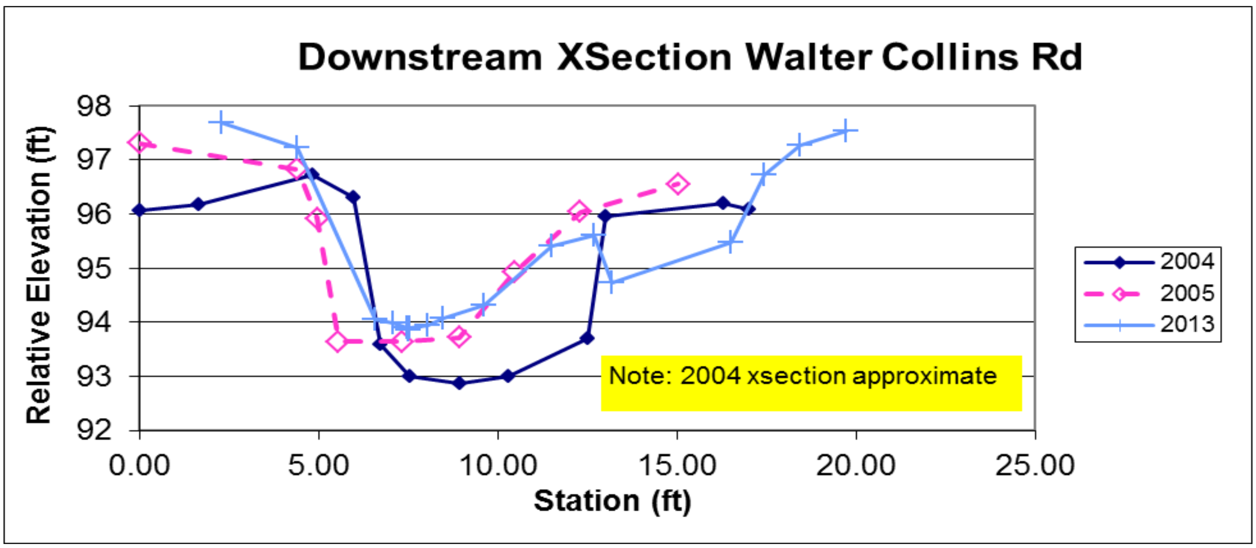

Figure 20. Downstream cross section of stream at Walter Collins site.

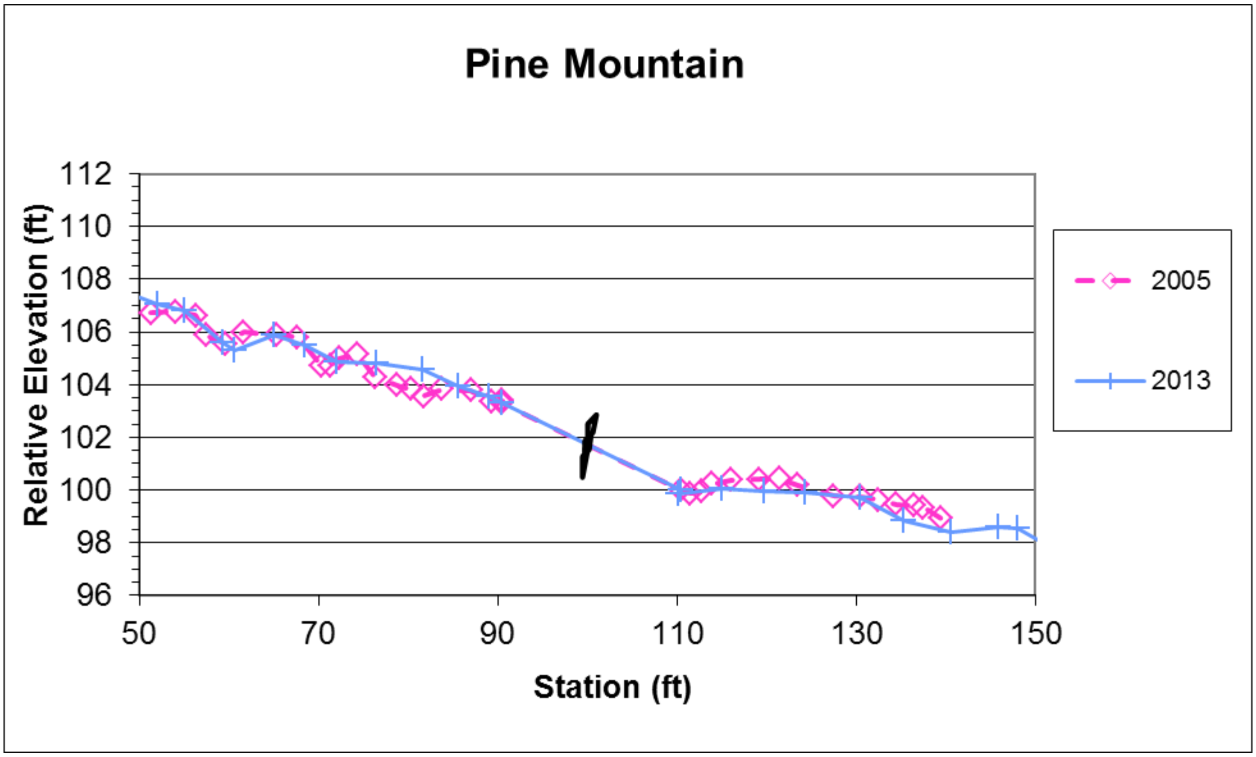

Figure 21. Longitudinal profile for stream at Pine Mountain site.

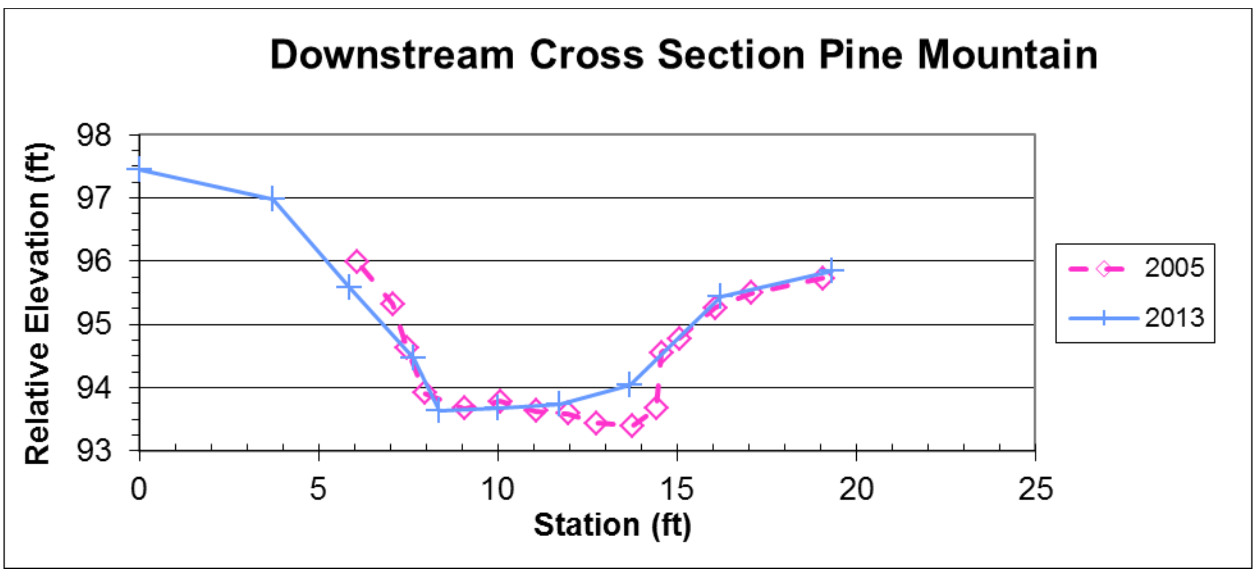

Figure 22. Downstream coss section at Pine Mountain site.

Figure 23. Upstream inlet (left) and downstream invert (right) of culvert at Pine Mountain site.

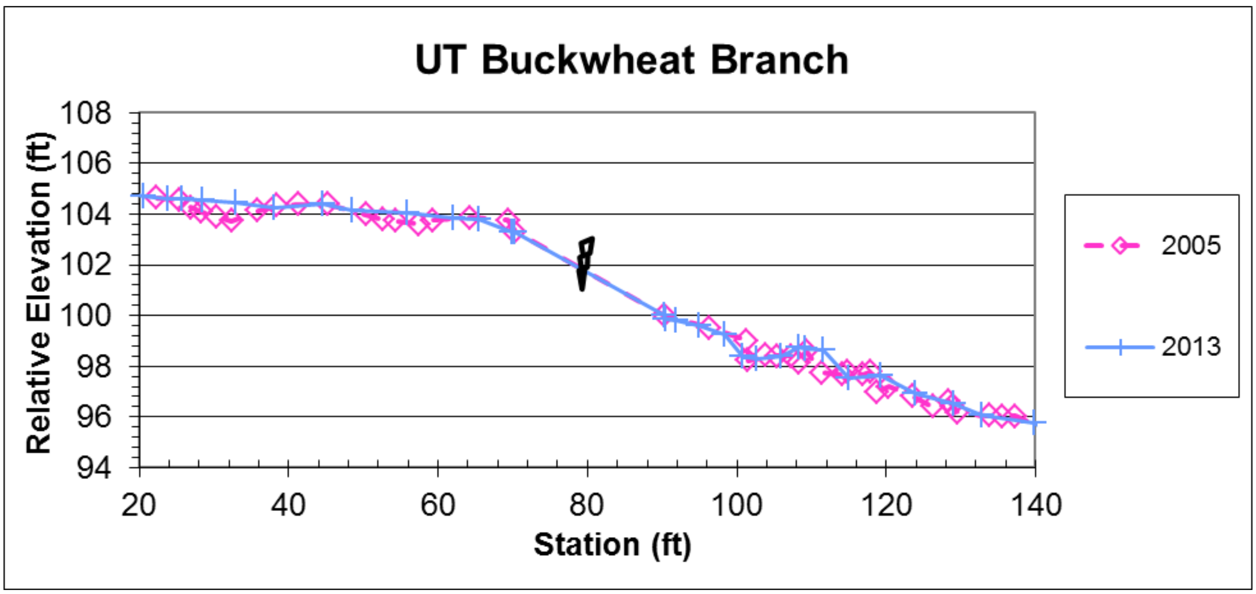

Figure 24. Longitudinal profile for an unamed tributary (UT) to Buckwheat Branch site.

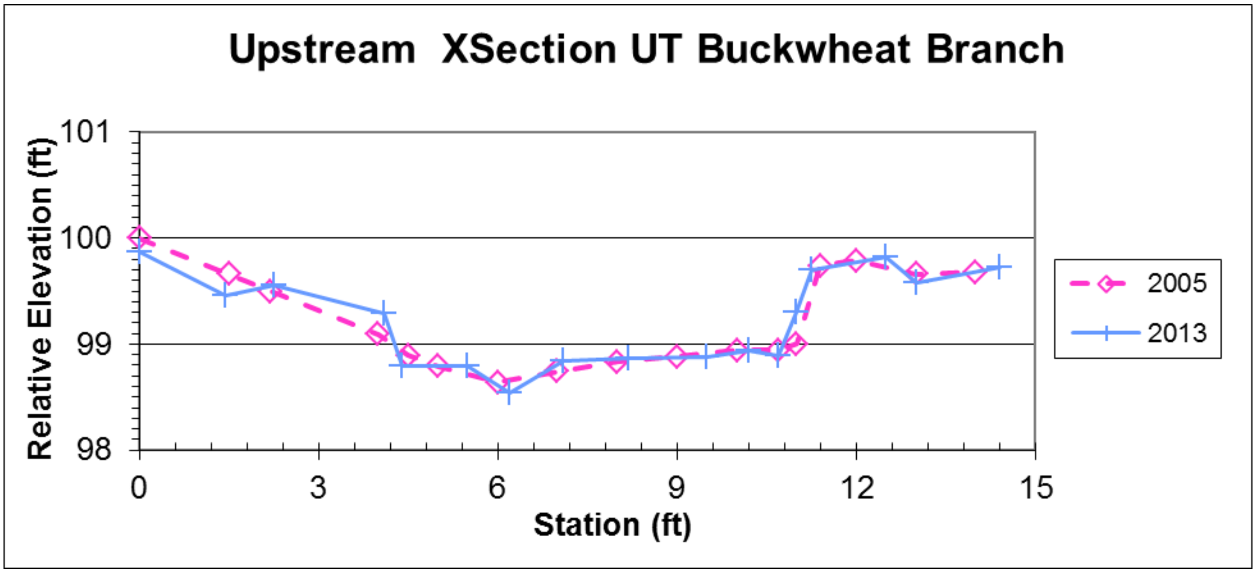

Figure 25. Upstream cross section for the UT Buckwheat Branch site.

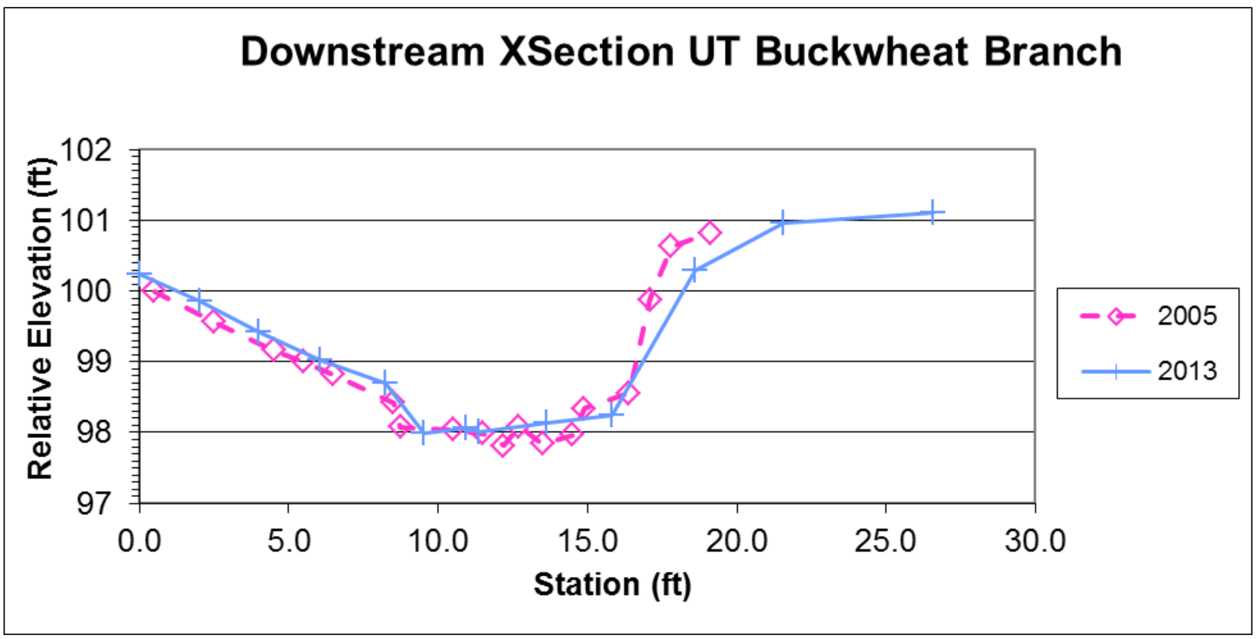

Figure 26. Downstream cross section for the UT Buckwheat Branch site.

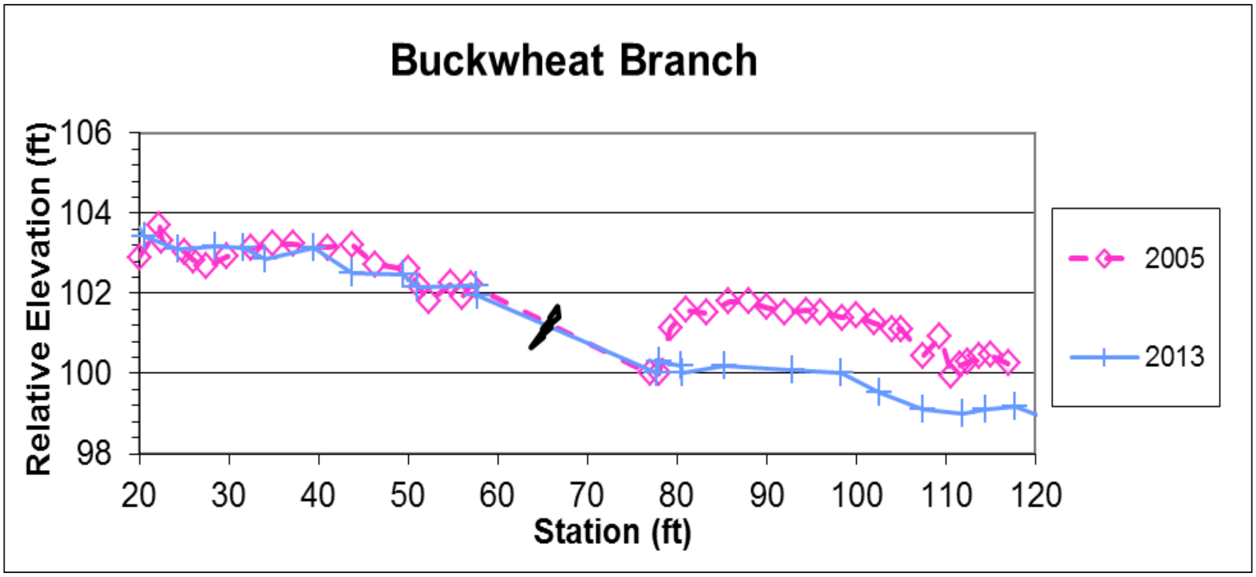

Figure 27. Longitudinal survey of stream at the Buckwheat Branch site.

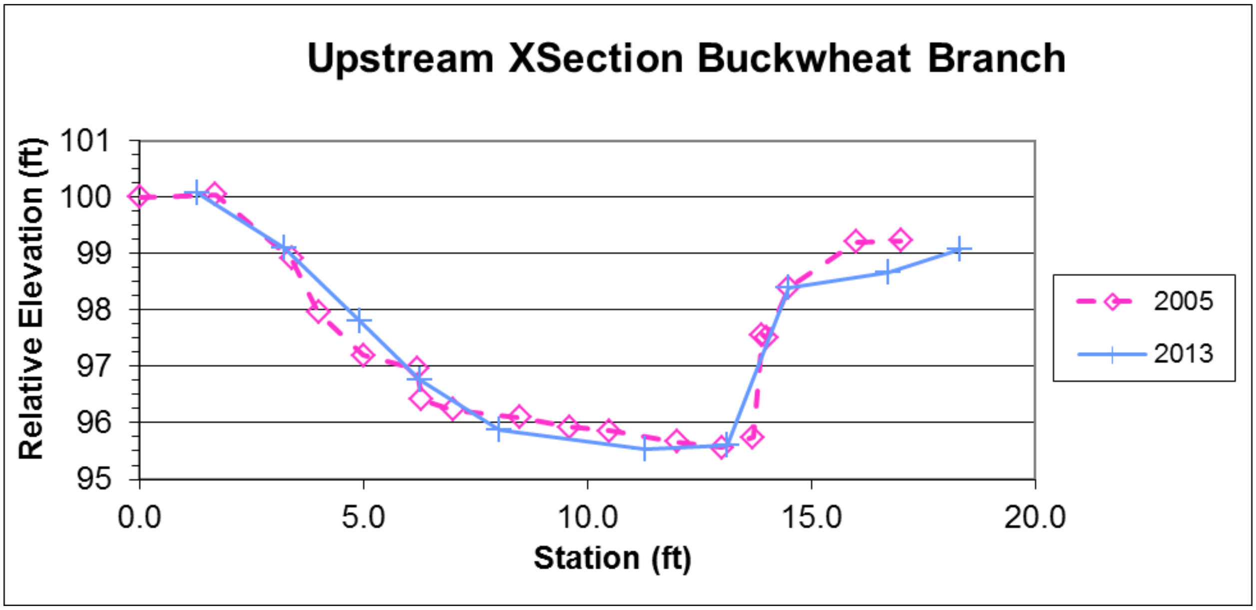

Figure 28. Upstream cross section on stream at Buckwheat Branch site.

Figure 29. Upstream (left) and downstream (right) ends of culvert at Buckwheat Branch site.

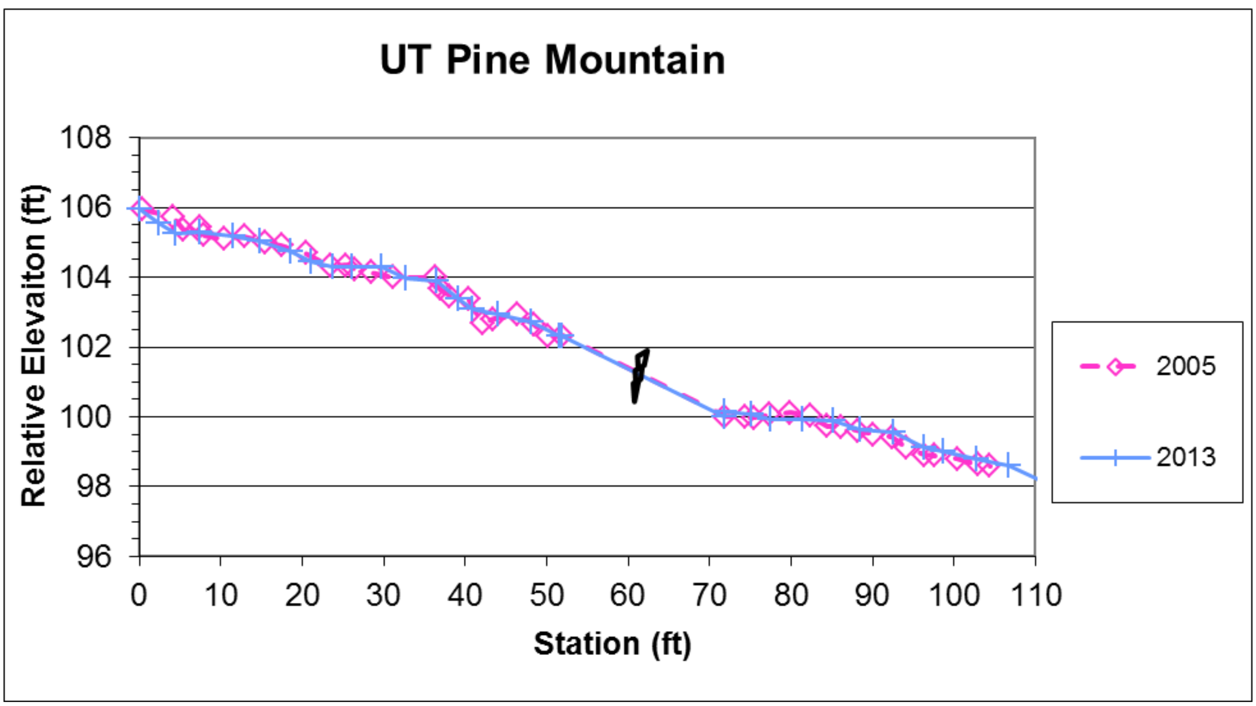

Figure 30. Longitudinal profile of stream at UT Pine Mountain site

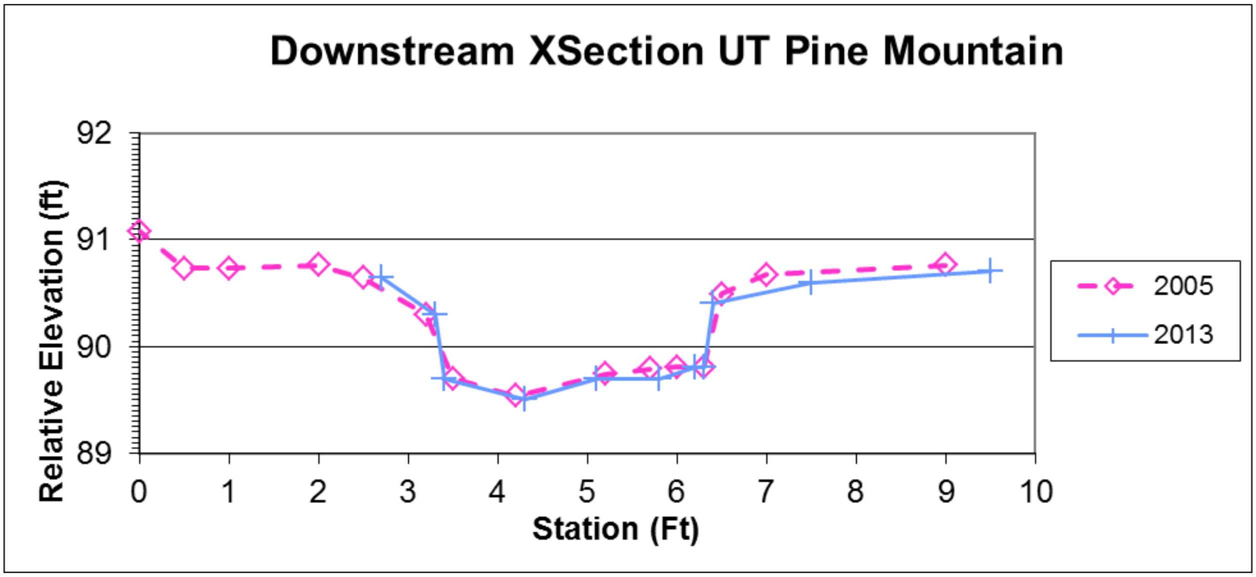

Figure 31. Downstream cross section for the stream at UT Pine Mountain site.

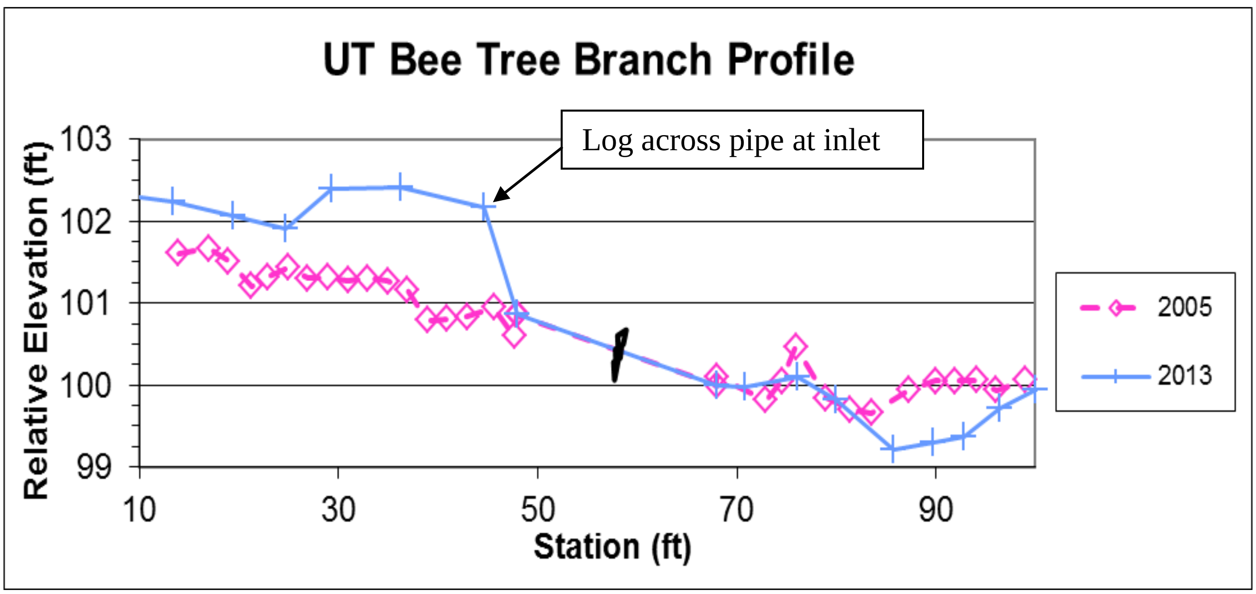

Figure 32. Longitudinal profile of stream at UT Bee Tree Branch site.

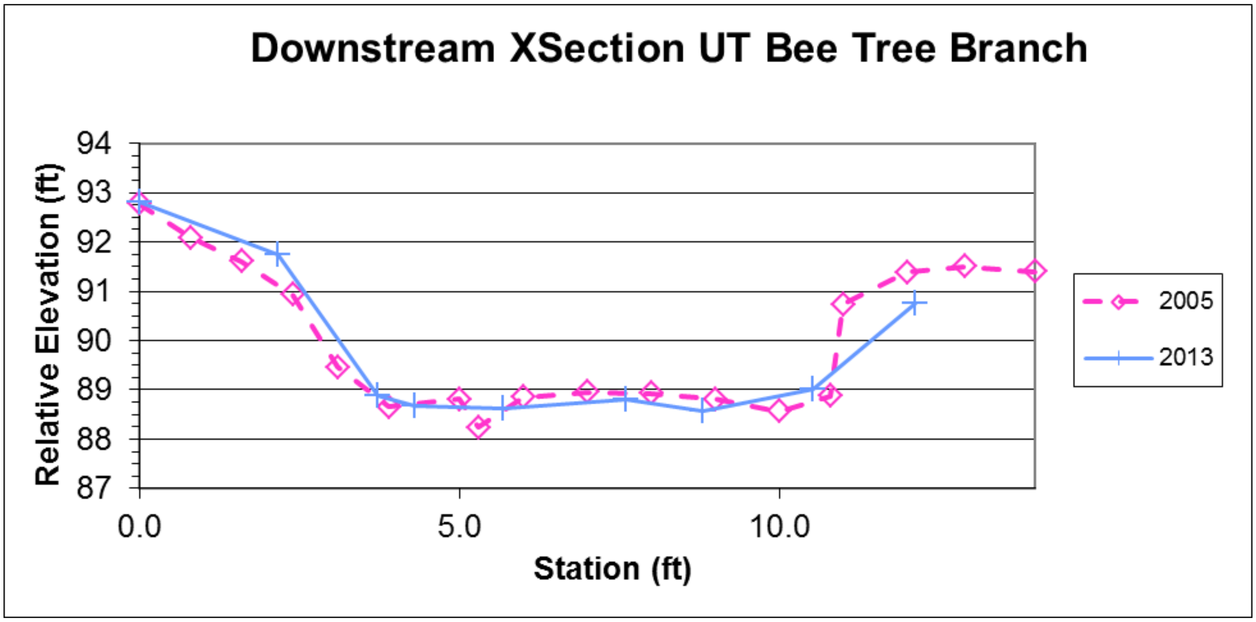

Figure 33. Downstream cross section for stream at UT Bee Tree Branch site.

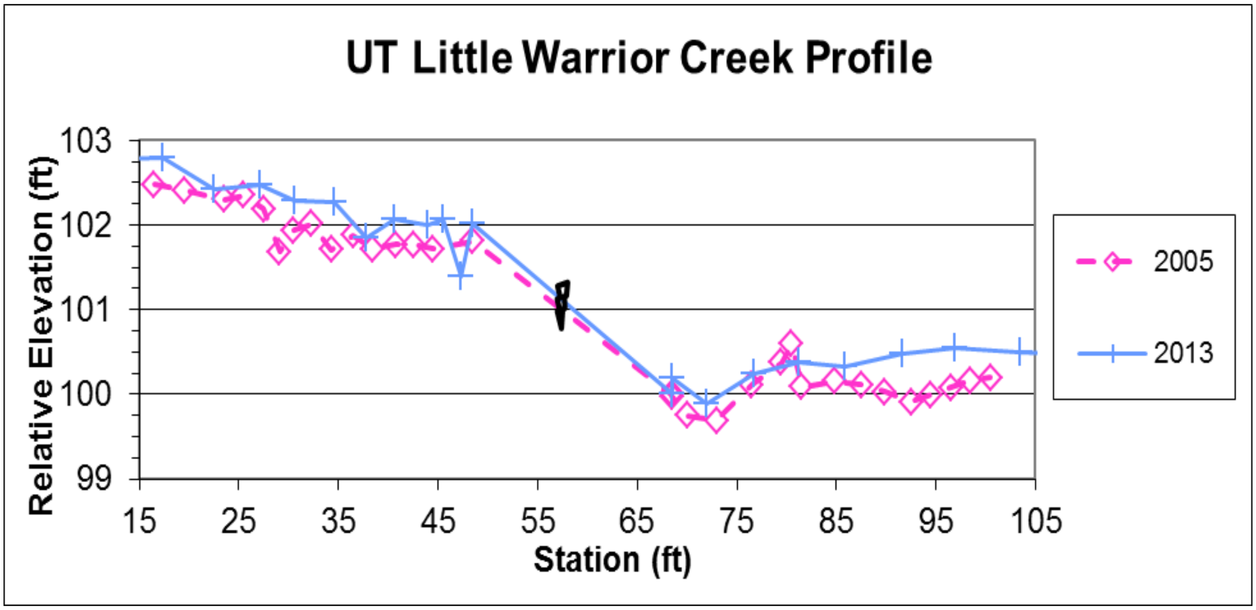

Figure 34. Longitudinal profile for UT Little Warrior Creek site.

Figure 35. Downstream channel at UT Little Warrior Creek site.

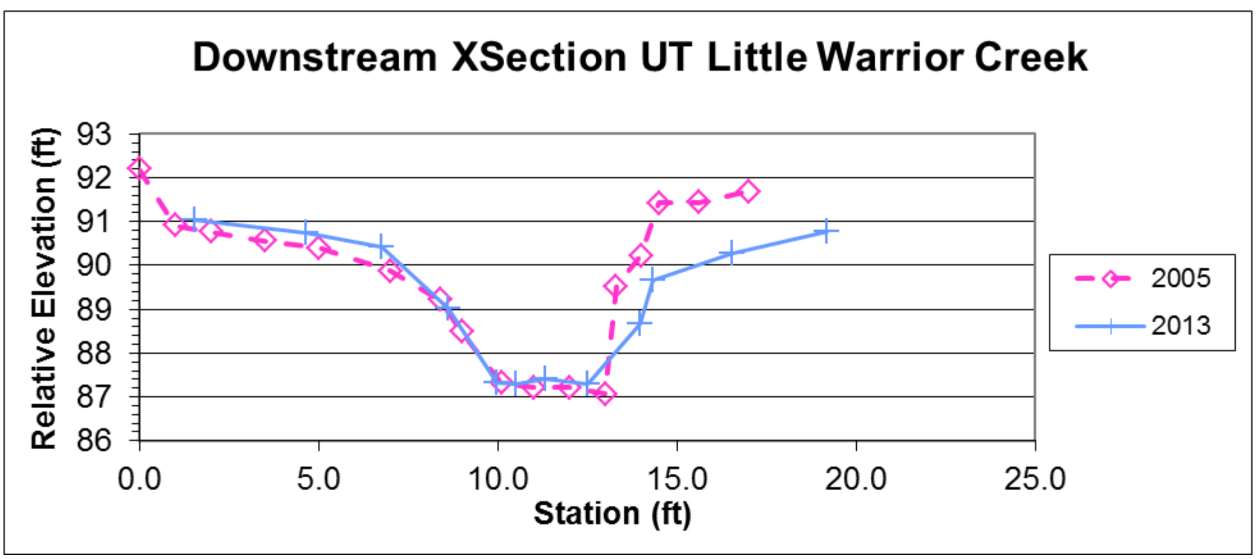

Figure 36. Downstream cross section for stream at UT Little Warrior Creek site.