Monitoring freshwater mussel relocation in Deer Creek, Rocks State Park, Maryland: Year 2 results.

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Larry Hogan, Governor

Mark Belton, Secretary

MARYLAND DEPARTMENT
OF NATURAL RESOURCES
Resource Assessment Service
Tawes State Office Building
580 Taylor Avenue
Annapolis, Maryland 21401

Toll free in Maryland: 877-620-8DNR
Out of State: 410-260-8021
TTY users: Call via the Maryland Relay
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Prepared by:

Matt Ashton, Natural Resource Biologist,
Kyle Sullivan, Natural Resource Technician
Maryland Department of Natural Resources
Monitoring and Non-Tidal Assessment Division
Tawes State Office Building
580 Taylor Avenue, C-2
Annapolis, Maryland 21401

Dave Brinker, Eastern Regional Ecologist
Maryland Department of Natural Resources
Natural Heritage Program

and

James McCann, State Zoologist
Maryland Department of Natural Resources
Natural Heritage Program
Appalachian Lab, Frostburg State University Campus
301 Braddock Road
Frostburg, Maryland 21532

Prepared for:

Maryland State Highway Administration
Office of Planning and Preliminary Engineering
Environmental Planning Division
707 North Calvert Street
Baltimore, Maryland 21202

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Executive summary

In accordance with permit conditions of the Maryland Department of the Environment and contract conditions with the Maryland State Highway Administration, the Maryland Department of Natural Resources conducted a relocation of freshwater mussels in 2014. The effort removed mussels from within the direct impact and indirect impact areas associated with instream construction activities to stabilize Maryland Route 24, Section A, along Deer Creek in Rocks State Park, Maryland. Mussels were relocated upstream of the impact area into presumably suitable habitat based on the presence of mussels. The relocation also entailed development of a rigorous monitoring plan to evaluate its efficacy as a conservation strategy to minimize harm to mussels since this represents the first such effort of size and scope in Maryland. Initiating the monitoring plan required that 1) sites stocked with mussels (translocation) and sites stocked with no mussels (control) be surveyed before relocation with the same methods used in the removal area to estimate their initial population size and 2) individual mussels be marked with uniquely numbered tags to track their condition over time. Baseline surveys at translocation sites also characterized the spatial distribution of mussel populations within sites to guide their stocking in a manor that reflected this pattern. This report summarizes findings from the first year of monitoring following mussel relocation in Deer Creek.

We surveyed the removal site over four days (July 29 -August 3). We collected 910 *Elliptio complanata* (Eastern elliptio) and one *Strophitus undulatus* (Creeper), which was found in the indirect impact area. Of the Eastern Elliptio, 39 were marked with shellfish tags indicating they had recolonized the site after being relocated in 2014. A comparison of mussel catch and estimated population size between years indicates the population is 80% to 50% smaller, respectively. In general, sections within the removal area that contained the most mussels in 2014 contained a relatively high number of mussels in 2015. However, these sections showed the greatest relative reduction in abundance.

We surveyed four control sites over three days (August 17-18, September 3) and collected 392 Eastern elliptio. Of these, 133 (34%) were previously marked with shellfish tags. Population estimates at control sites were similar between 2014 and 2015. Patterns of relative abundance within and among sites were similar between years.

We surveyed five translocation sites from August 31-September 2 and collected 602 Eastern elliptio and one Creeper. Of the Eastern elliptio, 302 were previously marked with shellfish tags. Approximately 80% of the recaptured mussels were from the relocation while the remaining mussels were from the baseline survey. Population estimates at translocation sites varied between 2014 and 2015, even though we previously increased them by four fold by transplanting mussels in 2014. Patterns of relative abundance within and among sites were similar between years.

We did not recapture any Creeper in 2015, although two more were found in 2015. They appear to be rare and difficult to detect in Deer Creek. The median mussel population size of control sites was similar between 2015 and 2014. Conversely, the median population size of translocation sites in 2015 was about 1.4 times less than the intended size after stocking them with mussels at a uniform rate relative to their baseline size in 2014. Minimal evidence of mortality (i.e., dead, tagged mussels) and movement was observed among all monitoring sites. Eight relocated mussels moved downstream into other translocation sites and another 40 were recaptured in the removal site.

Initial results from the first year of monitoring of the mussel removal survey suggested that the main objective of removing a majority (> 80%) of the estimated population at the substrates surface was met. A comparison of the number of mussels collected in 2015 with 2014 further supports this finding. However, in 2015, the population estimate of mussels at the surface in the removal site was higher than was expected. Estimating population size in highly clustered animals, like mussels, can be difficult and influenced by survey method and environmental factors. While the initial population estimate at the removal site had a narrow confidence interval our detection probabilities were low in 2014 and 2015. Mussels at the surface that were missed during the removal may in part account for the numbers observed in 2015. A portion of the population was also likely buried and not detectable during the removal survey using our methods. Refinement of the methods used in future mussel removal based on the findings from this project could help State Highway Administration address this uncertainty, while ensuring effort is focused in the areas of highest mussel concentration and greatest potential impact.

Introduction

Freshwater mussels are the most imperiled faunal group in North America. Nearly two-thirds of the continent's approximately 300 species are extinct, endangered, or declining (Williams et al. 1993). In Maryland, 14 of the state's 16 mussel species are listed as rare, threatened or endangered (Maryland Natural Heritage Program 2010). *Elliptio complanata* (Eastern elliptio) is the most common mussel species in Maryland (Bogan and Ashton 2016). It is considered relatively secure in the state and throughout most of its global range (NatureServe 2014). Still, its distribution and abundance has declined in various parts of the Mid-Atlantic (Strayer and Fetterman 1994). Streams that support it in high abundance like Deer Creek are uncommon in Maryland and indicative of high quality conditions (Maryland Biological Stream Survey 2014). *Strophitus undulatus* (Creeper) is a widely distributed, yet uncommon species in Maryland (Bogan and Ashton 2016). Although it is globally secure (Nature Serve 2014), it is typically found in low abundance in Maryland and is thus considered in need of conservation (Maryland Natural Heritage Program 2010).

Mussel relocation has been used as a conservation strategy for decades. For years, its efficacy was largely unknown because the ecology of most species was poorly understood. In a review of 37 projects, Cope and Waller (1995) reported that average survival for relocated mussels was approximately 50%. Only a few of these relocations were monitored and mussels recapture rate was often low. Subsequent studies found survival could be improved by decreasing handling and exposure times (Waller et al. 1995), relocating into suitable habitat (Hamilton et al. 1997), and stocking at appropriate density (Bolden and Brown 2002). Numerous state, regional, and national resource management agencies have developed mussel relocation guidelines to minimize the potential negative effects of relocation to a highly imperiled resource based on these empirical guidelines (e.g., Piette 2005, Mackie et al., 2008, Luzier and Miler 2009).

Assessments of freshwater mussel relocation success are hampered by low detection probabilities because mussels often exist at very low densities, are buried beneath the substrates surface, or in habitats difficult to survey. The probability of capture can be improved with the use of quantitative sampling designs (Strayer and Smith 2003). Sediment excavation is typically used to account for low capture probabilities and imperfect detection because a portion of the population is below the substrate and may be missed by qualitative, visual searches (Amyot and Downing 1997, Watters et al. 2001). However, visual searches are more cost-effective and suggested over quantitative sampling when the objective is to find rare species or track the fate of animals over time (Strayer et al. 1997, Metcalfe-Smith et al. 2000). Incorporating aspects of quantitative sampling, such as defining the survey area, can help overcome some limitations of qualitative sampling. Recapture rates of mussels can be further improved using PIT tag technology (Kurth et al. 2007). Increasing the quantity and quality of data should provide more accurate estimates of mussel survival, thus making the method ideal for monitoring relocated mussels.

Deer Creek is a 4th order tributary of the lower Susquehanna River in Harford County, Maryland. It is designated as a Scenic River, which requires the state protect and enhance its qualities (Maryland Natural Resources Article, 8-402). Land use upstream of the survey area is primarily agricultural (54%), with lesser amounts of forested (30%) and urban areas (15%) (Homer et al. 2007). The reach of stream is afforded further protection under the Maryland Clean Water Act because it supports healthy biological communities and its designated use (COMAR 26.08.02.04). Maryland Route 24 runs parallel to Deer Creek and the bedrock valley wall within Rocks State Park (Figure 1). Stream bank sloughing created concern that the road could fail without bank armoring, which required impacts to Deer Creek including temporary fill, excavation, and dewatering. Prior surveys in this reach of stream indicated patches of habitat supported mussels in high relative abundance (U.S. Fish and Wildlife Service, unpublished data, Maryland Natural Heritage Program, unpublished data). The potential take of a state listed mussel and alteration to its habitat necessitated the removal of mussels from the area of impact. Our main objectives were to 1) remove as many mussels as feasible from the direct and indirect impact areas, 2) minimize risk of relocation failure by stocking mussels in appropriate habitat and abundance, and 3) rigorously evaluate the action by monitoring the condition and fate of mussels over time.

Methods

Study sites

The upper and lower extent of sites were marked with surveyors flagging and recorded with a GPS unit (Garmin Vista H). Each site was divided into 10-m-long sections that were approximately half the wetted stream width to manage survey logistics and guide stocking of mussels within translocation sites. The removal site was approximately 380-m-long, beginning 30 m downstream of the direct impact area and ending 10 m upstream of the direct impact (Figure 2). Due to the lateral buffering of the direct impact area the survey included the entire width of the stream. Five, 40-m-long translocation sites were located upstream of the removal site (Figure 2). We stocked mussels within 10-m-long sections at these sites in proportion to their abundance observed during baseline surveys to reduce the potential effects of mussels being placed into unsuitable habitat. We limited the number of additional mussels each translocation site could receive to three times its initial population estimate to diminish the potential that these new populations might exceed resource availability (Cope et al. 2003). Four, 40-m-long control sites were located upstream of the translocation sites (Figure 3).

Survey methods

From July-September, we conducted timed, visual searches at sites in Deer Creek during periods of low flow and water visibility ≥ 2 m. Mussels at the substrates surface were collected using visual survey techniques, including snorkeling, glass-bottom view buckets, and SCUBA. Typically, an individual 10-m-long section was searched by four to six observers who were aligned perpendicularly with the stream bank and sampled in an upstream direction (Figure 4). We attempted to equalize sampling effort within and among sections by limiting effort to approximately 0.5 person-hours. The number of observers, mussels collected by species, and time spent searching within a section was recorded upon its completion. We used two-pass depletion sampling at sites to estimate population size and capture probability (Serber and LeCren 1967). Population size (N), probability of capture (p), and variance of N are calculated as:

(eq. 1) $N = C_1^2 / (C_1 + C_2)$

(eq. 2) $p = C_1 - C_2 / C_1$

(eq. 3) variance of $N = C_1^2 \times C_2^2 (C_1 + C_2) / (C_1 - C_2)^4$

Monitoring

A mark-recapture sampling design was employed to track the fate of individual mussels within translocation and control sites and allow estimation of population demographics, like growth, survival, and recruitment after a minimum of three survey events (Villella et al. 2004). After collection, mussels were processed at centralized stations following procedures to minimize exposure by holding them in flow through live wells or aerated coolers with routine changes of stream water (Luzier and Miller 2009). We identified mussels using taxonomic standards (Turgeon et al. 1998, Bogan and Ashton 2016).

To track rates of growth, all tagged mussels collected at the removal site and monitoring sites were measured (mm) with dial calipers. Mussels collected without tags (i.e., naive) at monitoring sites were marked with a uniquely numbered vinyl (Hallprint) shellfish tag affixed to each valve with cyanoacrylate adhesive. We externally adhered and encapsulated a 12 mm 134.2 kHz HDX PIT tag to each Creeper to increase the probability of recapture in successive monitoring events. At least 20% of Eastern elliptio were also marked with PIT tags, including all individuals < 50 mm in shell length. This cohort should exhibit more growth over time as opposed to larger mussels (i.e., Anthony et al. 2001). An accelerant (Turbo Set I, Palm Labs Adhesives) was used to reduce curing time. Prior to being returned to the stream, PIT tagged mussels were logged into portable readers (Biomark HPR+) to assure tags functioned properly. For each site, we recorded the shellfish tag numbers, section, and survey pass for naïve and tagged mussels recovered from baseline surveys or the relocation. Mussels were returned to the stream by placing them into the substrate anterior end down to mimic their natural orientation. We recorded the section within sites where we placed mussels along with their tag numbers to account for potential movement between years that might be due to monitoring (i.e., returning a mussel to a different section than their capture). PIT tagged mussels were logged with a submersible wand after bedding them in the substrate.

Because we lacked the minimum number of sampling events to model population demographics, we evaluated the relocation indirectly in multiple ways. First, we compared the change in estimated population size at translocation and control sites between 2015 (N_{pop1}) and 2014 (N_{pop0}). Since baseline populations at translocation sites were increased due to the relocation, we standardized population estimates and examined them as a rate of change (N_{pop1} / N_{pop0} + N_{pop0} x 3). Observed mortality was calculated as the number of dead mussels recaptured divided by the total number of mussels recaptured. We compared the average change in shell length ($L_1 - L_0$) for mussels recaptured at monitoring sites by the site of initial capture. We also contrasted length-frequency distributions at monitoring sites between years. Finally, we evaluated movement of recaptured mussels within monitoring sites to assess whether the relocation influenced their behavior. This was done by comparing the distance between locations of mussel release during baseline surveys or as a result of relocation (2014) with the location of their recapture during monitoring surveys (2015).

We resurveyed the removal site to assess the efficacy of our multiple-pass depletion survey approximately one year later. This was accomplished by comparing the total catch and two-pass population estimates (Serber and LeCren 1967) of mussels collected within the direct impact area between years. We also compared the total catch within sections between survey years to investigate if the change in population size was influenced by patterns of within site variability in depletion.

Results

Removal site

We spent 41.38 person-hours surveying the removal site in 2015 and collected 909 Eastern elliptio and one Creeper. Average total survey effort per section was 0.86 person-hours. Thirty nine of these Eastern Elliptio were marked with shellfish tags, indicating they were previously relocated upstream of the removal site. The average movement of these mussels was 960 m downstream, and ranged up to 1,500 m, based on the distance between the sections where mussels were relocated versus the section where they were observed in 2015. A single, dead mussel was also recaptured in the site. Mussel abundance and CPUE was highly variable among sections in the removal site (Appendix II). Recaptured Eastern elliptio ranged in size from 41.3 to 82.4 mm.

In 2015, we estimated 1,172±154 mussels were located within the direct impact area (Table 1). This estimate was approximately 50% of the population size estimated from the removal survey. Capture probabilities were similar between years suggesting changes in abundance were not likely due to differences in detectability. A comparison between the number of mussels collected from the left side of the removal site in 2014 (2,255) versus 2015 (828) resulted in a 77% reduction in the total catch. A side-by-side comparison of the number of mussels collected in each section indicates that sections with low initial mussel abundance may be difficult to deplete versus sections with high initial abundance (Table 2). For example, the number of mussels collected in 2015 was on average 52% lower in sections with ≤ 19 mussels (25th percentile) collected during the removal survey. In contrast, catch was on average 80% lower in 2015 for sections with ≥ 80 mussels (75th percentile) collected during the removal survey.

Control sites

We spent 22.03 person-hours surveying for mussels at four sites in 2015. Average total survey effort per section was 0.89 person-hours. A total of 392 Eastern elliptio were collected and of these mussels 133 were recaptured from the prior year (Table 3). We affixed shellfish tags to the remaining 259 mussels and PIT tags to 72 of these mussels. Mussel abundance and CPUE was highly variable among sections within sites (Appendix II). Shell lengths of Eastern elliptio ranged from 17.3 to 91.1 mm (Figure 5). No previously tagged mussels were found dead at control sites.

Average shell length of Eastern elliptio collected at control sites did not differ between years (Figure 6). Population estimates and detection probabilities were highly variable among sites (Table 1). There was little change observed in population estimates at C0 and C1 between years. The probability of detection at these sites varied by approximately 0.10. Sites C3 and C4 exhibited comparatively higher variability in population estimates and detection probabilities between years.

Translocation sites

We spent 33.87 person-hours surveying at five sites in 2015. Average total survey effort per section was 0.94 person-hours. A total of 602 Eastern elliptio were collected among the five sites (Table 3). Of these mussels, 240 were recaptured after being relocated from the removal site the prior year. Two previously tagged Eastern elliptio were found dead. We affixed shellfish tags to the remaining 307 mussels and PIT tags to 77 of these mussels. One naïve Creeper was also collected at T1 (Appendix III). Mussel abundance and CPUE was highly variable among sections within sites (Appendix II). Shell lengths of Eastern elliptio collected at translocation sites ranged from 24.0 to 90.7 mm (Figure 5).

Average length of Eastern elliptio collected at translocation sites did not differ between years (Figure 6). Estimated population size was highly variable among these sites during both years (Table 1). For example, mussel abundance one year after relocation differed between T1 and T2 by an order of magnitude. Capture probabilities among sites varied up to 40% during both years. Within sites, capture probabilities differed from 6% to 50%.

Effects of relocation

Median population size among control sites did not change between 2014 and 2015, suggesting changes observed at translocation sites were likely due in part to manipulation of population size. Median population size at translocation sites in 2015 was 2.63 times higher than the baseline survey estimate, which is 35% less than the population size intended following relocation (Figure 7). There was an apparent inverse relationship between the size of initial population estimate and magnitude of change in population size between years at translocation sites. Sites with small initial populations exhibited the largest decrease in estimated size between years (Table 1, Figure 7). The observed mortality of recaptured mussels at translocation sites was insignificant (<1%) and no mortality was observed at control sites.

Relocated mussels exhibited less growth than mussels initially captured at translocation or control sites during baseline surveys (Figure 8). Nearly half of the relocated mussels recovered also exhibited negative growth compared to just 15% of mussels recovered at control sites. Differences in growth were not likely due to differences in population structure because the average initial length of Eastern elliptio recovered in 2015 was similar among sites. Eight mussels were recaptured in different translocation sites than they were released following relocation in 2014. These mussels moved downstream an average of 125 m. In contrast, no mussels from baseline surveys at translocation and control sites were recaptured at different sites. Relocated mussels exhibited less movement within sites than mussels initially collected at monitoring sites (Figure 9). Approximately two thirds of the relocated mussels were recovered in the same section as they were released in the prior year. Nearly half of the mussels recaptured at control sites were found in the same section of their release. Forty percent of mussels recaptured from baseline surveys at translocation sites showed no movement.

Discussion

In 2014, we accomplished the primary goals of 1) relocating a majority of the observed freshwater mussel population from the direct and indirect impact areas and 2) conducting the relocation in a manor to reduce causes of mortality often associated with the practice. The mussel community present within Deer Creek was almost entirely composed of Eastern elliptio. Creeper, while present in at least one site in each part of the study area, appears rare. The community composition, abundance, and size-structure documented were comparable to past surveys (U.S. Fish and Wildlife Service, unpublished data). We observed evidence of recent (i.e., smaller mussels) and regular recruitment (i.e., normally distributed length-frequency). Provided suitable habitat remains in the removal area following stream bank stabilization, recolonization of the area seems likely. In 2015, we observed minor recolonization due to long-distance movements of relocated mussels. About half of these mussels were moved during a single event (July 23, 2014), which preceded a rise in the hydrograph due to precipitation (Ashton et al. 2015). Annual rates of long-distance movement between mussel beds are unknown. It is not clear if this pattern will continue or can be attributed to the particular relocation event.

Freshwater mussels exhibit patchy distributions within streams over space and time, which makes estimating their population size difficult (Downing and Downing 1992, Meador et al. 2011). Various sampling designs have been assessed for their accuracy at predicting population size and the logistical complexity required to implement versus its precision (i.e., cost-benefit), but there are few comparisons illustrate when one method is more appropriate than another (Strayer and Smith 2003). Multiple-pass surveys in 2014 documented an 80% reduction in the total catch of mussels at the substrates surface within the direct impact area, which was a primary objective. Further, the total catch in 2015 was nearly 80% less than the total catch in 2014. Conversely, a comparison of population estimates suggests the survey effort may not have been sufficient to deplete the population, including undetected mussels. Two factors could explain this pattern. The observed capture probabilities imply a portion of the population was overlooked even though population estimate confidence intervals were relatively small. The removal survey also coincided with a period of higher than median flow and lower water temperature, which may have resulted in a greater number of buried mussels. Mussel position (surface vs. buried) is influenced by multiple environmental variables (Amyot and Downing 1997). Mussels that went undetected during the removal in 2014 may have been at the surface in 2015 when flows were lower and temperature was higher.

Rates of mortality following mussel relocation have been high or difficult to quantify and is a major critique of using relocation as a conservation strategy (Cope and Waller 1995). We used population size and spatial distribution observed in baseline surveys to guide stocking of mussels at translocation sites in an attempt to reduce the potential that survival would be influenced by resource quality. Using this guide assumes that habitat with less mussels could be stocked with fewer additional mussels than habitat with more mussels (Hamilton et al. 1997, Bolden and Brown 2002). We observed negligible evidence of mortality in recaptured mussels one year after relocation, suggesting this assumption was at least partially valid. Declines in the intended population size after relocation at four of the five translocation sites while populations remained stable at control sites suggests that 1) a uniform stocking rate may not be appropriate and 2) the quality of habitat may influence survival of relocated mussels. There was also little movement detected among sites and a majority of movement within sites was to an adjacent section suggesting mussels remained bedded in the vicinity of their release. Together, these findings indicate that at least some of the potential effects of mussel relocation may have been minimized by following survey guidelines (e.g., Cope et al. 2003, Luzier and Miller 2009). Monitoring was conducted in a way that cannot evaluate short term mortality, but had it been high immediately after relocation we would expect to have recaptured more tagged shells.

We accomplished the initial steps of our secondary goal by designing and conducting the mussel relocation in a way that can monitor the fate of mussels over time. The success of past relocation efforts has been hampered by a lack of monitoring and poor recapture rates (Cope and Waller 1995). Recapture rates among sites ranged from 13% to 55% and were on average > 25%. Eight studies reviewed by Cope and Waller (1995) that relocated a comparable number of mussels (> 1000) to our study recovered on average 10% of those mussels. We observed recovery rates two to three times higher at all but one monitoring sites and found rates increased as mussel abundance increased. We propose this pattern may be a result of dividing our sites into smaller sections for surveying and relocation (e.g., Waller et al. 1993) rather than haphazard placement of mussels into translocation sites.

Incorporating PIT tags can improve recapture rate by including mussels that may be buried in the substrate (Kurth et al. 2007). However, we recovered ≤ 4 mussels at any monitoring site using the PIT tag reader to search for mussels undetected by visual surveys. We also did not recover any Creeper that we PIT tagged in 2014. As a result, we gained little additional demographic data by integrating telemetry technology. Its efficacy can be limited by the depth of buried mussels, water chemistry, mineral composition of substrate, or require further effort to detect mussels than we expended. We also observed a few mussels recaptured in the removal site with shattered PIT tags. A combination of insufficient encapsulation in adhesive and the distance traveled by these mussels likely contributed to tag damage.

Detecting rare mussel species requires considerable survey effort or complex sampling designs. Capture probability affects population demographic estimates and can vary by species, size, habitat, and season (Meador et al. 2011). In Midwestern streams, 2.5-4 person-hours were needed to detect all species present at 100 to 300-m-long sites (Metcalfe-Smith et al. 2000, Tiemann et al. 2009). In Mid-Atlantic streams, 1 person-hour was necessary to detect Eastern Elliptio at very low densities (< 0.001 mussels / m²) with high probability at 100 to 200-m-long sites (Strayer et al. 1997). How these relationships apply to species poor streams (i.e., Deer Creek) or smaller study sites is unknown. Most 10-m-long sections received at least 0.75 person-hours of total effort and just one 40-m-long monitoring site received < 3.00 person-hours of total effort, yet detection probabilities were variable among sites and no Creeper were recaptured. We detected Creeper within a section with as little as 0.33 person-hours of total effort, but up to 3.84 person-hours. We have no data indicating a majority of the Creeper population might be buried and undetectable by visual survey methods, although prior surveys in Deer Creek found 25% of Eastern elliptio were buried in the summer (U.S. Fish and Wildlife Service, unpublished data).

Lessons

Even after expending a considerable amount of survey effort in 2014, a higher than expected number of mussels was observed within the removal site the following year. Low detection probabilities may require additional survey effort (i.e., more time or passes) to truly remove the target percent of a population. Incorporating particular methods to improve detection in mussel removal surveys deserves further investigation.

Habitat with relatively low (< 50 mussels) or imprecise population estimates (CI > 50% N_{pop0}) may represent unsuitable relocation sites. As a precaution, lower stocking rates should be considered to avoid local relocation failure or the habitat should only be used to relocate mussels after more suitable habitat has been exhausted. Stream hydrology at T2 may have been altered by park visitors who created wing dams upstream for tubing.

Total survey effort > 1 person-hour may be needed at small scales (100 to 1000 m²) to detect species that exist at very low abundance with high probability since half of the Creeper collected were found during the second or third-passes. Their persistent presence highlights the importance of having recent survey data and an understanding of the data's limitations to make conclusions about species absence within impact areas.

An assessment of shell measurement variability should be made prior to conducting mussel removals to account for potential differences due to investigator. We noted a small number of large, recaptured mussels with shell lengths near a multiple of 10 (e.g., 79.2) with growth rates of ±10 mm between years. Given these animals are mature and near the asymptote of their expected growth curve such deviations were likely due to a measurement or error. Having investigators measure and then re-measure the same batch of mussels could quantify variability associated with how mussels are measured.

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Table 1. Population size and capture probabilities from freshwater mussel surveys in Deer Creek. Abundance estimates (± 95% confidence intervals) are calculated from two-pass surveys at removal and monitoring sites.

Site	Estimated abundance (±95% CI)		Capture probability	
	2014	2015	2014	2015
Removal	2,444±169	1,172±154	0.50	0.45
T1	83±15	322±70	0.64	0.54
T2	41±9	33±7	0.54	0.70
T3	42±67	77±42	0.31	0.44
T4	76±93	200±34	0.30	0.57
T5	49±17	129±31	0.57	0.54
C0	37±23	24±6	0.59	0.69
C1	274±44	277±66	0.55	0.47
C3	68±4	140±15	0.82	0.69
C4	-64±593	45±3	-0.13	0.84

Table 2. Section-by-section comparison of total mussel catch within the removal site.

Section	Number of mussels removed in 2014	Number of mussels observed in 2015	Difference in raw abundances	Percent of 2014 total catch observed in 2015
0 L	23	20	-3	47%
10 L	35	16	-19	31%
20 L	52	16	-36	24%
30 L	20	5	-15	20%
40 L	7	6	-1	46%
50 L	37	13	-24	26%
60 L	54	25	-29	32%
70 L	92	30	-62	25%
80 L	52	78	26	60%
90 L	64	47	-17	42%
100 L	62	23	-39	27%
110 L	442	31	-411	7%
120 L	111	86	-25	44%
130 L	39	51	12	57%
140 L	113	25	-88	18%
150 L	11	16	5	59%
160 L	13	8	-5	38%
170 L	34	8	-26	19%
180 L	58	20	-38	26%
190 L	142	37	-105	21%
200 L	100	29	-71	22%
210 L	62	45	-17	42%
220 L	37	34	-3	48%
230 L	14	12	-2	46%
240 L	31	7	-24	18%
250 L	34	9	-25	21%
260 L	113	13	-100	10%
270 L	71	8	-63	10%
280 L	59	9	-50	13%
290 L	69	6	-63	8%
300 L	109	12	-97	10%
310 L	13	13	0	50%
320 L	33	12	-21	27%
330 L	12	11	-1	48%
340 L	10	10	0	50%
350 L	6	9	3	60%
360 L	21	17	-4	45%
Total	2,255	817	-1,438	27%

Table 3. Summary of mussel relocation monitoring effort by survey site. The number of mussels each translocation sites could approximately receive in addition to existing populations was calculated from two-pass population estimates ($N_{pop0} + N_{pop0}$ x 3) based on recommendations of Cope et al. (2003).

Site	No. collected 2014	No. mussels relocated	No. PIT tagged 2014	No. collected 2015	No. PIT tagged 2015	No. recaptured (%)
T1	72	248	53	254	63	122 (38)
T2	36	125	28	30	8	21 (13)
T3	22	133	21	53	10	31 (20)
T4	39	224	55	162	34	23 (26)
T5	40	145	60	102	26	52 (29)
C0	31	---	6	22	11	8 (26)
C1	220	---	57	200	55	85 (39)
C3	66	---	16	126	29	36 (55)
C4	17	---	17	44	16	4 (24)

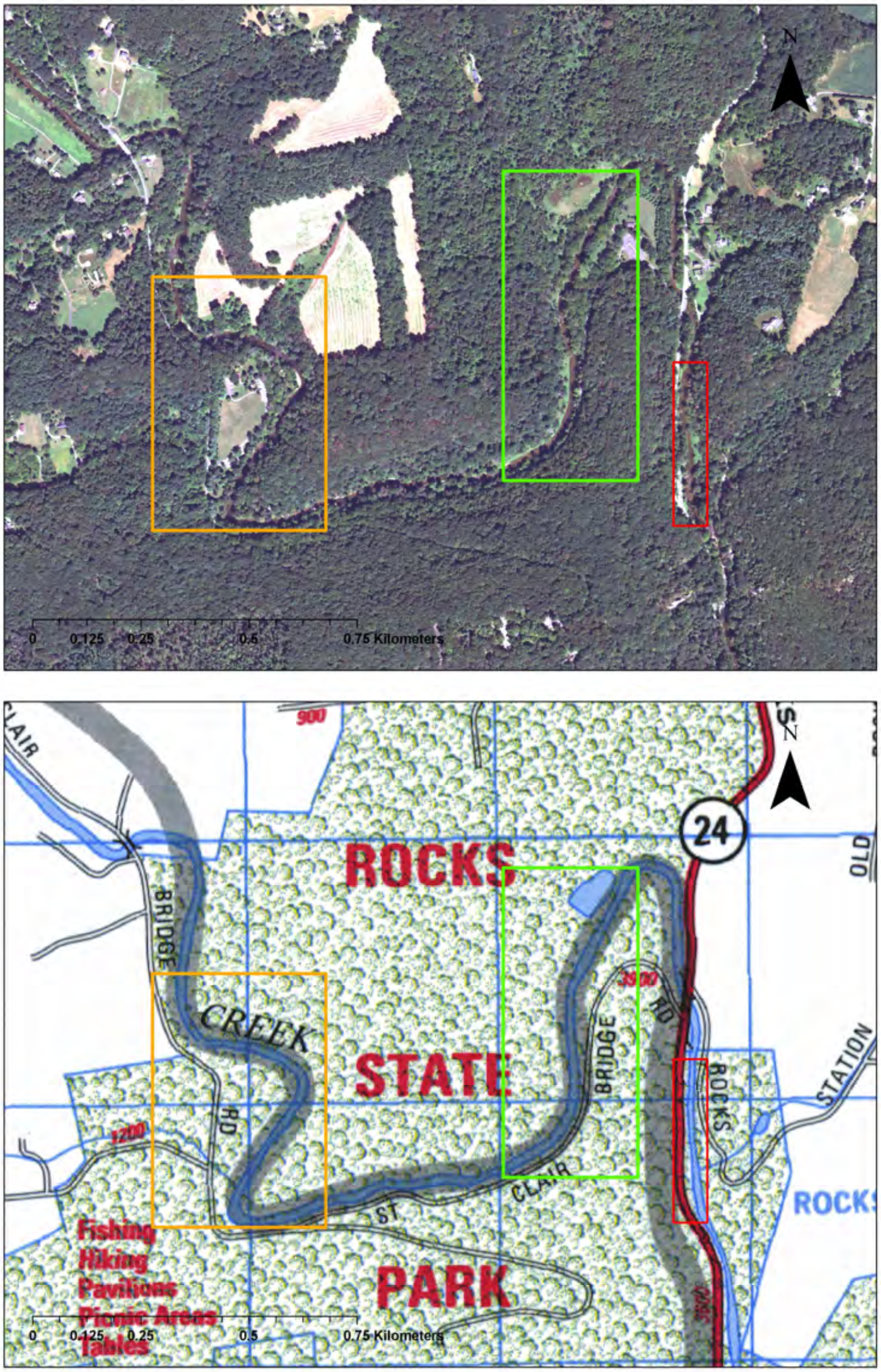


Figure 1. Freshwater mussel relocation study area, Harford County, Maryland. Approximate location of survey and monitoring areas are denoted in orange (control), green (translocation), and red (removal).

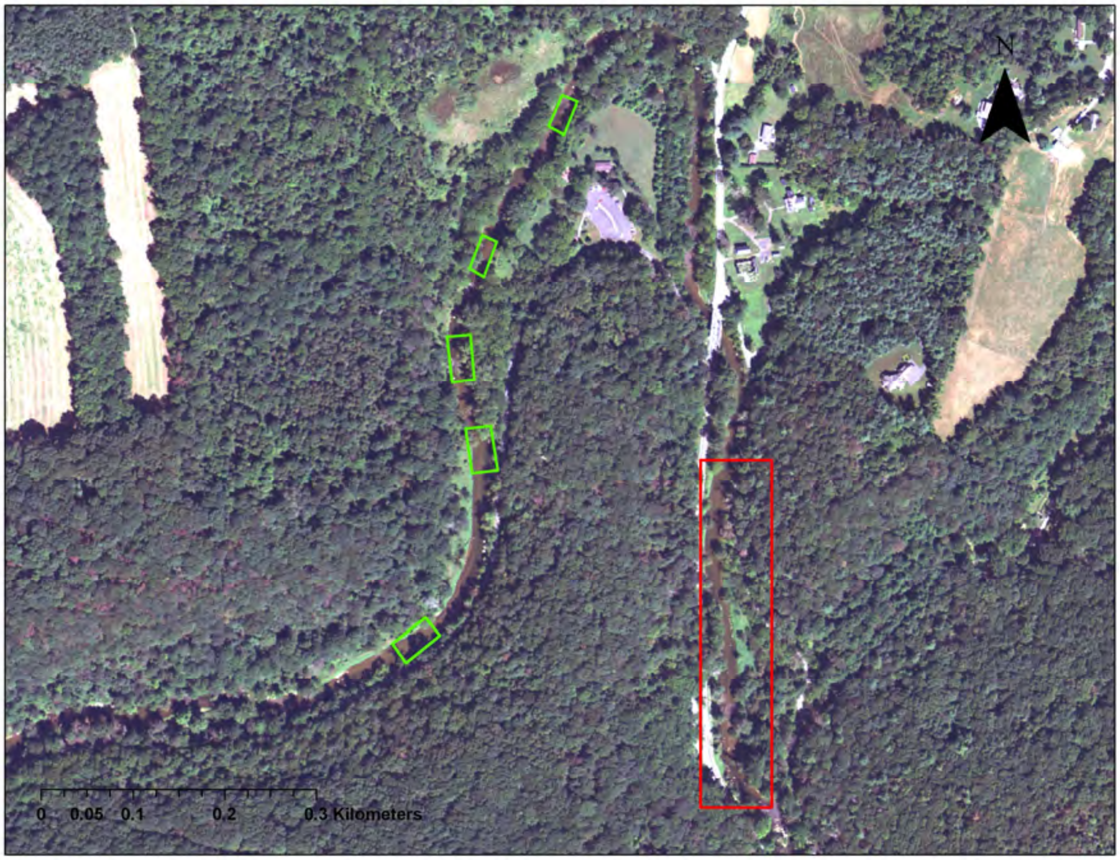


Figure 2. Locations of freshwater mussel translocation (green) and removal (red) sites in Deer Creek, Harford County, Maryland.

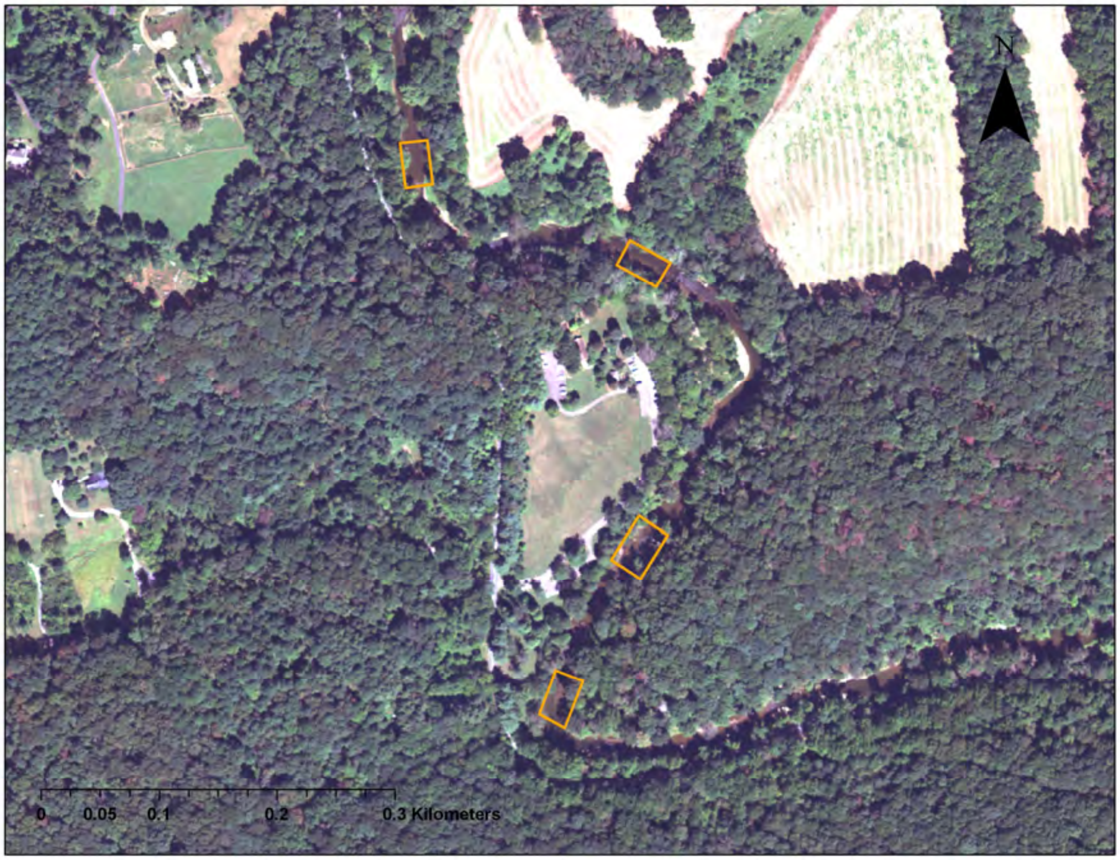


Figure 3. Locations of freshwater mussel control monitoring sites (orange), Deer Creek, Harford County, Maryland.

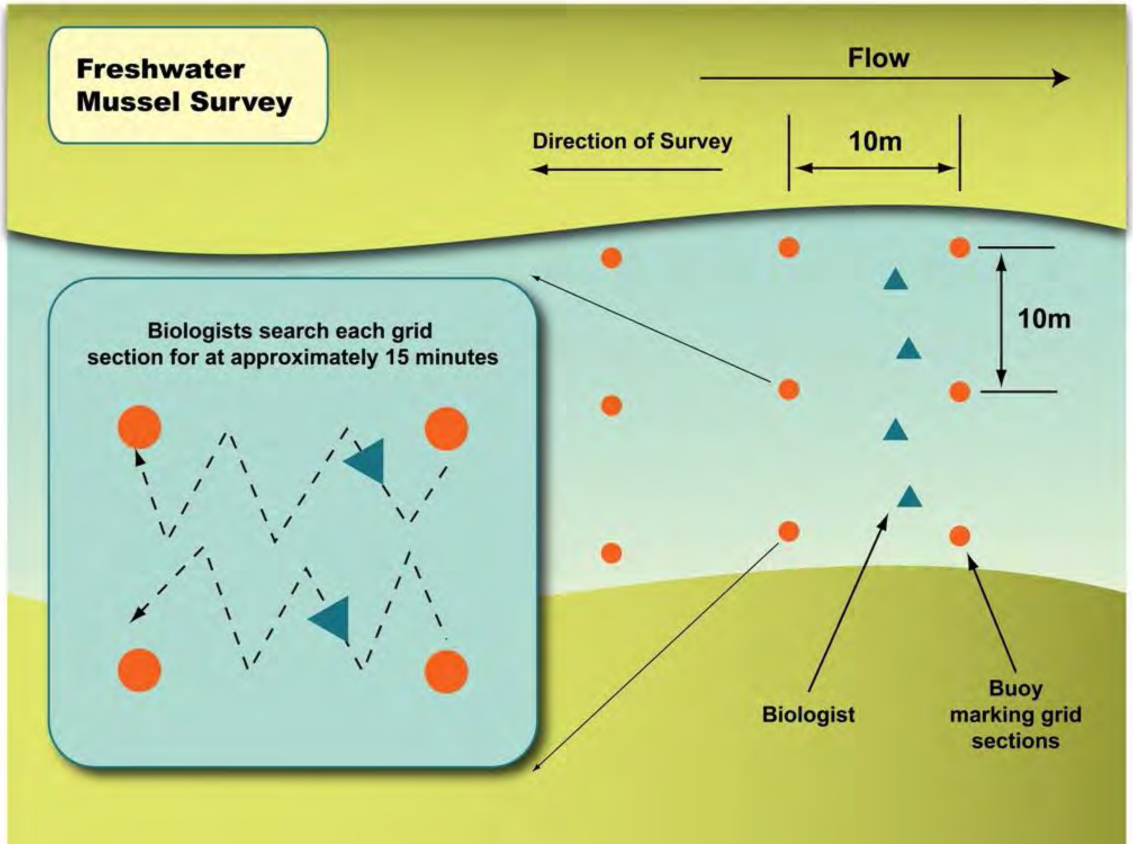


Figure 4. Schematic of a mussel survey pass within a section.

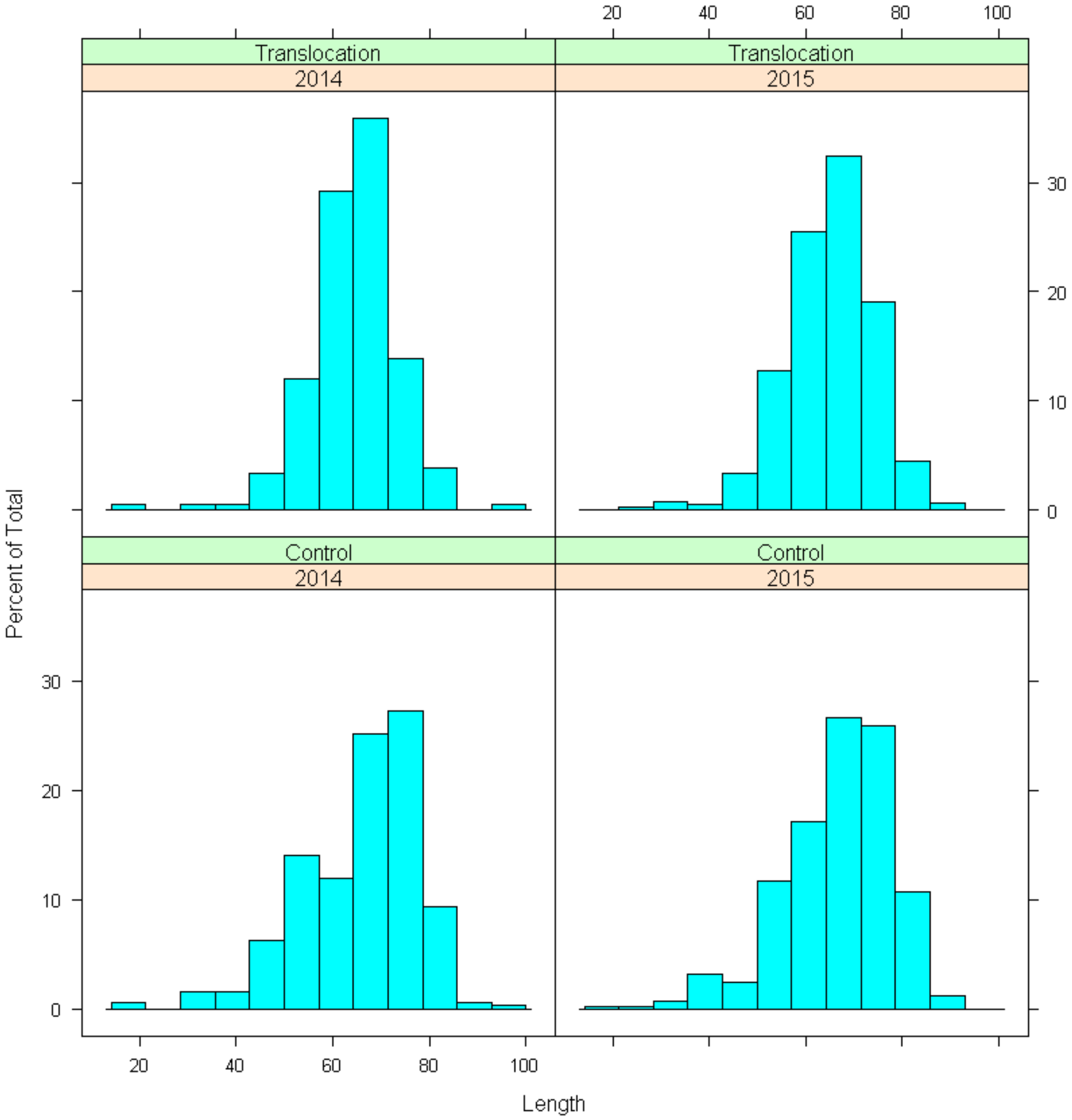


Figure 5. Length-frequency distribution of Eastern elliptio by survey and sites.

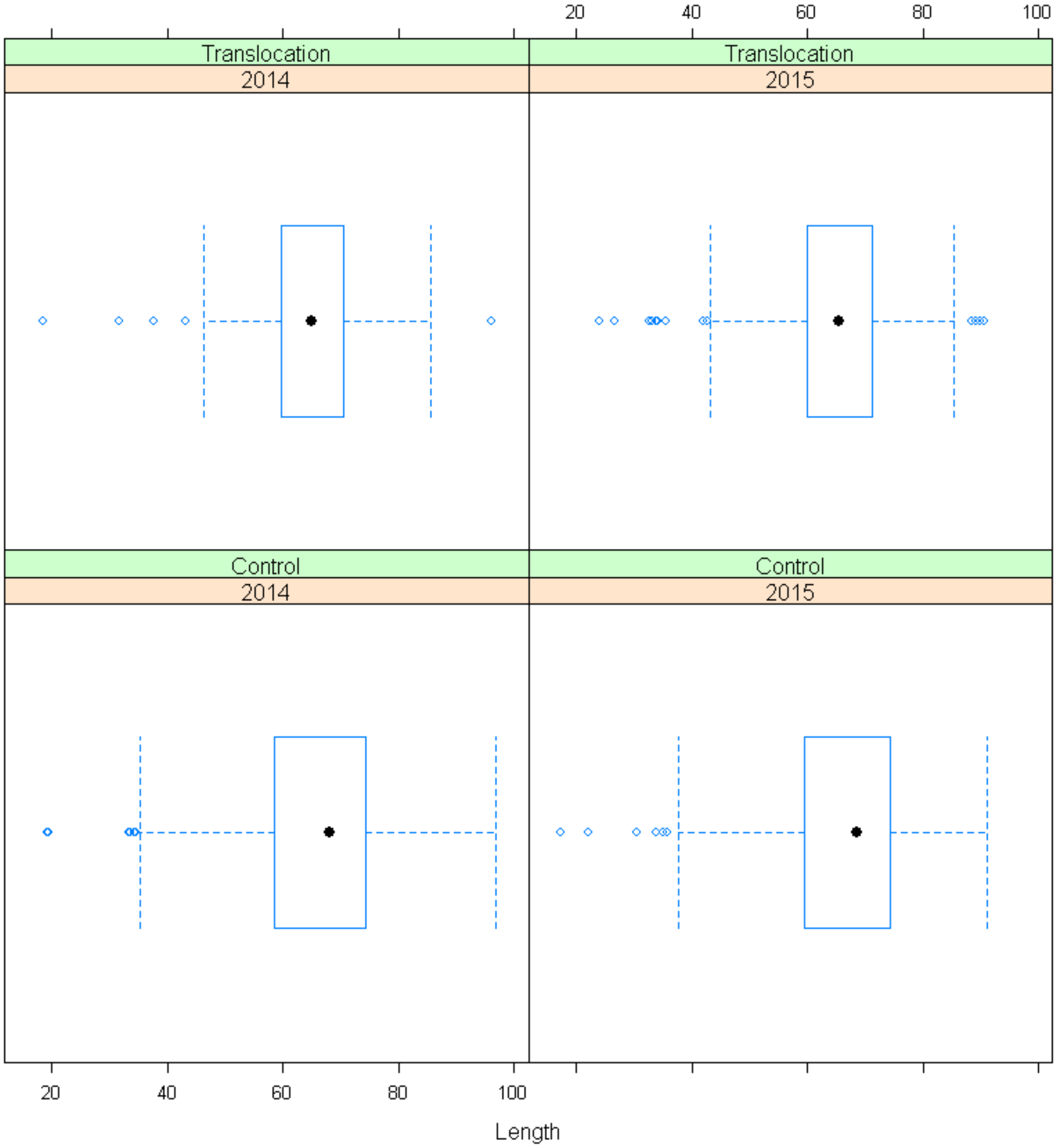


Figure 6. Box-and-whisker plots of Eastern elliptio shell lengths collected at control and translocation sites.

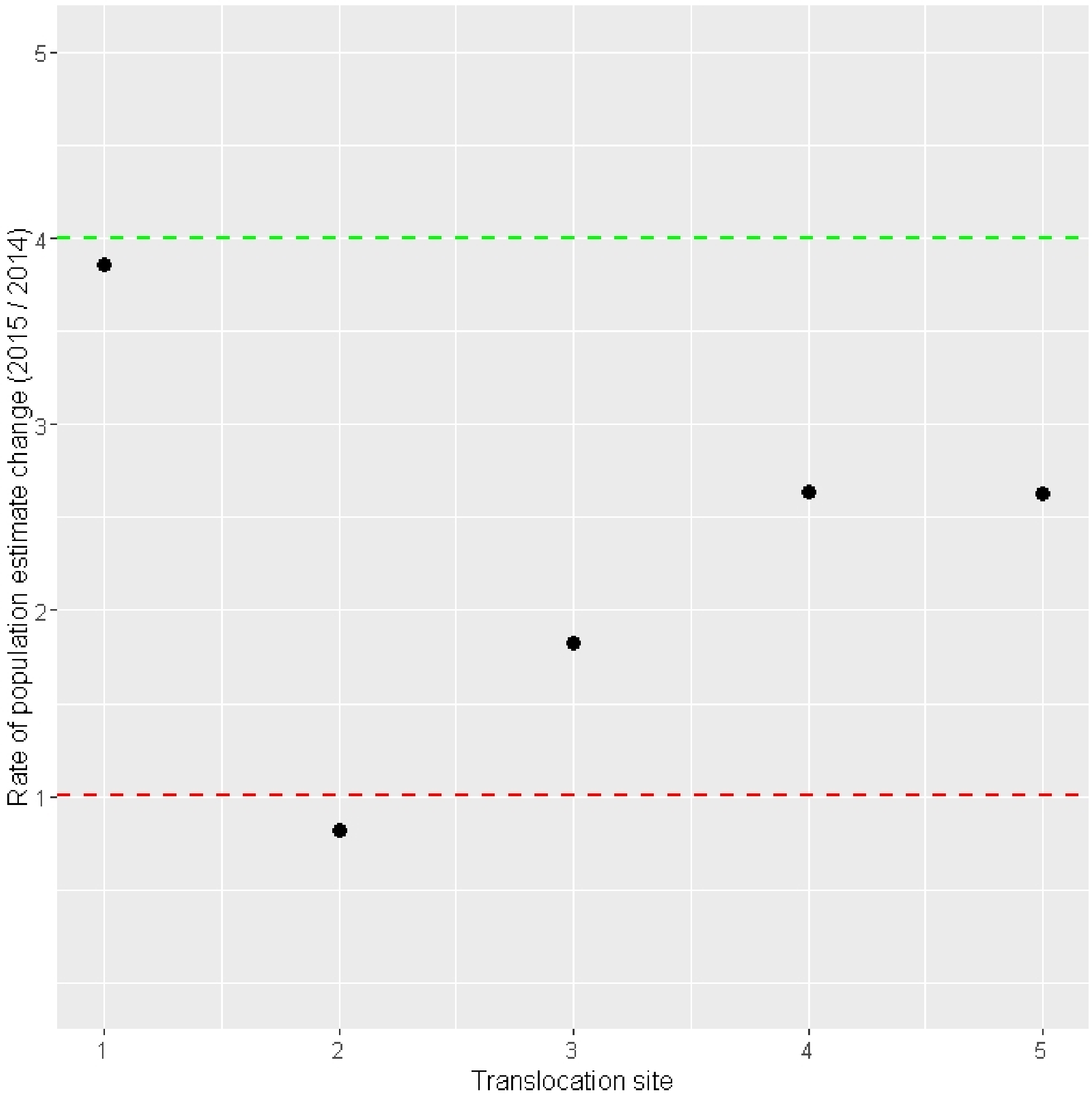


Figure 7. Rate of change in estimated mussel population size between 2015 and 2014. The dashed green line indicates the rate of population change from baseline surveys at all translocation sites following the mussel relocation in 2014 (N_{pop0} + N_{pop0} x 3). The red dashed line indicates the median rate of population change observed at control sites between 2015 and 2014.

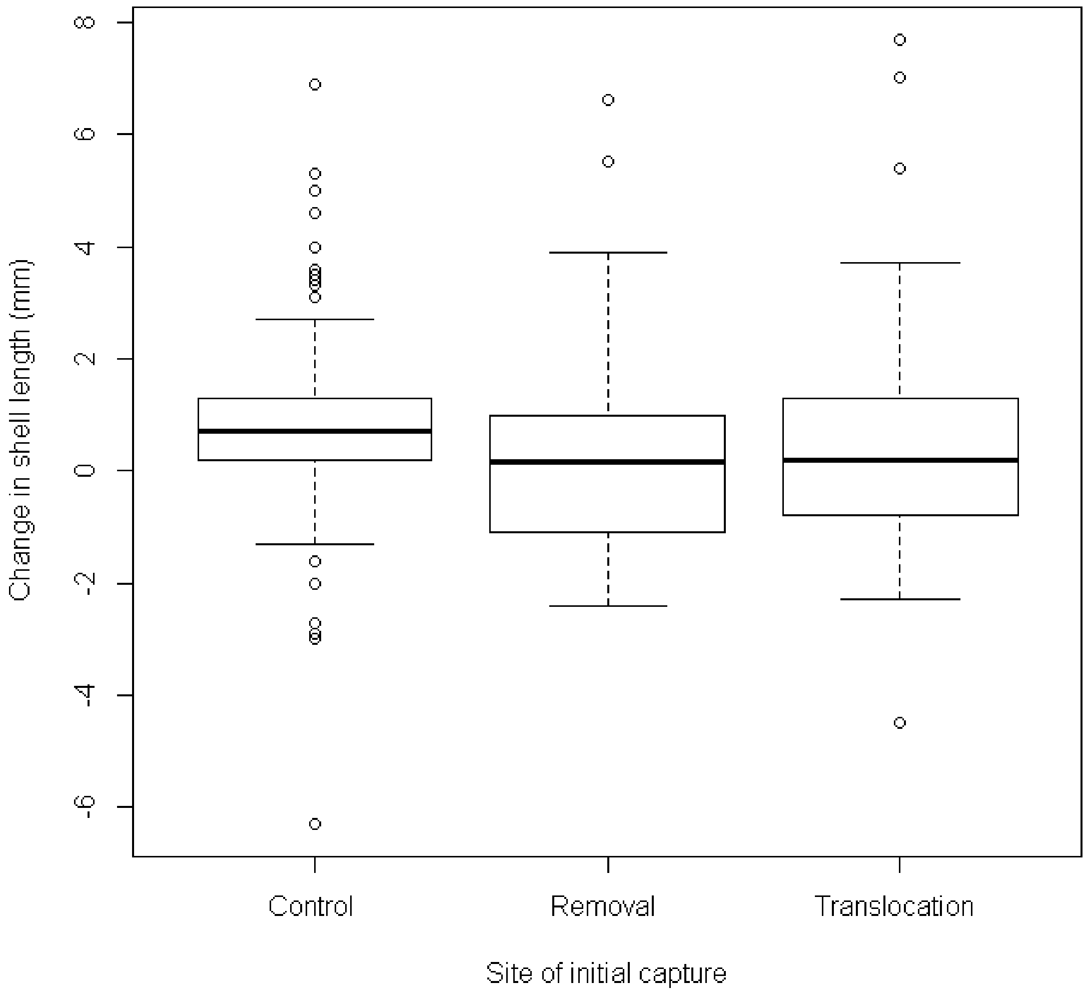


Figure 8. Box plots illustrating the change in shell length (mm) from 2015 to 2014 ($L_1 - L_0$) in mussels recaptured at control sites and translocation sites by their site of initial capture. Mussels initially captured at the removal site were relocated to translocation sites in 2014 and recaptured in 2015.

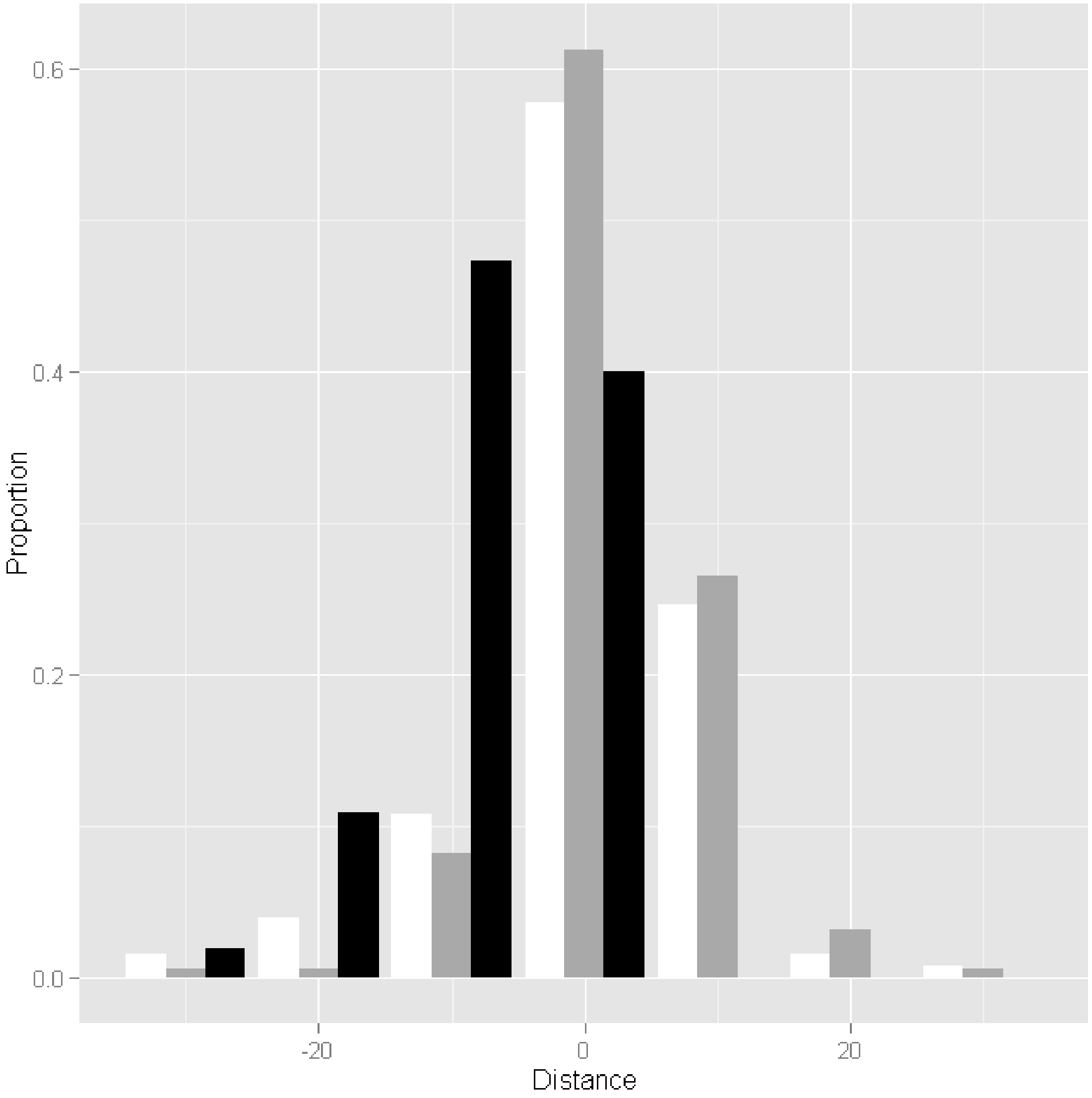
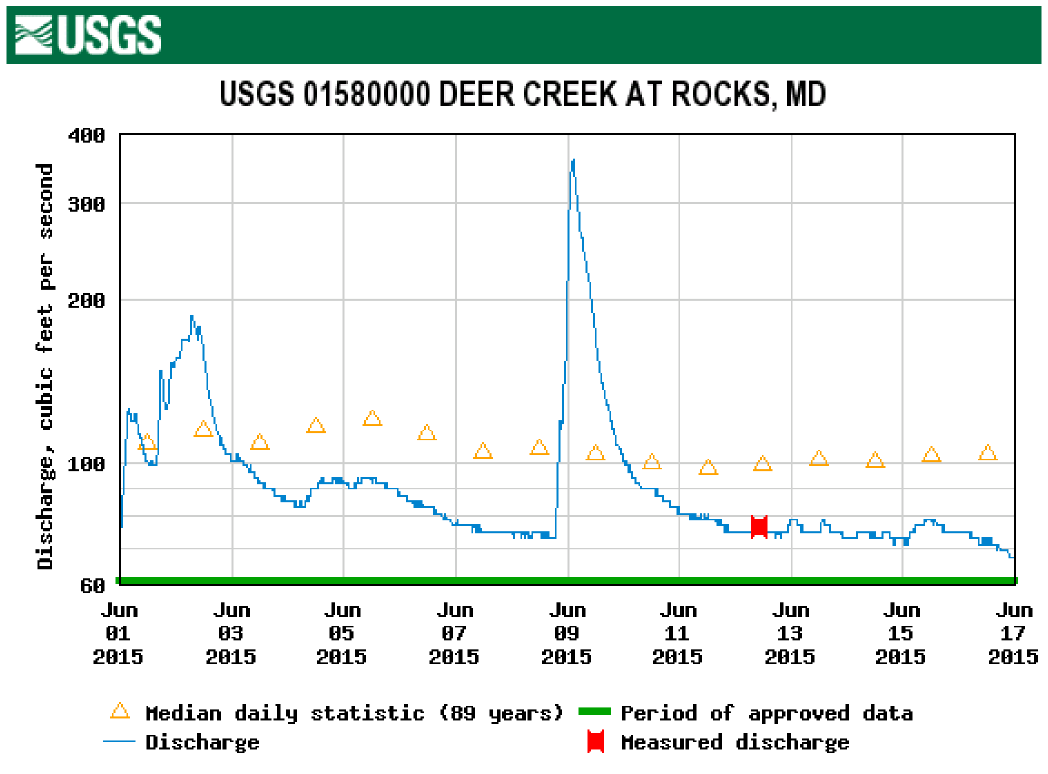
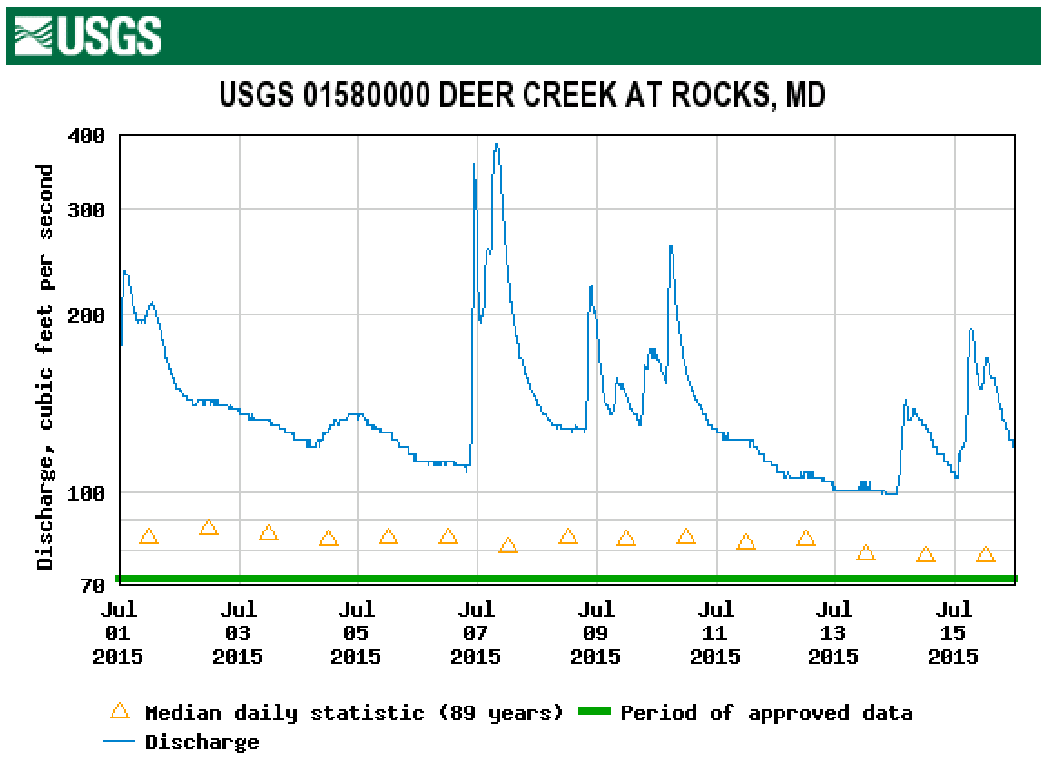
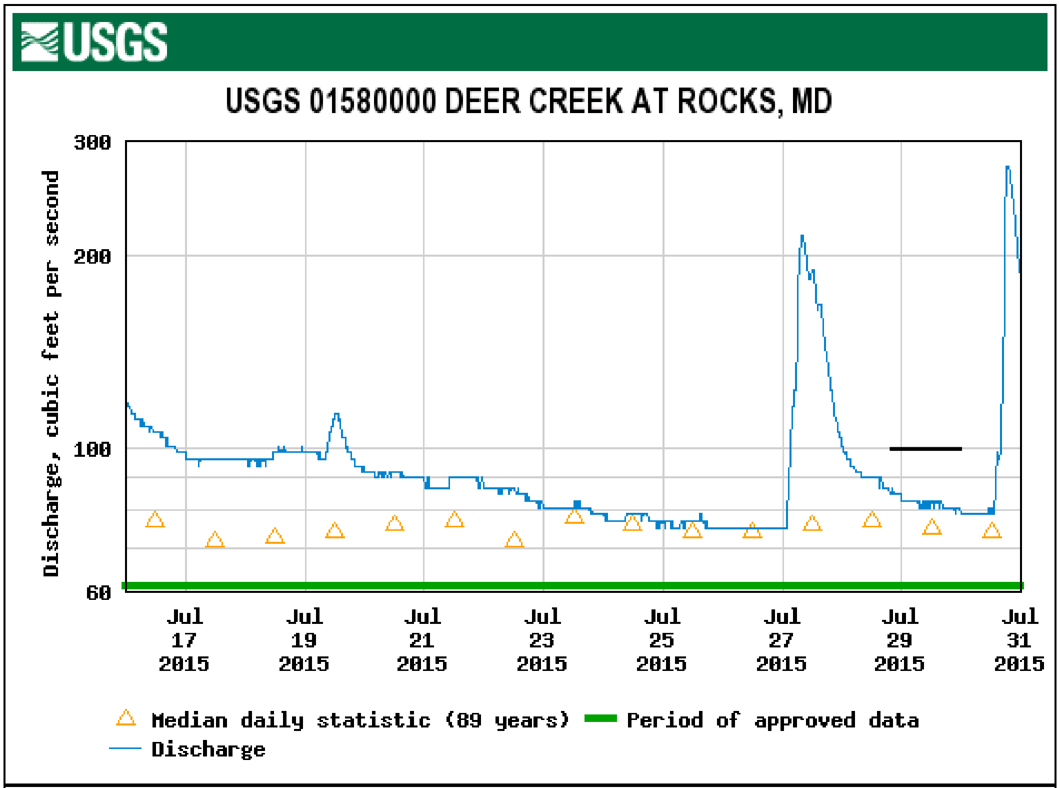


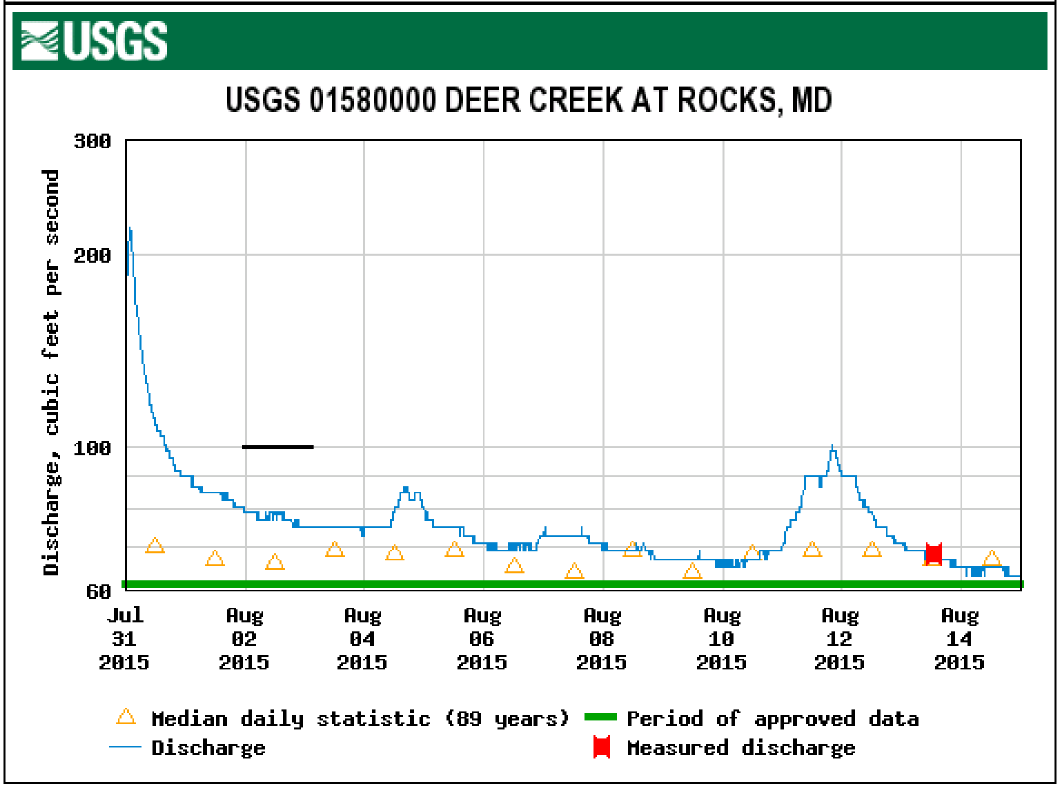
Figure 9. Proportion of mussels collected in baseline surveys of translocation (white) and control (black) sites or relocated into translocation sites (gray) that were recaptured (2015) in a different section than the section they were released (2014). Negative values of distance (meters) represent recapture in a section that was downstream of the release section and positive values of distance represent recapture in an upstream section.

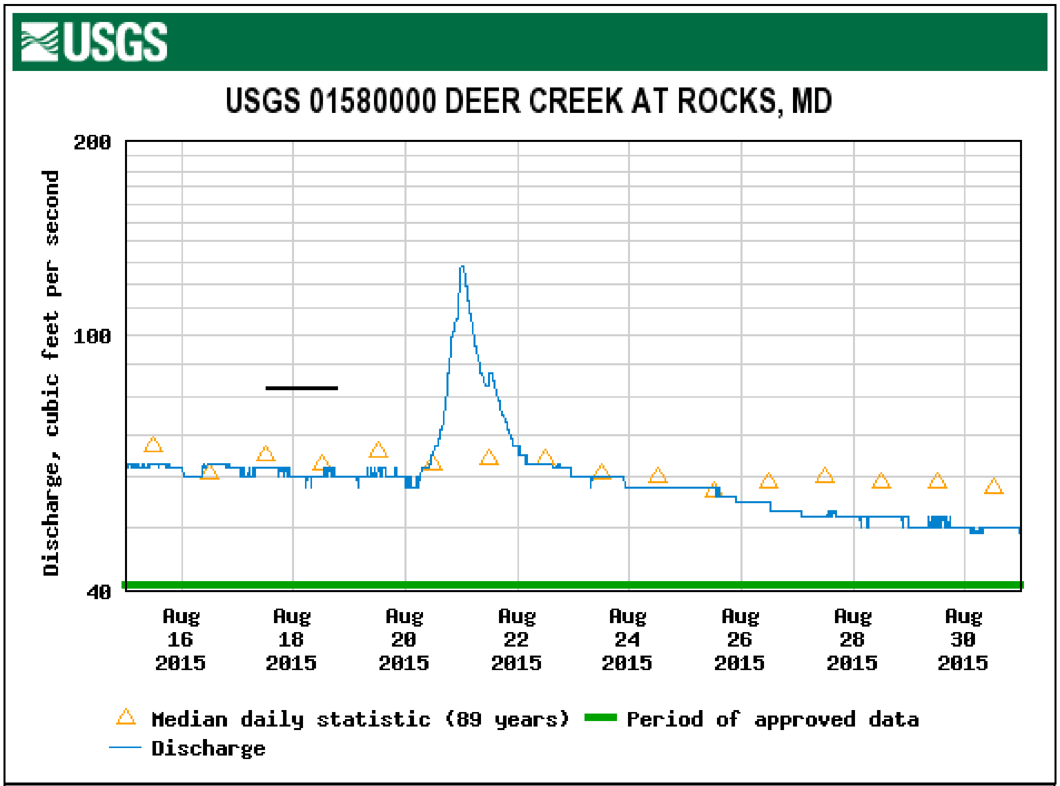
Appendix I. Stream discharge in Deer Creek at Rocks, Maryland. Gauging station (01580000) is located approximately 1.5 stream kilometers downstream of removal site. Hydrographs are broken into two-week intervals from June 1 to September 15. Survey periods are denoted with black horizontal lines.

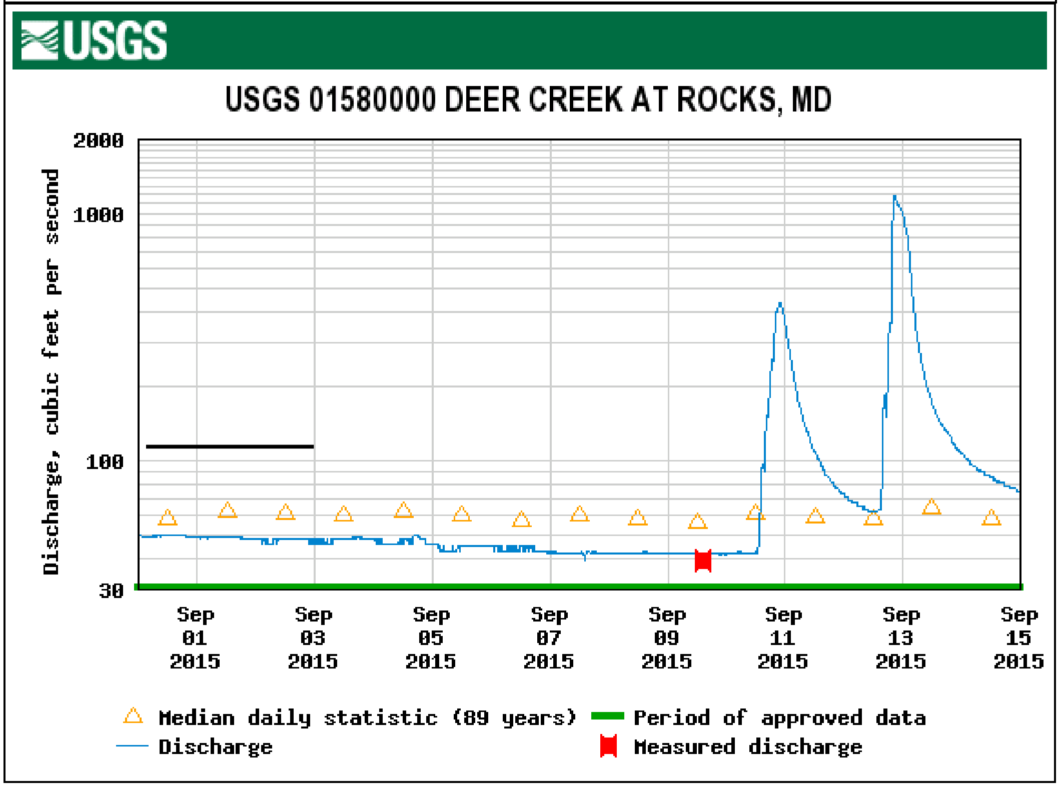





USGS
USGS 01580000 DEER CREEK AT ROCKS, MD
Discharge, cubic feet per second
300
200
100
60
Jul 17 2015
Jul 19 2015
Jul 21 2015
Jul 23 2015
Jul 25 2015
Jul 27 2015
Jul 29 2015
Jul 31 2015
△ Median daily statistic (89 years)
Period of approved data
Discharge


USGS
USGS 01580000 DEER CREEK AT ROCKS, MD
Discharge, cubic feet per second
300
200
100
60
Jul 31 2015
Aug 02 2015
Aug 04 2015
Aug 06 2015
Aug 08 2015
Aug 10 2015
Aug 12 2015
Aug 14 2015
△ Median daily statistic (89 years)
Period of approved data
Discharge
Measured discharge


USGS
USGS 01580000 DEER CREEK AT ROCKS, MD
Discharge, cubic feet per second
200
100
40
Aug 16 2015
Aug 18 2015
Aug 20 2015
Aug 22 2015
Aug 24 2015
Aug 26 2015
Aug 28 2015
Aug 30 2015
△ Median daily statistic (89 years)
Period of approved data
Discharge


USGS
USGS 01580000 DEER CREEK AT ROCKS, MD
Discharge, cubic feet per second
2000
1000
100
30
Sep 01 2015
Sep 03 2015
Sep 05 2015
Sep 07 2015
Sep 09 2015
Sep 11 2015
Sep 13 2015
Sep 15 2015
△ Median daily statistic (89 years)
Period of approved data
Discharge
Measured discharge