THE EFFECTS OF IMPERVIOUS SURFACE, GEOMMORPHOLOGY, AND STREAMBED SCOUR DEPTH ON ESSENTIAL BROOK TROUT HABITAT

by

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B.S. (Sacred Heart University) 2014

THESIS

Submitted in partial satisfaction of the requirements

for the degree of

MASTER OF SCIENCE

in

ENVIRONMENTAL BIOLOGY

in the

GRADUATE SCHOOL

of

HOOD COLLEGE

December 2017

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ABSTRACT

Results of this study determined whether percentage of impervious land cover and geomorphology within the upstream drainage area of designated field sites would be predictive of average scour depth and whether this scour depth would have the potential to affect essential brook trout habitat. Impervious land cover in the upstream drainage area of all field sites, reach-level geomorphological data, and scour measurements collected throughout the summer and fall semesters of 2015 and the spring semester of 2016 were analyzed to determine any predictive or correlative relationships between brook trout density and stream geomorphology. These data were compared to total and young of the year (YOY) brook trout density data obtained from the Maryland Department of Natural Resources (MD DNR) and Maryland Biological Stream Survey (MBSS).

A Pearson correlation matrix and simple linear regression were used to analyze data within this study. Analyses showed brook trout density to be positively correlated with stream gradient and negatively correlated to impervious land cover. Total and YOY brook trout were negatively correlated to percent impervious cover ($p < 0.05$). Only total brook trout was positively correlated to stream gradient ($p < 0.05$). This indicated brook trout density to be predicted by percentage of impervious land cover and stream gradient. Additionally, pebble count modes were significantly correlated to stream gradient ($p = 0.01$). Scour depth, width to depth ratio, pebble count, and upstream drainage area were not statistically correlated to brook trout density in this study.

ACKNOWLEDGEMENTS AND SPONSORSHIPS

First and foremost, I would like to thank God, whose many blessings have made me who I am today. I would also like to thank my family for always believing in me and encouraging me to follow my dreams. The following document summarizes nearly four years' worth of effort and achievement. Undertaking this M.S. has been an eye-opening experience and it would not have been possible to complete without the support and guidance I have received from many individuals.

I would first like to acknowledge the funding received towards my thesis from the Washington Biologists' Field Club 2015 Research Awards. Next, I would like to extend a sincere thanks to my thesis adviser Dr. M. Drew Ferrier for the support he has given me, during the long months spent undertaking field work and time spent reviewing the contents of this document. Without his guidance and constant feedback, this thesis would not have come to fruition.

Many thanks to Dr. Eric R. Annis, Dr. Jeff Feaga, and Mrs. Claire Hudson for their relentless efforts in guiding me through the conception, research, and writing of this thesis. Their patience and support were essential in the creation of this graduate level document and my formation as a future researcher. I am also, grateful to Mr. Randy Smith for his support as a Geographic Information Systems (GIS) specialist. A very special thank you to Dr. April M. Boulton for her invaluable advice and support throughout my time as a graduate student at Hood College. Lastly, I am very grateful to Hannah Zinnert, Ashley McAvoy, and Dianna Loescher for their help during various stages of my thesis.

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INTRODUCTION

Brook trout (*Salvelinus fontinalis)* are native to eastern North America. Their distribution extends as far west as Minnesota and as far south as the mountains of Georgia. They migrate upstream, spawn from mid-October to early December, and leave their eggs in gravel nests (redds) to develop throughout the spring months (MD DNR 2006). Fall–spawning brook trout are most sensitive to changes in scour depths due to increased discharge and scour associated with winter precipitation and floods (Tonina et al. 2008). The historical range of brook trout encompasses the northeast, mid-Atlantic, and a portion of the southeast region of the United States (US) (Hudy et al. 2008; Figure 1). In Maryland, there are 100 streams containing self-sustaining native brook trout populations, with a portion of these streams located in the Catoctin Mountains of Frederick County (Heft 2014).

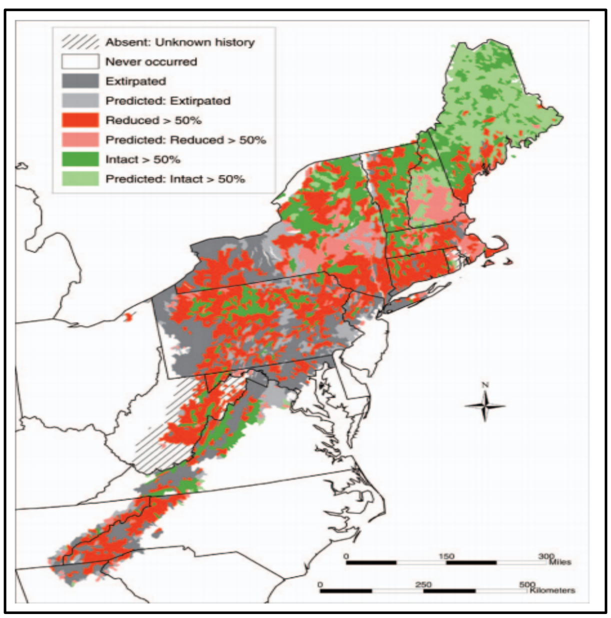

Figure 1. Brook trout distribution and status throughout its eastern range of the US. Figure from Hudy et al. 2008 used with permission.

Brook trout are Maryland's only native freshwater charr species and are valuable to Maryland due to their aesthetic, recreational, economic, and biological benefits. Anthropogenic changes to Maryland's environment such as deforestation, establishment of large agricultural areas, and urbanization have led to the extirpation of brook trout from 62% of their historic habitat in Maryland (MD DNR 2006). As a biologically important species, they impact diverse relationships between many aquatic and terrestrial organisms occupying similar habitats. Therefore, the loss of brook trout is indicative of negative changes within habitats and the overall ecosystem (MD DNR 2006). While the impact of increased temperature and urbanization is currently under investigation in Maryland, scour is a factor that could be influencing brook trout success that has not been investigated extensively in Maryland. The impact of this factor could partly explain the action of the Maryland Department of Natural Resources (MD DNR) to list brook trout as a "Species of Greatest Need of Conservation" (Heft 2014).

Links between Scour, Infiltration of Fine Sediments, and Brook Trout Success

Scour is a natural process leading to the premature removal and transport of streambed sediment, which if deep enough, can dislodge brook trout eggs and newly spawned trout with yolk intact (alevins) from redds. Measurement of streambed scour and fill is necessary to improve the understanding of spawning habitats and dynamics (Lachance et al. 2008; Nawa and Frissell 1993). Substrate type is among the most important characteristics in site selection for brook trout spawning. Brook trout bury their eggs an average of 8 cm deep. Eggs incubate through the winter months and hatch in early spring (Heft 2014). Female brook trout use their tail fins to construct a shallow depression (redd) in the sediment (Hartman and Hakala 2006). This redd is then covered by the female brook trout using nearby gravel. Most spawning size gravel is stored in riffles with finer sediment being found in pools. The ideal size range for spawning gravel has been cited by different sources with similar ranges covering similar orders of magnitude. Hartman and Hakala (2006) approximate the range to be between 4-32 mm and DeVries (2008) reported a range of 4-78 mm. Sediment size < 4 mm appears to be associated with a diminished rate of brook trout reproduction (Hartman and Hakala 2006). Fine sediments infiltrate through redds, lowering the supply of oxygen to developing eggs and alevins (Louhi et al. 2008). Sedimentation is detrimental to spawning sites of brook trout. Low abundance of accessible, good-quality spawning sites can limit recruitment of this species (Lachance et al. 2008).

Baxter and McPhail (1999) studied depth of scour using artificial redds made of 12 cm x 2 cm of stainless steel capsules. The ends of the artificial redds were covered with plastic caps with 2 mm holes drilled into them to allow for water and oxygen flow. In addition, a male and female bull trout (a close relative of brook trout) were captured and their eggs and sperm were extracted and combined. Fifty capsules were filled with small to medium size gravel (5-30 mm) as well as 30 fertilized eggs and buried to 10 cm, 20 cm, and 30 cm. The capsules were retrieved after 195 days. The results of the experiment noted all redds buried to 10 cm were completely scoured leaving the remaining artificial redds untouched. These data support a range of scour depths affecting redds to be anywhere from 0-19 cm. The depth of average bull and brook trout egg burial and the scour depths measured using artificial redds suggests the deeper brook trout bury their redds, the less likely they are to be impacted by scour (Baxter and McPhail 1999). Steen and Quinn (1999) noted a relationship between redd burial depth and size of a spawning female. In their study, larger females buried their eggs deeper relative to the original substrate level than smaller females (Steen and Quinn 1999). Suitable streams for spawning and egg incubation play a key role in the life cycle of stream-dwelling brook trout. However, anthropogenic impacts, such as urbanization, forestry, and agriculture have destroyed stream habitats, reducing the success of natural fish reproduction. At reach-scale, brook trout prefer spawning in pool-riffle transition zones avoiding step pools and cascades (Louhi et al. 2008).

Brook trout survival is influenced by scour and subsequent sedimentation due to the long intragravel time spent as developing embryos. The two primary mechanisms leading to reductions in brook trout success are entombment and asphyxiation. Scour facilitates the infiltration of fine sediment following periodic spates, indirectly influencing mortality by entombing redds and suffocating the developing eggs within. The entombment of redds decreases water flow which inhibits waste removal and oxygen delivery to developing embryos. Entombment occurs when macropores used by larvae to emerge from their redds are too small or have been clogged with fine sediment. Entombment occurs due to post-spawning deposition of fine sediment within the interstitial spaces of a redd. Frassen et al. (2012) determined entombment to be negatively related to the amount of fine substrate in a surrounding area (DeVries 2008). Asphyxiation is related to the flow of oxygen throughout the redd microhabitat and occurs at any stage of brook trout development when the concentration of oxygen drops below critical thresholds for survival. Vigorous scour can also lead to the transport of sediment away from redds, potentially dislodging eggs and alevins (Frassen et al. 2012).

Scour, fill, and infiltration are cyclic processes with direct impacts on each other and potentially direct impacts on essential brook trout habitat.

Links between Brook Trout and Land Use Changes

Impervious lands are those covered by materials such as concrete, asphalt, and rooftops or are the result of severe compaction of soils, all of which restrict infiltration. Percent impervious cover is typically low in natural landscapes, intermediate in agricultural landscapes, and high in urban landscapes. Percent impervious cover is a metric that integrates various types of human development activities in watersheds. Transitions from natural forest cover to agricultural and urban landscapes have resulted in increased impervious cover and have led to reduced infiltration of precipitation into soils and increased runoff (Stanfield and Kilgour 2006). Stanfield and Kilgour (2006) found fish species' richness declined linearly with impervious cover, such that catchments with more than 10% impervious cover were either severely impaired or fish species were absent. Even low percentages of impervious cover significantly altered flow patterns, and after reaching 6% impervious cover, there was an irreversible loss of aquatic system function (Stanfield and Kilgour 2006). Stanfield and Kilgour (2006) suggested locally applied best management practices (BMPs) and restoration activities to be most effective when applied to streams with less than 10% impervious cover (Stanfield and Kilgour 2006).

The current socioeconomic environment favors the conversion of agricultural land to urban and residential land. As agriculturally dominated watersheds become urbanized, the increase in impervious land cover becomes a major controlling factor of watershed hydrology. This increase in impervious land cover decreases overall hydraulic efficiency in streams and their watersheds. Precipitation falling on rooftops and pavement of newly urbanized land quickly runs off instead of infiltrating into the soil as it would do on a natural or farmed landscape (Pappas et al. 2008). Land use change and subsequent habitat degradation is a dominant driver in global biodiversity declines across multiple ecosystems. Distinct patterns of fish species' responses to land use exist among contiguous regions in Maryland and brook trout are one of the most highly sensitive species in relation to impervious land cover across the state of Maryland (Utz et al. 2009).

Impervious land cover has unique properties as a watershed metric in that it can be measured, tracked, forecasted, managed, priced, regulated, mitigated, and traded. In addition, impervious land cover is a common currency understood and applied by watershed planners, storm water engineers, water quality regulators, economists, and stream ecologists (Schuler et al. 2009). Within a watershed, impervious cover leads to major changes in organismal distribution along with rapid and dramatic degradation of ecosystems (Wang et al. 2001). Recent brook trout declines in Maryland streams have been attributed to less than 2% of total impervious land cover (Stranko et al. 2008). Distance of impervious cover from streams and the amount of directly connected impervious cover are other important factors when estimating the impact of impervious cover on stream ecosystems (Wang et al. 2001).

Land use activities are a primary driver of stream hydrology, channel geomorphology, water quality, and biodiversity. Initial reductions of brook trout range in the late 1960s were attributed to pollution, siltation, and temperature increases caused by land use changes (Stranko et al. 2008). Understanding how land use within a watershed influences a stream's ecosystem provides an important tool for the development of appropriate land management strategies to improve and maintain stream quality (Wang et al. 2001).

As topographical low points in the landscape, streams collect and disperse water, sediment, and heat, integrating changes throughout watersheds, making them highly sensitive to anthropogenic disturbances such as urbanization (Nelson et al. 2009). Landscape alterations, including forest clearing, agriculture, and urbanization, have led to the physical and chemical degradation of stream habitats. Minimal levels of development, agriculture, and deforestation substantially alter hydrological and biological stream conditions (Stranko et al. 2008).

Upper Monocacy Watershed Characterization

A characterization conducted by Frederick County and the MD DNR led to the identification of 38 streams within the Upper Monocacy Watershed in need of better watershed management, development, and protection (MCWA 2005). Water quality impairments affecting these areas include excess nutrients, sediment, and fecal coliform bacteria. Impaired water quality in the Upper Monocacy Watershed is a direct result of agriculture, business and residential expansion, municipal practices, and air pollution. The watershed is comprised of 45% forest and 45% agriculture, including large dairy and beef operations, orchards, horse farms, and crop farms (Schultz et al. 2005). Urban land use comprises the remaining 10% and is expanding rapidly. Urban land use includes municipalities and unincorporated areas with residential, commercial, or industrial development. Impervious cover is also expanding in watersheds of naturally reproducing trout streams including Hunting and Owens Creeks near Thurmont, MD (Schultz et al. 2005).

In the Upper Monocacy Watershed, many streams in the Catoctin Mountains support high-quality cold-water fisheries with the ability to sustain naturally reproducing brook trout populations. As these streams flow into lowland areas, their temperature increases in streams with lower gradients, less canopy cover, less riparian buffer, and more impacts from agriculture and urban development. Hunting Creek has naturally reproducing brook trout and brown trout populations. Fishing Creek is an excellent fishery for native brook trout in both the right (Little Fishing Creek) and left (Steep Creek) branches above the reservoir in the City of Frederick Municipal Forest. Clifford Branch has small populations of native brook trout in headwater areas, which are mostly forested (MD DNR 2005).

Objectives

The objectives of this study were to determine if there are significant relationships and correlations between essential brook trout habitat and geomorphological variables. The geomorphological variables noted in this study included scour, percent impervious cover, sediment size, channel width to depth ratio, stream gradient, and upstream drainage area.

In this study, the following hypotheses were investigated: (1) watersheds with greater percentages of impervious cover would be predictive of greater scour depths and lower brook trout densities and (2) stream reaches with scour depths greater than 8 cm would have lower brook trout densities. It was predicted that: (1) percent impervious cover and scour depth would be positively correlated, (2) brook trout density and percent impervious cover would be negatively correlated, and (3) brook trout density and scour depth would be negatively correlated.

MATERIALS AND METHODS

Sampling Sites

In coordination with the USGS and MD DNR, 14 field sites were selected within Little Antietam Creek, Hunting Creek, Steep Creek, Fishing Creek, Little Fishing Creek, Clifford Branch, Tuscarora Creek, Little Tuscarora Creek, and Rock Creek watersheds of Frederick and Washington counties, Maryland (Figure 2). Each sampling site comprised a 50-foot reach. Stream reaches were chosen based on MD DNR brook trout sampling sites and qualitative characteristics likely to support brook trout redds. These characteristics included stream flow, sediment distribution, water depth, stream gradient, and the presence of alternating riffles and pools. Stream reaches were considered to be representative of an entire stream system based on the characteristics noted above.

Sites expected to have a greater percentage of impervious cover were along Tuscarora, Little Tuscarora, and Rock Creeks. These sites were primarily in urban areas, along major highways, and within residential neighborhoods. Sites expected to have a lower percentage of impervious cover were along Clifford Branch, Little Antietam, Hunting, Steep, Little Fishing, and Fishing Creeks. These sites were primarily in rural areas surrounded by minimal residential development and minor roadways. Dominant land uses surrounding field sites included forest, agriculture, and residential land based on the Maryland Department of Planning 2010 Land Use/Land Cover dataset (Figure 3). Primarily forested land cover surrounded the five northern-most sites. When traveling south, increased amounts of agricultural and residential land surrounded the nine additional sites.

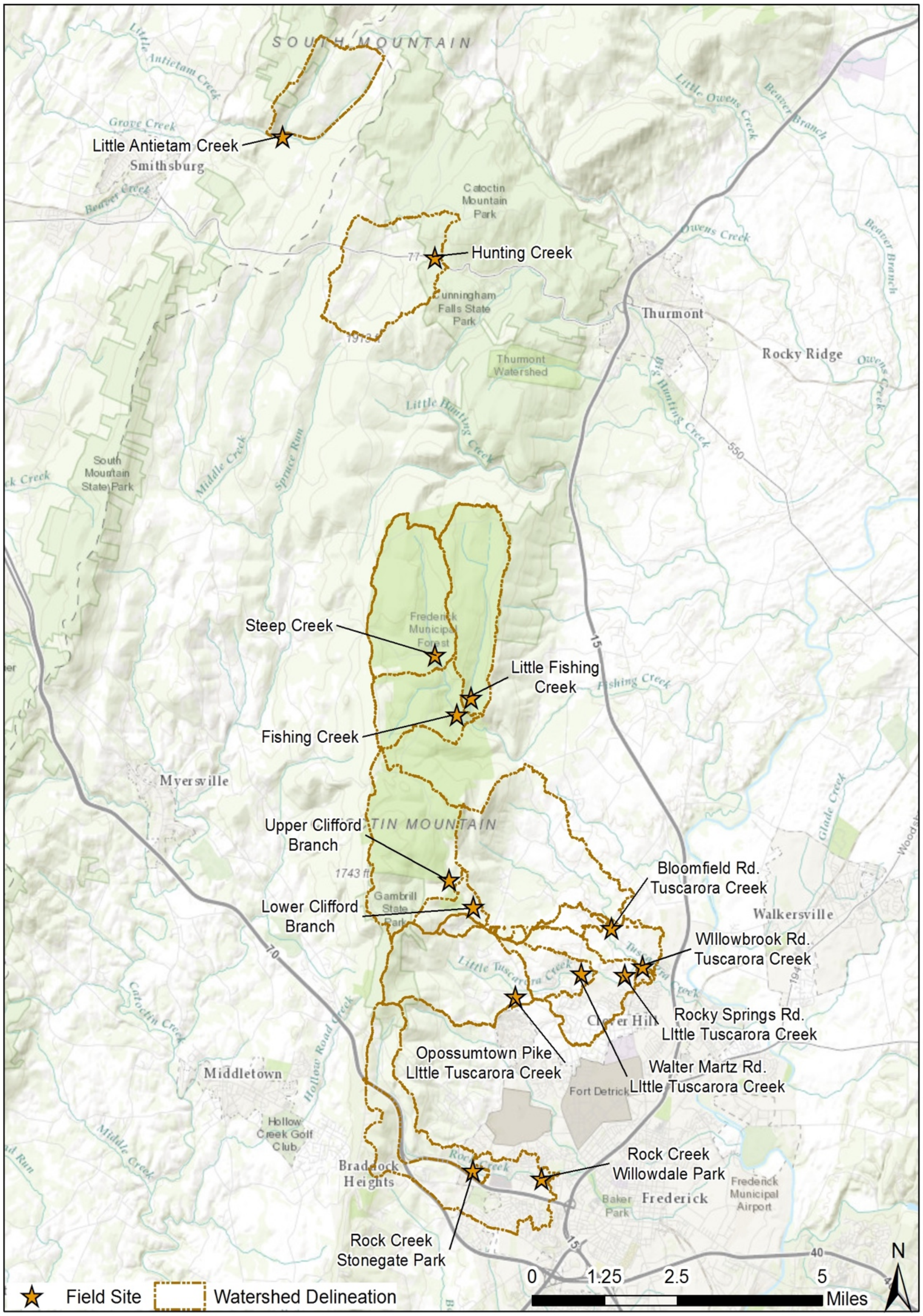

Figure 2. Topographic map depicting locations of all field sites in Frederick and Washington counties, MD.

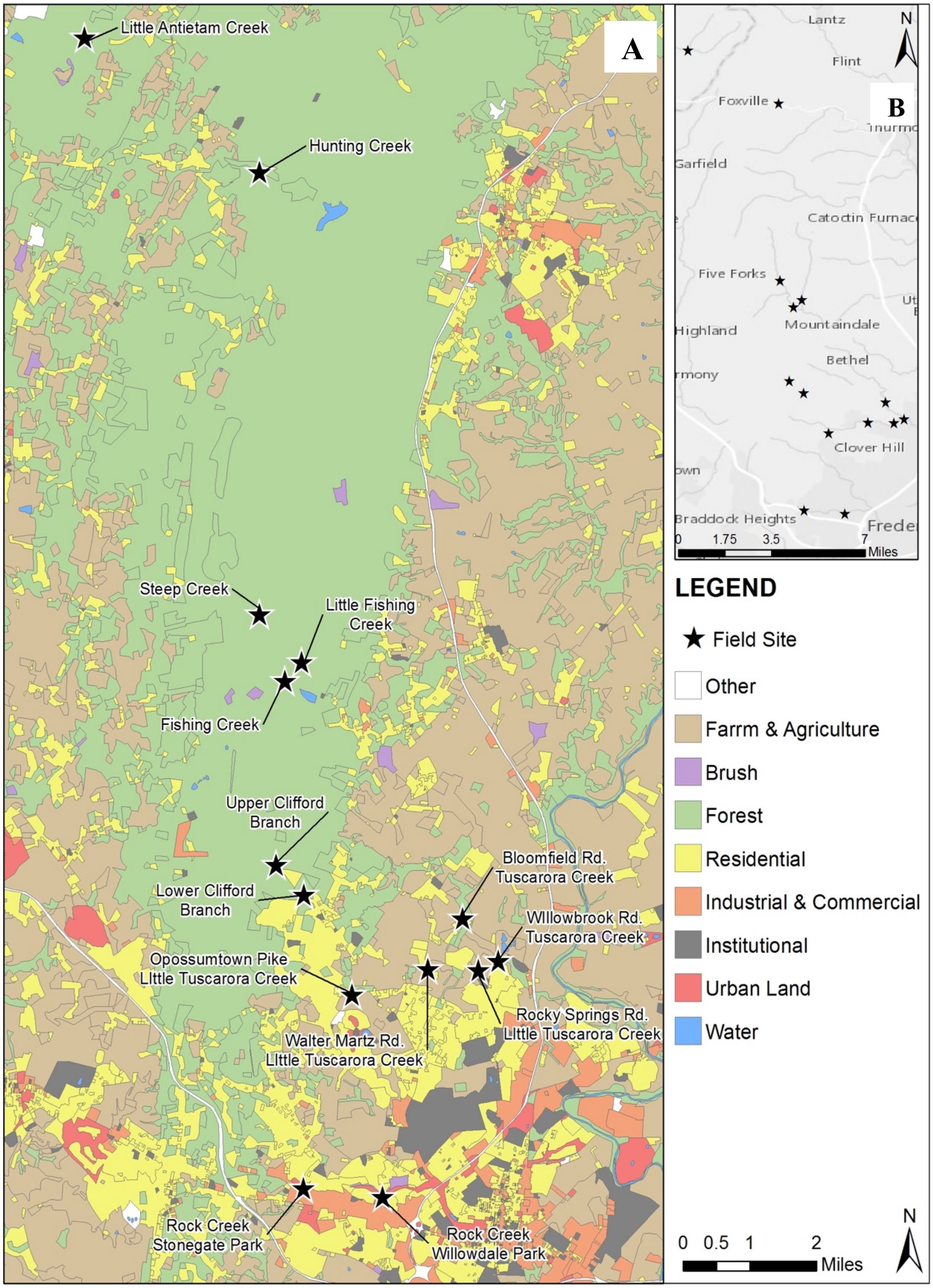

Figure 3. (A) Primary land use categories surrounding field sites within and around the project area. (B) An overview of field sites in relation to common geographical features (Base data from MD Department of Planning).

Total and young of the year (YOY) density data from 2005-2015 of native brook trout within these same streams were obtained from the MD DNR (Appendix A). The brook trout sampling period ranged from June to September. Scour monitors in this study were installed at the center-point of the fish sampling reaches. Sampling at field sites did not occur on an annual basis making data comparison imperfect. Sampling within the Frederick County region is generally completed on larger, more populated trout streams on either an annual, biennial, or triennial basis. Smaller, less frequented streams are included in sampling efforts as time permits (M. Toms, personal communication, June 21, 2017). The MD DNR performed a minimum of four samplings at each stream site in the 2005-2015 period. To make the brook trout data equally representative, all sites with greater than four sampling efforts had four sampling dates randomly selected using a random numbers chart. The average of these four sites was utilized for statistical analyses.

One stream in this study was sampled and yielded zero brook trout. Other streams not recently sampled by the MD DNR were removed from the analysis of brook trout data. According to the MD DNR's database records, neither Tuscarora, Little Tuscarora, nor Rock Creeks had been sampled by the MD DNR since 2005. Historically the above-mentioned streams, although once populated with brook trout, have become degraded, limiting brook trout populations if not eliminating them all together (M. Sell and M Toms, personal communication, June 21, 2017). Additional brook trout density data were obtained from the Maryland Biological Stream Survey (MBSS) for streams not sampled by the MD DNR from 2005-2015. These data indicated one field site along Little Tuscarora Creek on Opossumtown Pike was sampled by the MBSS and yielded zero brook trout. Therefore, when analyzing brook trout density data in this study, only data from streams sampled from 2005-2015 were incorporated. Double-pass electrofishing of 75 m stream sites was used by the MD DNR and MBSS to collect these data. Electrofishing occurs only during the Summer Index Period (June - September). This time period was chosen to characterize fish communities during low flow periods. Sampling during this period is advantageous because spawning effects are minimized, temperatures are conducive to wading, and capture efficiency using electrofishing is typically greater (Stranko 2007).

Scour Monitor Design

Devices to measure scour depth include chains, stacked and sliding ping pong balls or beads, sliding plastic golf balls, tracer stones, and artificial redds (Schuett-Hames et al. 2005). Nawa and Frissell (1993) compared two different scour monitor devices, the sliding bead monitor and the chain monitor. Based on the more successful sliding bead monitor, a modified version of methods developed by Nawa and Frissell (1993) was used to construct the methodology for this experiment. Scour depth was measured using the sliding bead monitor, a device not requiring excavation because of its visibility along the water's surface. This decreased the surface area available for debris accumulation and deposition. The beads' small diameter limited disturbance to the streambed during installation. Its base was constructed of a galvanized iron plug and a PVC connector. Braided wire was strung with 25 1 cm beads along 60 cm of wire connected to a brightly colored rope to aid in retrieval (Figure 4). A rubber band was placed at the top of the beads to secure them during burial. To implant the monitors, a steel pipe and post driver were used. When a streambed was scoured, the exposed portion of beads slid to the unburied end of the wire. The quantity of exposed beads indicated scour depth. Upon returning to the streams, the number of beads at the end of the wire was counted (Nawa and Frissell 1993).

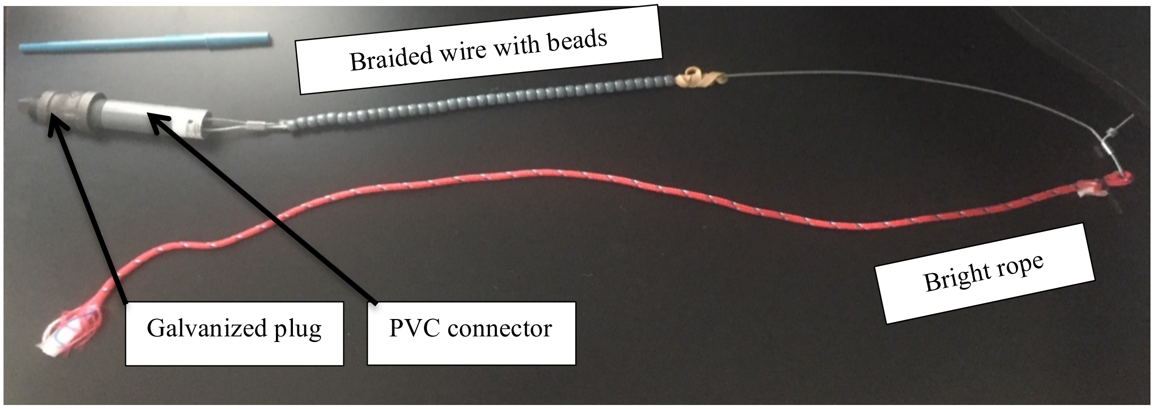

Figure 4. Scour monitor device developed for this study.

Data Collection and Analysis

A total of 70 sliding bead devices were deployed at the sampling sites to quantify scour depth. Five devices were placed at each of the 14 sites and were distributed haphazardly based on the number of suitable locations available within each stream reach (Figure 3). Specific locations for each device were determined by the presence of proper surface gravel (i.e., gravel between 4–60 mm) in areas likely to support brook trout spawning, such as riffles or areas with large woody obstructions. All devices were buried in areas frequently covered by water except during infrequent or severe drought events, in inner portions of the stream, and along the edge of the stream (Nawa and Frissell 1993).

Scour devices were placed at each location prior to the spawning season. At the start of the spawning season rubber bands were removed from each monitor to initiate data collection. Scour measurements were adjusted to account for beads uncovered prior to the removal of the rubber band by subtracting the number exposed. Scour devices were monitored monthly (every 30 days) from October 1st to April 1st to ensure their success, and notes were taken regarding the number of beads exposed. The five subsamples decreased the chances of insufficient data due to accidental loss or breakage of a scour device. Any monitors lost over the brook trout spawning and incubation period were noted. All scour devices developed for this study had a maximum measurement potential of 25 cm. However, not all monitors were successfully buried to their maximum depth. Scour was calculated by taking the mean of the five scour measurements from each field site monthly from October to April (DeVries 2008). Hartman and Hakala (2006) found average brook trout and bull trout egg burial depth to be 8 cm and 10 cm, respectively. This range was used when analyzing scour depths throughout this study.

Additional geomorphological characteristics of stream site reaches were quantified by performing pebble counts and taking measurements of the stream cross section and longitudinal gradient. Pebble counts were performed using a gravelometer by carefully selecting 100 pieces of gravel after each step along one stream cross-section and measuring their median axis. The gravelometer categorizes sediment particles based on a range of sizes. The size ranges utilized in this study included < 4 mm, 4 mm, 5.7 mm, 8 mm, 11.3 mm, 16 mm, 22.5 mm, 32 mm, 45 mm, 60 mm, 90 mm, 128 mm, and > 128 mm. For example, a sediment particle falling within the 128 mm category indicates the sediment particle is larger than 90 mm and smaller than 128 mm. Stream cross-sections were measured from bankfull to bankfull with elevation measurements using a Spectra Precision laser level taken at 2-foot intervals across a riffle. Longitudinal measurements were taken at 4-foot intervals along the 50-foot reach of the stream to determine stream gradient elevation.

Width to depth ratio of each stream was calculated by dividing the width of the stream from bankfull to bankfull against the deepest bankfull point of the stream. Stream gradient was measured by the ratio of drop in elevation of a stream per horizontal unit and was calculated by graphing elevation data taken at 4-foot intervals along a 50-foot reach and determining the slope of the linear trend line. These additional geomorphological measurements aided in the explanation of differences in scour depth between sites with similar amounts of impervious cover in their respective watersheds. Geomorphology was also used to create a detailed qualitative site description for all streams monitored in this study through the development of a correlation matrix. Meaningful flow velocity measurements were hindered due to: difficulties performing consistent flow measurements, the dangers of performing flow measurements at peak flow, the vast amount of leaf litter in the streams during the fall months, and the need to avoid disturbing the streams during the brook trout spawning and incubation period.

Precipitation data were obtained from Weather Underground to determine both conditions during the study and historically, but these data were not used for additional data processing.

Planimetric data were collected through photogrammetric processes using overlapping aerial photos. The features were collected in 2005 at a map scale of 1:100. The 2014 update features were collected at 1:200. Impervious coverage data were unable to be retrieved from Washington County government due to differences in collection techniques and collection years compared to Frederick County.

Using ArcMap, upstream drainage areas of all field sites were calculated using Digital Elevation Models (DEM). These drainage areas were later overlaid with planimetric data from Frederick County to quantify the percent of impervious land cover. Planimetric impervious cover data were estimated using land cover data for subwatersheds in the Upper Monocacy Watershed. Generally, impervious cover includes rooftops and roads preventing storm water from infiltrating into the ground. For these data, roads, parking areas, roofs, sidewalks, and other human constructions are collectively categorized as impervious surfaces (MD DNR 2005). For Frederick County, corrections to the final dataset were made to account for patios, pools, recreational features, and secondary sidewalks (MDE 2012).

The ArcMap Spatial Analyst Hydrology toolset used a known point and the contributing area of each site to develop flow accumulation and flow direction datasets. The Hydrology toolset modeled the flow of water across a defined surface. The Flow Direction tool created a raster of flow direction data from each cell to its steepest downslope neighbor. The Flow Accumulation tool created a raster of accumulated flow data within each cell. The Watershed tool determined the contributing areas upstream of a set of cells within the designated raster. The final datasets produced through these toolsets were used to determine the impact of the upstream discharge area on each field site. Pour point layers were created for each field site based on the GPS location of the chosen field sites and the snap to pour point tool found the DEM pixel receiving the greatest flow accumulation closest to each field site. The Watershed tool created a raster dataset of the upstream watershed area draining into the pour point. This watershed raster layer was converted into a shapefile and overlain with the impervious cover data layer obtained from Frederick County. Percent impervious cover was calculated by dividing total impervious land cover by total land cover within the upstream watershed area of each field site individually. Subwatersheds within each drainage area were cut and merged to determine accurate amounts of total and impervious land within each drainage area. Maps developed based on these data were interpreted using a gradient to show increasing levels of impervious cover within and surrounding the upstream drainage area (Appendix B).

Using the SPSS software package, correlations between all variables including scour, impervious cover, pebble counts, mean brook trout density, stream gradient, stream width to depth ratio, and upstream drainage area were determined using a Pearson correlation matrix. Variables determined to be significantly correlated through the Pearson correlation matrix were analyzed with simple linear regression. Simple linear regression was used as opposed to multiple linear regression due to the collinearity of the geomorphological variables.

RESULTS

Correlation Matrix and Linear Regression

Data analyzed throughout the study are listed in Table 1. Using SPSS, all variables including scour, percent impervious cover, width to depth ratio, stream gradient, upstream drainage area, pebble count modes, and mean total and YOY brook trout density data were compared to determine the nature of any correlations (Table 2). Variables with significant correlations to mean total and YOY brook trout included percent impervious cover and stream gradient. Other variables with significant correlations included stream gradient and pebble count modes.

Table 1. All variables and data analyzed throughout the study. All brook trout density and scour data were calculated as means. Pebble counts were calculated as modes.

Stream	Total Brook Trout/km	YOY Brook Trout/km	Scour (cm) +/- 1 S.D.	Impervious Cover (%)	Width: Depth	Pebble Count (mm)	Stream Gradient (%)	Upstream Drainage Area (ac.)
Little Fishing Creek	736.70	336.585	4.5 +/- 2.1	0.4	0.15	128	13.67	1702.11
Steep Creek	1116.67	443.33	7.2 +/-8.0	0.72	7.81	128	21.84	2073.55
Fishing Creek	530.45	236.04	14.4 +/- 9.2	0.73	9.89	128	8.24	4941.98
Little Antietam Creek	483.31	483.31	17.4 +/- 11.5	n/a	11.28	16	0.77	n/a
Lower Clifford Branch	416.31	164.35	3.3 +/- 6.6	2.44	6.35	128	10.29	3835.24
Hunting Creek	208.33	43.17	0.0 +/- 0.0	3.16	7.04	128	12.22	2047.16
Upper Clifford Branch	385.29	146.75	8.1 +/- 9.2	0.72	7.04	128	11.12	3387.88
Little Tuscarora Creek (Opossumtown)	0	0	17.9 +/- 21.3	7.05	3.82	16	2.51	2511.31
Tuscarora Creek (Bloomfield)	n/a	n/a	3.0 +/- 1.5	3.23	8.48	22.5	5.54	6967.68
Tuscarora Creek (Willowbrook)	n/a	n/a	1.2 +/- 1.23	8.07	4.48	4	4.19	5237.12
Little Tuscarora Creek (Walter Martz)	n/a	n/a	20.7 +/- 22.5	6.80	3.78	16	10.28	3167.98
Little Tuscarora Creek (Rocky Springs)	n/a	n/a	5.4 +/- 6.2	7.77	3.39	128	4.75	4687.95
Rock Creek (Willowdale)	n/a	n/a	2.1 +/- 7.7	23.05	7.26	16	6.47	2664.18
Rock Creek (Stonegate)	n/a	n/a	12.9 +/- 17.3	15.84	3.52	16	3.03	1247.35

Table 2. Correlation matrix depicting relationships and significance between all variables in streams sampled for brook trout between 2005-2015 (n = 7 or 8). Values denoted with an asterisk (*) are those significant at the 0.05 level. Values denoted with a double asterisk (**) are those significant at the 0.01 level. Table includes all sites (n = 13 or 14).

		Total Brook Trout/km	**YOY Brook Trout/km**	**Scour (cm)**	**Impervious Cover (%)**	**Width: Depth**	**Pebble Count Mode (mm)**	**Stream Gradient (%)**	**Upstream Drainage Area (ac.)**
Total Brook Trout/km	Correlation	1	0.988**	-0.214	-0.757*	0.070	0.446	0.724*	-0.164
	Sig. (2-tailed)	-	0.000	0.611	0.049	0.877	0.268	0.042	0.726
	N	8	8	8	7	8	8	8	7
YOY Brook Trout/km	Correlation		1	-0.150	-0.759*	-0.003	0.420	0.666	-0.125
	Sig. (2-tailed)		-	0.722	0.048	0.991	0.301	0.072	0.790
	N		8	8	7	8	8	8	7
Scour (cm)	Correlation			1	-0.014	-0.150	-0.400	-0.274	-0,196
	Sig. (2-tailed)			-	0.965	0.620	0.156	0.343	0.522
	N			14	13	14	14	14	13
Impervious Cover (%)	Correlation				1	-0.133	-0.517	-0.535	-0.211
	Sig. (2-tailed)				-	0.668	0.071	0.060	0.490
	N				13	13	13	13	13
Width: Depth	Correlation					1	0.205	0.179	0.413
	Sig. (2-tailed)					-	0.503	0.559	0.160
	N					14	14	14	13
Pebble Count Mode (mm)	Correlation						1	0.665**	-0.156
	Sig. (2-tailed)						-	0.010	0.610
	N						14	14	13
Stream Gradient (%)	Correlation							1	-0.343
	Sig. (2-tailed)							-	0.251
	N							14	13
Upstream Drainage Area (ac.)	Correlation								1
	Sig. (2-tailed)								-
	N								13

Total and YOY mean brook trout densities were negatively correlated (r = -0.757 and r = -0.759; Table 2) to percent impervious cover, indicating streams with lesser percentages of impervious cover in their upstream drainage area have greater brook trout densities. These results support the hypothesis that watersheds with greater percentages of impervious cover would be associated with lower native brook trout densities and the prediction that brook trout density and percent impervious cover would be negatively correlated. The correlation coefficient for brook trout density and percent impervious cover indicated a significant relationship (Table 2; Figure 5). Total mean brook trout density was also positively correlated (r = 0.724) to stream gradient indicating streams with lesser gradients would contain minimal brook trout densities. Total brook trout density and stream gradient were also significantly correlated (Table 2; Figure 6).

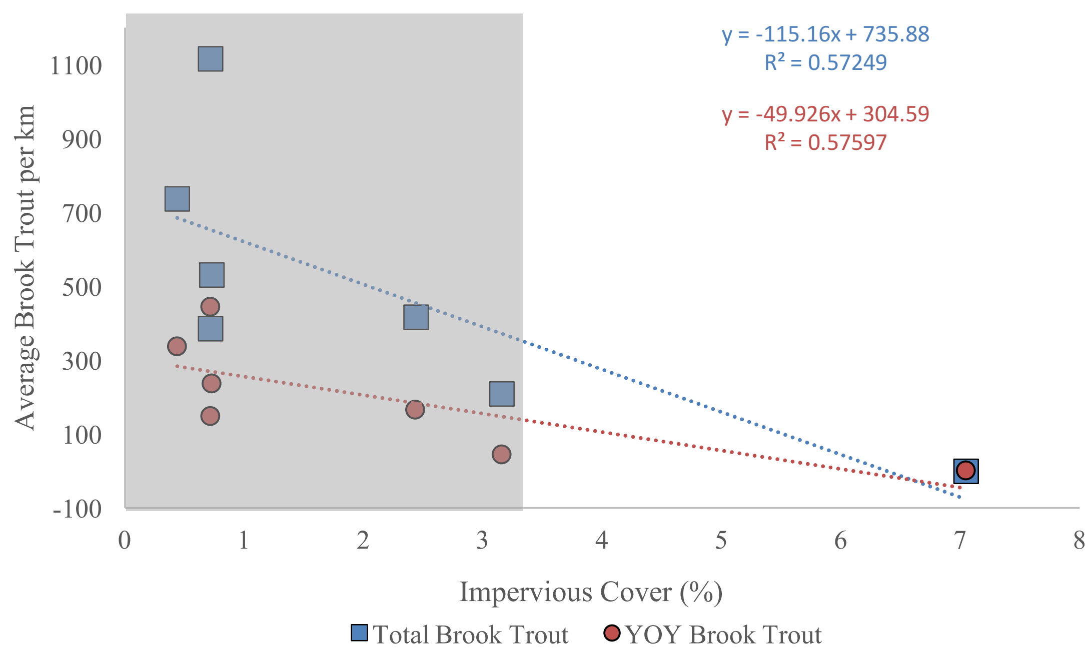

Figure 5. Average total and YOY brook trout density compared to percent impervious cover. Graph includes streams sampled for brook trout from 2005-2015. Trend lines represent significant correlations as presented in Table 2. Shaded area highlights 3.16% threshold where impervious surface reaches its limit in relation to brook trout density.

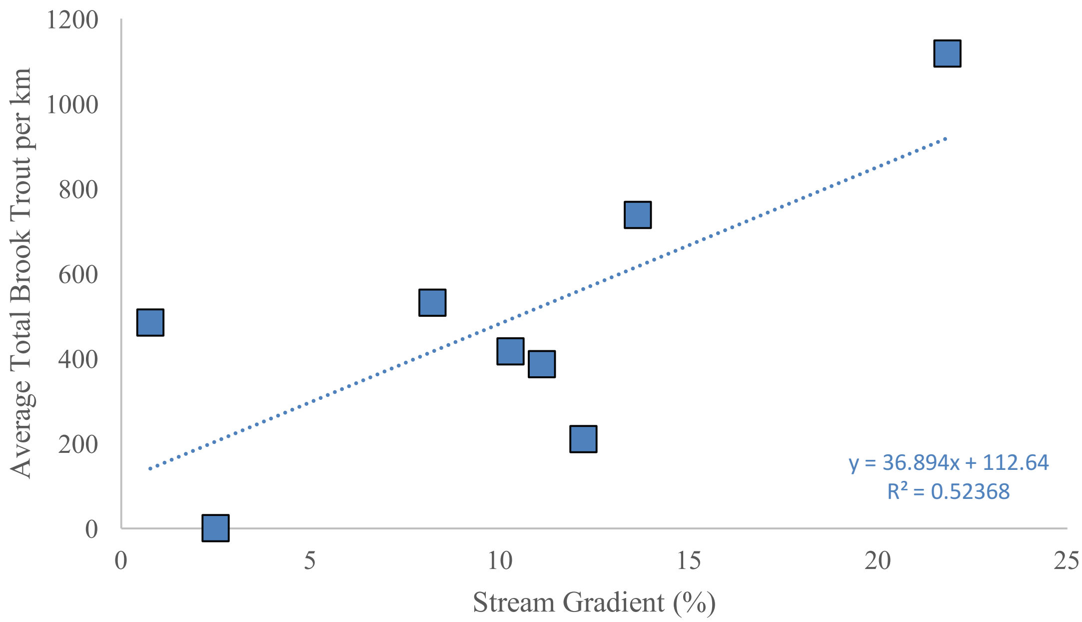

Figure 6. Average total brook trout density compared to stream gradient. Graph only includes streams sampled for brook trout from 2005-2015. Trend line represents significant correlation as presented in Table 2.

Pebble count modes were significantly ($p = 0.01$; Table 2) and positively correlated ($r = 0.665$) to stream gradient indicating streams with fine sediment would be associated with lesser gradients. The correlation coefficient for stream gradient and pebble count indicated a positive and significant relationship as pebble count modes decrease with decreasing average stream gradient (Table 2; Figure 7). Seven of the fourteen streams sampled in this study had a pebble count mode range of 128 mm or greater (Table 1).

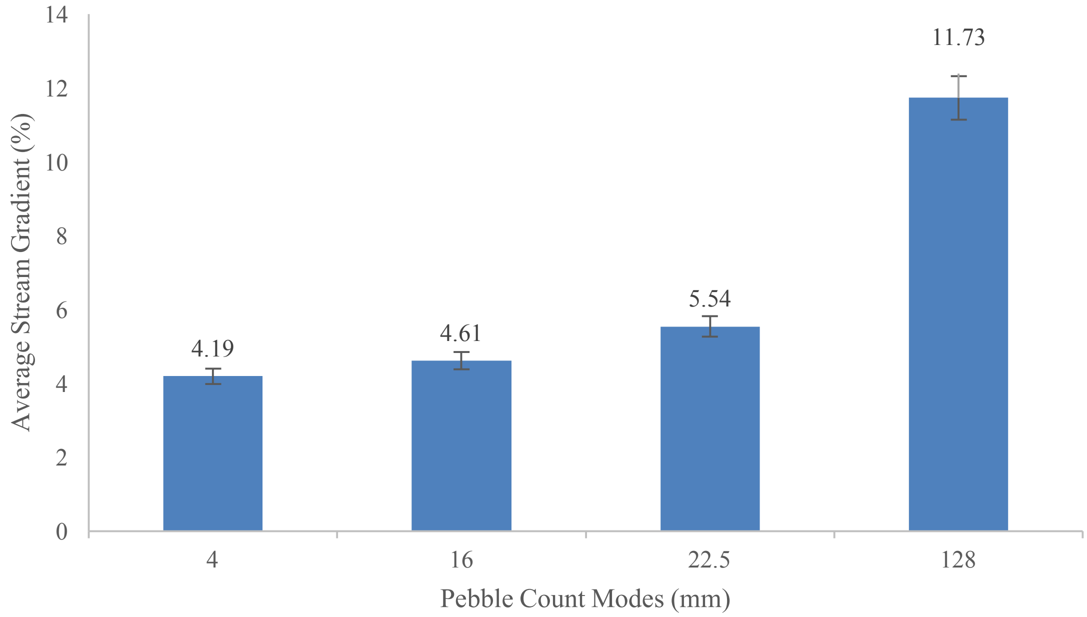

Figure 7. Average stream gradient compared to pebble count modes and standard deviation at all field sites.

Brook Trout Density

When analyzing streams sampled for total and YOY brook trout there is a negative trend between brook trout density and impervious cover (r^2 = 0.5725 and r = 0.5760; Figure 5). A threshold percentage is evident between brook trout density and percent impervious cover. Populations of brook trout were primarily found in streams with less than 3.16% impervious cover. The one stream (Little Tuscarora Creek along Opossumtown Pike) with zero brook trout was surrounded by greater than 7% impervious cover. The decrease in brook trout per km as impervious land cover increased was greater for YOY than total brook trout density (Figure 5).

Total brook trout density was positively and significantly correlated (r = 0.724) to stream gradient. There was no distinct threshold value affecting the presence of total brook trout as there was for impervious cover. There is a positive trend with brook trout density increasing as stream gradient increases (Figure 6). YOY brook trout density was not significantly correlated to stream gradient.

Scour

Brook trout density was not significantly correlated to scour. Scour depth was also not significantly correlated to impervious cover (Table 2). However, trends indicated scour was negatively correlated to brook trout density and weakly negatively correlated to percent impervious cover. The relationship between scour and brook trout density relates to the prediction that scour depth and brook trout density would be negatively correlated. The relationship between percent impervious cover and scour depth does not support the prediction that these variables would be positively correlated.

Mean scour depths and their standard deviations are graphed to better visualize the variation between stream reaches (Figure 8). The black dashed line indicates the 8 cm threshold. Five streams in this study had scour depths greater than 8 cm with the standard deviation of one stream reach also reaching the threshold. Based on these results, three of the eight streams containing brook trout had average scour depths greater than the 8 cm threshold. Conversely, three of the six streams not sampled for brook trout due to historically low or missing populations had average scour depths much lower than the 8 cm threshold. Over half the stream reaches had scour depths shallower than 8 cm and would be expected to support successful brook trout populations.

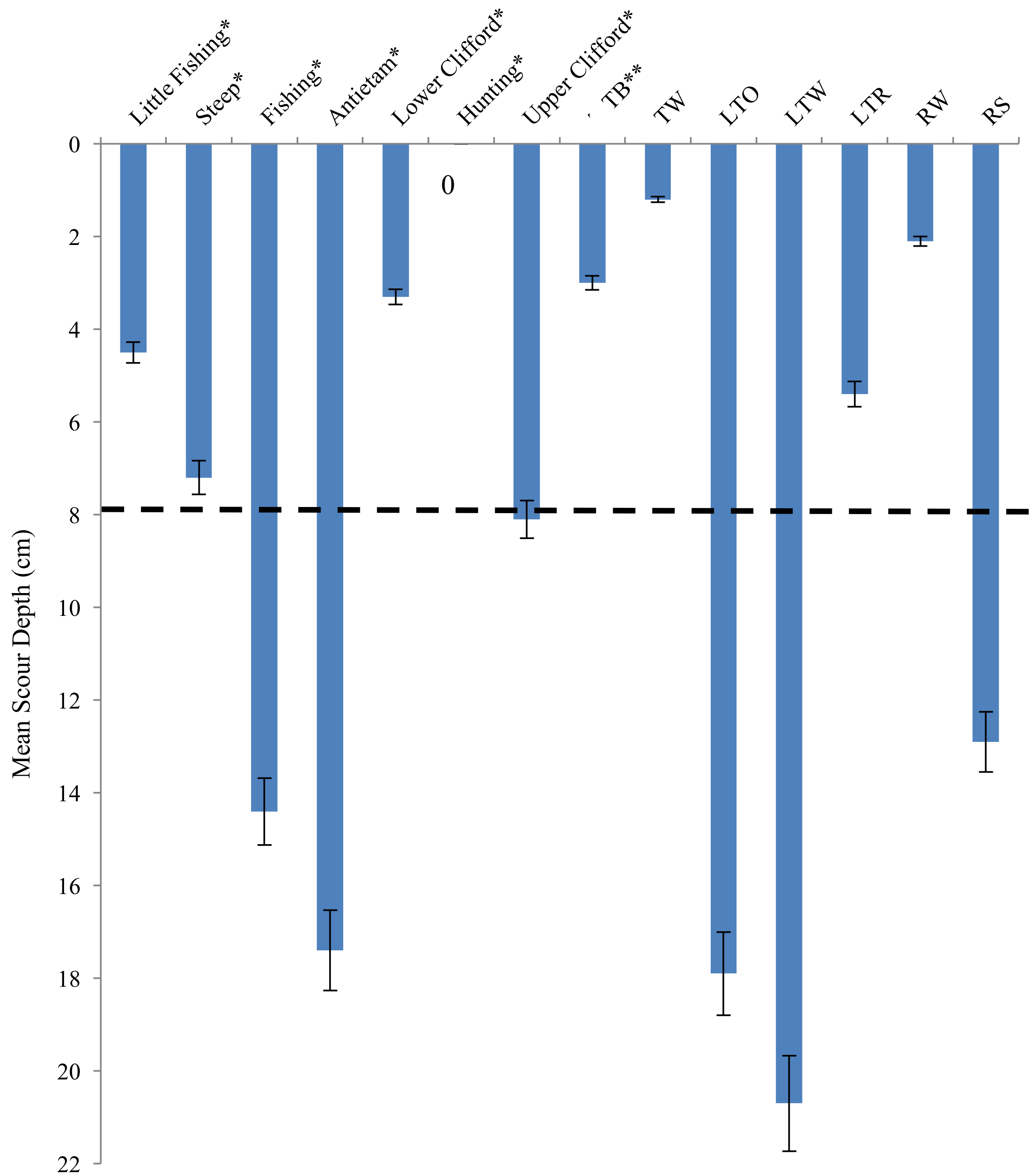

Figure 8. Mean scour and standard deviation. Dashed line marks the 8 cm threshold hypothesized to harm brook trout redds. TB (Tuscarora on Bloomfield Rd.), TW (Tuscarora on Willowbrook Rd.), LTO (Little Tuscarora on Opossumtown Pike), LTW (Little Tuscarora on Walter Martz Rd.), LTR (Little Tuscarora on Rocky Springs Rd.), RW (Rock in Willowdale Park), RS (Rock in Stonegate Park). Streams with brook trout are marked with an asterisk (*). Streams sampled but yielded no brook trout are marked with a double asterisk (**). Streams not sampled for brook trout are unmarked.

Precipitation

The October 2015 to April 2016 period of this investigation exhibited notably less precipitation than the 70-year historical average for this region. Average historical precipitation in Frederick, MD was much greater than the amount of precipitation received by the scour monitors during this study (Table 3). Frederick County only received 22% of its average precipitation during this field season, indicating a dry season. There were no precipitation events at or above the lowest historical average (6.60 cm) throughout the field seasons.

Table 3. Comparison of average precipitation values to precipitation received during the field season in which scour was monitored. Weather monitor is located at the Frederick Municipal Airport, 21701 (Weather Underground 1947-2017).

Month	70-year Historical Precipitation (cm)	Field Season Precipitation (cm)
October	8.31	1.42
November	8.31	2.11
December	8.51	1.83
January	7.70	2.87
February	6.60	1.12
March	8.79	1.19
SUM	48.22	10.54

DISCUSSION

Brook Trout Density and Impervious Land Cover

Total and YOY mean brook trout densities were negatively and significantly correlated to percent impervious land cover. Recent brook trout declines in Maryland have been associated with impervious land cover percentages as low as 2% (Stranko et al. 2008). The predictive nature of percent impervious land cover and brook trout density indicates streams surrounded by greater percentages of impervious land cover are less likely to support successful populations of brook trout.

The six streams containing brook trout populations had 3.16% impervious land cover or less within their watershed. This included: Hunting Creek, Steep Creek, Fishing Creek, Little Fishing Creek, Upper Clifford Branch, and Lower Clifford Branch. These streams were in more rural areas within the Catoctin Mountains of Frederick County. The other stream site sampled for brook trout within Little Tuscarora Creek was surrounded by greater than 7% impervious cover. This stream was in a more urban area within the Frederick City limits. The remaining stream sites were not sampled for brook trout from 2005-2015.

Many studies have demonstrated fish assemblages respond to various levels of urbanization. Wenger et al. (2008) found a negative relationship between impervious land cover and fish species. Based on their models, the occurrence of several fish species was strongly related to low levels of impervious land cover. Other studies have also reported declines in aquatic fauna within watersheds surrounded by more than 10% impervious land cover (Wenger et al. 2008; Stranko et al. 2008). Wenger et al. (2008) noted some species become rare at impervious cover percentages as low as 2% which is lower than the 3.16% threshold determined in this study. The 2% impervious cover threshold value for the most sensitive species was consistent with additional studies suggesting impervious cover must remain below 2% to maintain natural ecological conditions (Wenger et al. 2008; Stranko et al. 2008).

Rock Creek at Willowdale Park was surrounded by the greatest amount of impervious land cover with 23.05%, followed by Rock Creek at Stonegate Park surrounded by 15.84% impervious land cover. Both streams have much higher impervious land cover within their watersheds and fell within the Schueler et al. (2009) category of an impacted stream. Waco and Taylor (2010) found declines in brook trout in Maryland streams to be strongly influenced by changes in land use and land cover. Their investigations found increases in water temperature and erosion to be associated with increased percentages of urban land and impervious surface and decreased forested land cover (Waco & Taylor 2010).

Urbanization is a complex phenomenon impacting fish populations through multiple interacting pathways (Wenger et al. 2008). Streams with 10%-25% impervious land cover are considered impacted and often show clear signs of declining health. Streams with 25%-60% impervious land cover no longer support fish species and become so degraded they never fully recover their function and diversity. Streams exceeding 60% impervious land cover are often extensively modified and merely function as conduits for flood waters. These streams are classified as urban drains and are noted to have poor water quality, highly unstable channels, and poor habitat diversity (Schueler et al. 2009). Generally, stream fish communities rapidly degrade as watershed impervious cover exceeds 10%-15%. Results from Utz et al. (2009) suggested degradation and biodiversity loss occurs at the lowest levels of land use conversion (Utz et al. 2009).

Impervious Land Cover and Scour

Average scour measurements were not significantly correlated to percent impervious land cover in this study. The hypothesis that watersheds with greater percentages of impervious cover would be predictive of greater scour depths was not supported. In fact, scour and impervious land cover resulted in a negative correlation meaning in this study scour decreased in areas surrounding by greater percentages of impervious land cover.

Given this study occurred during a relatively dry fall and winter season, additional studies during wetter years could support the hypothesis that streams surrounded by greater percentages of impervious land cover would be predictive of greater scour depths. As impervious cover increases, runoff volume and rate increases following precipitation events resulting in augmented frequency and magnitude of floods. Greater flooding leads to less stable streambeds, excessive bank erosion, loss of habitat and canopy cover, and excessive scour and deposition. These physical changes harm stream ecosystems leading to declines in diversity and productivity of aquatic organisms, namely brook trout (Wang et al. 2001). Long-term research by Rosgen (2011) indicates that river morphology is shaped by storms with a return frequency of approximately two years, not average precipitation. Therefore, it is possible for one storm event to drive the action of scour for an entire season. It is the less frequent and larger flows that shape channels, not base flow or small flows. Additional field seasons are needed to determine the relationship between scour and impervious land cover as well as scour depths under varying precipitation conditions.

Results from Elmore and Kaushal (2008) were comparable to results of this study as scour depths varied distinctly between rural and urban areas. Elmore and Kaushal (2008) also found streambed scour to be related to the connectedness of impervious area which was not a focal point of this study. The importance of the connection of impervious land cover stems from the ability of disconnected impervious land to allow some amounts of runoff to filter through the earth, whereas areas with fully connected impervious land force runoff to flow directly into storm water systems. Many studies note the importance of connected impervious land cover and distance of impervious lands from hydraulic systems when predicting stream and biotic changes associated with urbanization (Elmore & Kaushal 2008; Pappas et al. 2008). Knowledge of the impact of land cover on stream habitats can allow for the implementation of strategies mitigating the impacts of urbanization (Waco & Taylor 2010; Wenger et al. 2008).

Brook Trout Density and Scour

In this study, average scour measurements were not significantly correlated to brook trout density. This result led to the conclusion that the hypothesis stating streams with greater scour depths would lead to lower brook trout densities was not supported. However, brook trout density did have a negative correlation with average scour, indicating that brook trout density decreased in areas with greater scour depths. The lack of significance indicates additional variables besides scour within these watersheds affect essential brook trout habitat. They may also indicate scour is highly variable by nature and true scour rates are difficult to predict using a sampling scheme similar to the one used in this study. Additionally, other factors in this study strongly influencing brook trout success, such as stream gradient and percent impervious cover, could have impacted the streams and their surrounding area in such a way that brook trout density was predetermined regardless of scour depth.

The low amount of precipitation during this study's field season likely impacted the lack of significance between brook trout density and scour depth as scour is highly dependent on precipitation events during the incubation period (October to March). For example, Shelburg et al. (2010) determined that catchments dominated by precipitation events during the incubation period of salmonids lead to greater scour depths making fall spawning salmonids highly vulnerable. In contrast, areas receiving less than average precipitation often recorded shallower scour depths. The precipitation measured throughout this study was lower than the historical average and still many field sites recorded scour depths at or greater than the 8 cm average brook trout egg burial depth. Therefore, it could be expected for additional sites to exceed the 8 cm threshold during field seasons experiencing average or greater than average precipitation (Shelburg et al. 2010).

The risk of streambed scour is also dependent on the timing of precipitation events relative to embryo incubation, location of spawning, and egg burial depths. Fall spawning salmonids are at high risk in areas receiving high volumes of rainfall, thereby increasing the frequency and magnitude of winter flood events, when eggs of fall spawning salmonids are in the streambed. Climate change is expected to have persistent effects on aquatic ecosystems through alterations of stream temperature, flow regimes, and precipitation. Future projections predict negative consequences for various life stages of salmonids in relation to precipitation and scour (Goode et al. 2013).

There are many factors not investigated in this study that could have driven brook trout density and occupancy. Brook trout could have been extirpated from streams due to thermal or nutrient alterations leading to low oxygen events, with limited options for recolonization and distribution. This is likely the cause for many of the streams within the limits of Frederick City to be unoccupied by brook trout (Waco & Taylor 2010; Xu et al. 2010). There is also high competition with brown trout in some streams used in this study which could be another factor leading to their extirpation. Variation of spawning locations is another factor driving scour sensitivity of brook trout (Goode et al. 2013).

Stream Gradient and Pebble Counts

Stream gradient was positively and significantly correlated to total brook trout density. Stream gradient was also significantly and positively correlated to pebble count modes. Therefore, stream gradient appears to be a driving force in relation to brook trout density and sediment size. The positive correlations between stream gradient and pebble counts as well as stream gradient and total brook trout indicated higher gradient streams are likely to be more suitable for brook trout and larger sediment.

Wenger et al. (2008) identified stream gradient as a critical variable influencing the distribution of brook trout. Weigel and Sorensen (2001) found brook trout were typically located in high gradient (> 15%) reaches of Appalachian streams in the Eastern US, which is supported by this study. Stream systems with lesser gradients have been known to have less riffle habitat, making these systems less suitable for brook trout.

Wenger et al. (2008) found stream gradient to be a potential filtering mechanism limiting the presence and absence of fish species in streams. Brook trout are dominant in stream headwaters characterized by winding, unconfined channels with high gradient, slower velocity, and canopy cover. These habitat variables explain much of the variation in brook trout abundance and success (Wenger et al. 2008; Weigel and Sorensen 2001). Although no hypotheses or predictions were made regarding stream gradient, it is evident stream gradient was strongly associated to brook trout density and sediment size in this study.

The significant and positive relationship between stream gradient and pebble counts indicates that stream gradient is highly predictive of sediment distribution as streams with more gradual gradients are expected to have greater amounts of fine sediment. This occurred within sites along Tuscarora Creek, Little Tuscarora Creek, and Rock Creek with the exception of one site in Little Tuscarora Creek along Rocky Springs Road.

The relationship between stream gradient and pebble counts aligns with previous studies noting that streams with larger sediment distributions are more conducive for brook trout (Wenger et al. 2008; Weigel and Sorensen 2001). Larger sediments have greater porosity which increases water flow throughout redds allowing for efficient waste removal and oxygen delivery (Colosimo and Wilcock 2007). The accumulation of fine sediment can severely limit reproductive success of brook trout. A high percentage of fine sediment limits fry emergence due to suffocation or entombment (Lachance et al. 2008). Survival of brook trout eggs to emergence has been associated with coarser substrates, suggesting increased mortality in finer substrates may be associated with reduced oxygen flow. Substrates with greater proportions of sand and smaller-sized sediments not only reduced entombment survival but also affected the fitness of surviving larvae (Frassen et al. 2012). Large inputs of fine sediment can smother gravel spawning beds, decreasing survival to emergence of salmonid embryos by reducing intra-gravel flow of oxygen and entombing alevins (Goode et al. 2013).

Stream Temperature and Flow Regime

In addition to stream gradient and impervious land cover, brook trout density may be influenced by stream temperature and flow regime. Kozarek et al. (2010) found the most important reach-scale abiotic factors affecting brook trout to be temperature and flow rate. Climate models predict increases in temperature to occur across the northeastern US, and these changes are expected to lead to increased stream temperatures (Warren et al. 2012). Brook trout are cold-water obligates whose geographical distribution is strongly constrained by stream temperature. Stream warming alters community biodiversity, contributes to species extirpation, and facilitates the invasion of non-native species. Changes in water temperature may also alter brook trout metabolism affecting their rates of resource consumption and reproduction (Kaushal et al. 2010; Xu et al. 2010). All fish have a thermal range over which they can survive and a smaller window within which growth is optimized. Brook trout metabolic rates are elevated in warmer water and therefore require more resources than under cooler conditions. Increased stream temperature is also anticipated to disrupt seasonal timing of brook trout spawning and larval development. While the timing of spawning for most salmonid species is seasonally consistent, it can be controlled by local factors. These increased water temperatures have been correlated with a delay in spawning and a decrease in the total number of redds (Kaushal et al. 2010; Warren et al. 2012).

Impervious land cover is frequently used as an indicator of human disturbance and is correlated with increases in stream temperature (Wenger et al. 2011). Increasing urbanization and the spread of impervious surfaces can substantially impact runoff and water quality in streams. The most rapid rates of increased stream temperature have been observed near urban areas. These increases in stream temperature correspond to local increases in surface temperature due to urbanization. Large increases in stream temperature are associated with urban runoff from hot pavements within watersheds (Kaushal et al. 2010).

Habitat selection by brook trout may be affected by different spatial flow factors such as vorticity, the rotation of the water flow, and velocity gradients. High vorticity improves substrate aeration and removes fine sediments (Louhi et al. 2008). Brook trout often inhabit and utilize complex flow patterns, such as riffles, eddies, transverse flows, and velocity gradients. The vorticity and velocity around obstructions provides favorable migration corridors for juvenile salmonids. Velocity characteristics and flow structures play a role in the brook trout habitat preferences at the local scale as these hydraulic characteristics have been found to predict salmonid presence and density. However, the relationships between variables are complex and difficult to predict as with any natural system (Kozarek et al. 2010).

Although brook trout favor some hydraulic characteristics, low summer flows tend to have the largest negative effect on brook trout populations within smaller streams. Xu et al. (2010) determined decreases in summer streamflow decreased brook trout survival rates in the headwaters of smaller streams. Additionally, Wenger et al. (2011) noted a strong negative relationship between brook trout and winter high flow velocities.

It was determined that a combination of increasing temperature, low summer flows, and winter high flow frequencies were driving brook trout losses. Therefore, multiple drivers including temperature and flow regime determine the response of trout species to climate change. However, despite the important influence of flow regime, it was determined temperature increases themselves were likely the dominant player in driving future declines of brook trout. Although this study did not consider temperature as a variable, had temperature been analyzed, I predict it may have helped clarify the relationship between impervious land cover and scour (Wenger et al. 2011).

CONCLUSIONS

Frederick is a rapidly urbanizing area, and these data only touch on the significant relationships between brook trout success, sediment size, stream gradient, upstream drainage area, impervious land cover, and width to depth ratio. It is evident multiple geomorphological variables, including percent impervious land cover and stream gradient affect the density of mean total and YOY brook trout, as well as other factors. However, there is a lack of evidence to support a relationship between scour and brook trout density as well as scour and impervious land cover. This could be explained by the minimal precipitation at the field sites in comparison to the average precipitation for the area, in addition to other geomorphological variables. The significant correlation between mean brook trout density and percent impervious cover was confirmed by similar results in previous studies noting the harm impervious cover at or greater than 2% can impart on brook trout success (Dougherty et al. 2004). This study detected a threshold effect for impervious land cover on brook trout presence. Density of brook trout appeared to occur primarily in streams with impervious cover percentages of 3.16% or less.

The majority of streams in this study experiencing scour depths greater than 8 cm have not been home to brook trout in over 10 years, except for Fishing Creek and Little Antietam Creek. The streams along Tuscarora Creek, Little Tuscarora Creek, and Rock Creek were all located in more urban settings and may be exposed to additional environmental conditions harming brook trout success as compared to the other sites in this study. Direct monitoring of salmonid density changes resulting from scour is needed to better understand their response and provide data for validating predictive models developed based on physical factors, such as sediment size and distribution, width to depth ratio, stream gradient, upstream drainage area, and impervious land cover (Goode et al. 2013).

There are several potential limitations in applying this study to more specific questions. This approach is limited to reach-average predictions across the stream network and does not consider the spatial complexity of spawning habitats and sub-reach scales, which are also important to brook trout. Another potential bias acknowledged is the effect of nested watersheds on data collection and analyses. Most streams utilized in this study were located within nested watersheds. When this occurs there is some overlap of watershed areas and data collected at one site is not independent of data collected at a second site within the neighboring upstream drainage area (Figure 2). It should also be noted brook trout density data were temporally separate from all other data collected. Brook trout populations vary seasonally which is why population counts were performed during the summer months prior to the egg deposition and incubation period throughout the fall and winter months when data in this study were collected.

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APPENDIX A

Table 4. Table of brook trout density data obtained from the MD DNR and MBSS.

Year	Watershed	Site ID	Total Brook Trout/km	YOY Brook Trout/km
2005	Hunting Creek	Hemlock Bridge	525.526	165.165
2006			307.808	135.135
2007			292.793	30.030
2008			285.285	120.120
2009			330.330	157.658
2010			172.673	0.000
2011			67.568	15.015
2012			82.583	30.030
2014			60.060	7.508
2015			195.195	127.628
2005	Fishing Creek	Lower Left-Hand Fork	791.139	327.004
2007			365.854	12.195
2009			507.692	276.923
2011			164.794	44.944
2013			494.382	89.888
2015			800.000	560.000
2005	Little Fishing Creek	Lower Right-Hand Fork	786.164	377.358
2007			981.997	278.232
2009			905.218	585.729
2011			231.980	157.415
2013			798.246	508.772
2015			946.447	533.333
2005	Antietam Creek	Rt. 491	890.688	418.354
2006			746.562	186.640
2007			1013.333	560.000
2008			238.322	95.329
2011			93.333	26.667
2014			80.000	0.000
2006	Clifford Branch	Lower	451.895	204.082
2007			720.000	400.000
2010			293.333	0.000
2014			200.000	53.333
2006	Clifford Branch	Upper	567.823	347.003
2007			653.333	213.333
2010			213.333	13.333
2014			106.667	13.333
2014	The Ford	Delauter Rd.	986.667	373.333
2014			426.667	0.000
9/8/2015			1813.333	706.667
9/10/2015			1240.000	693.333
2015	Little Tuscarora Creek	Opossumtown Pike	0.000	0.000

APPENDIX B

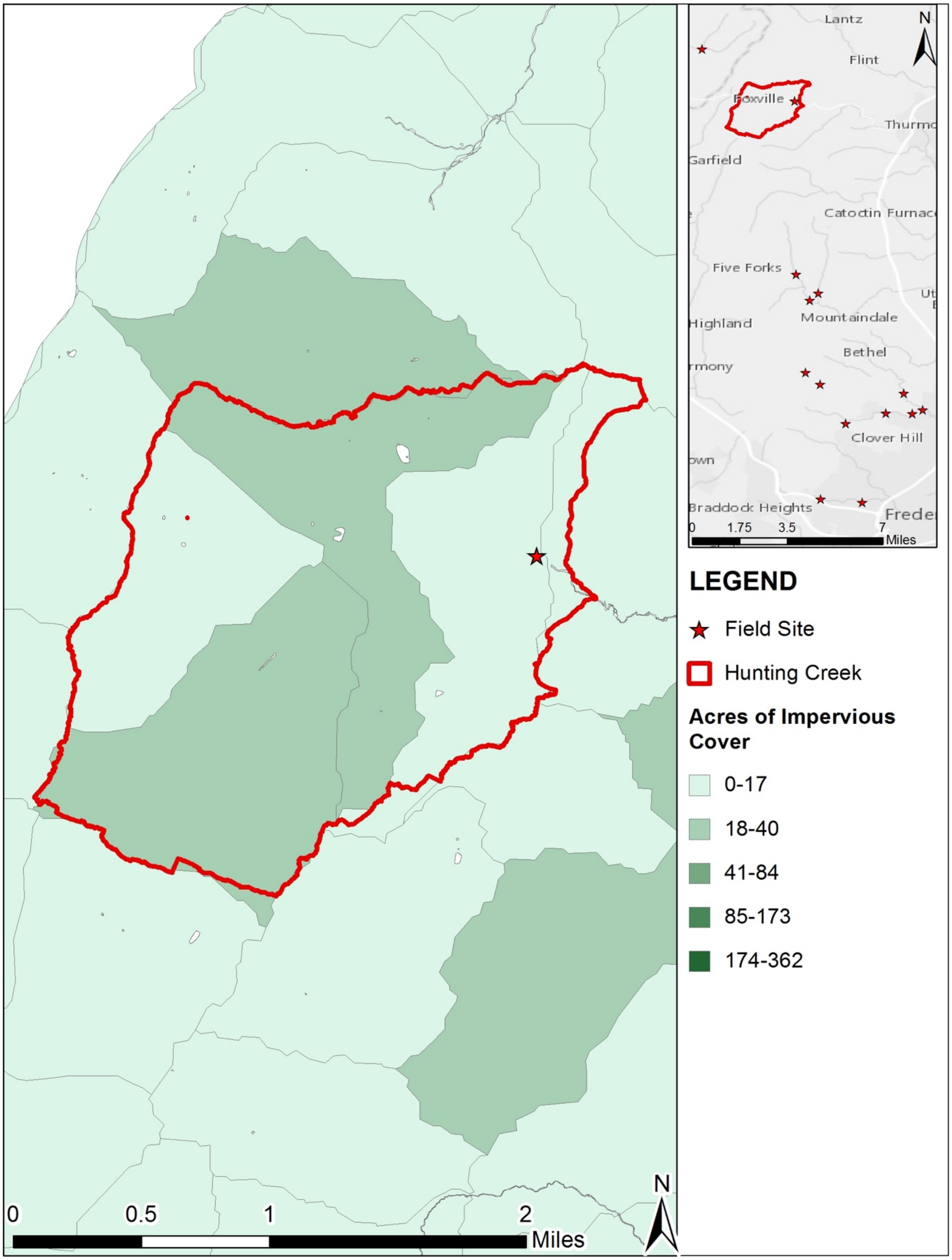

Figure 9. Map of Hunting Creek watershed delineation and total acres of impervious cover.

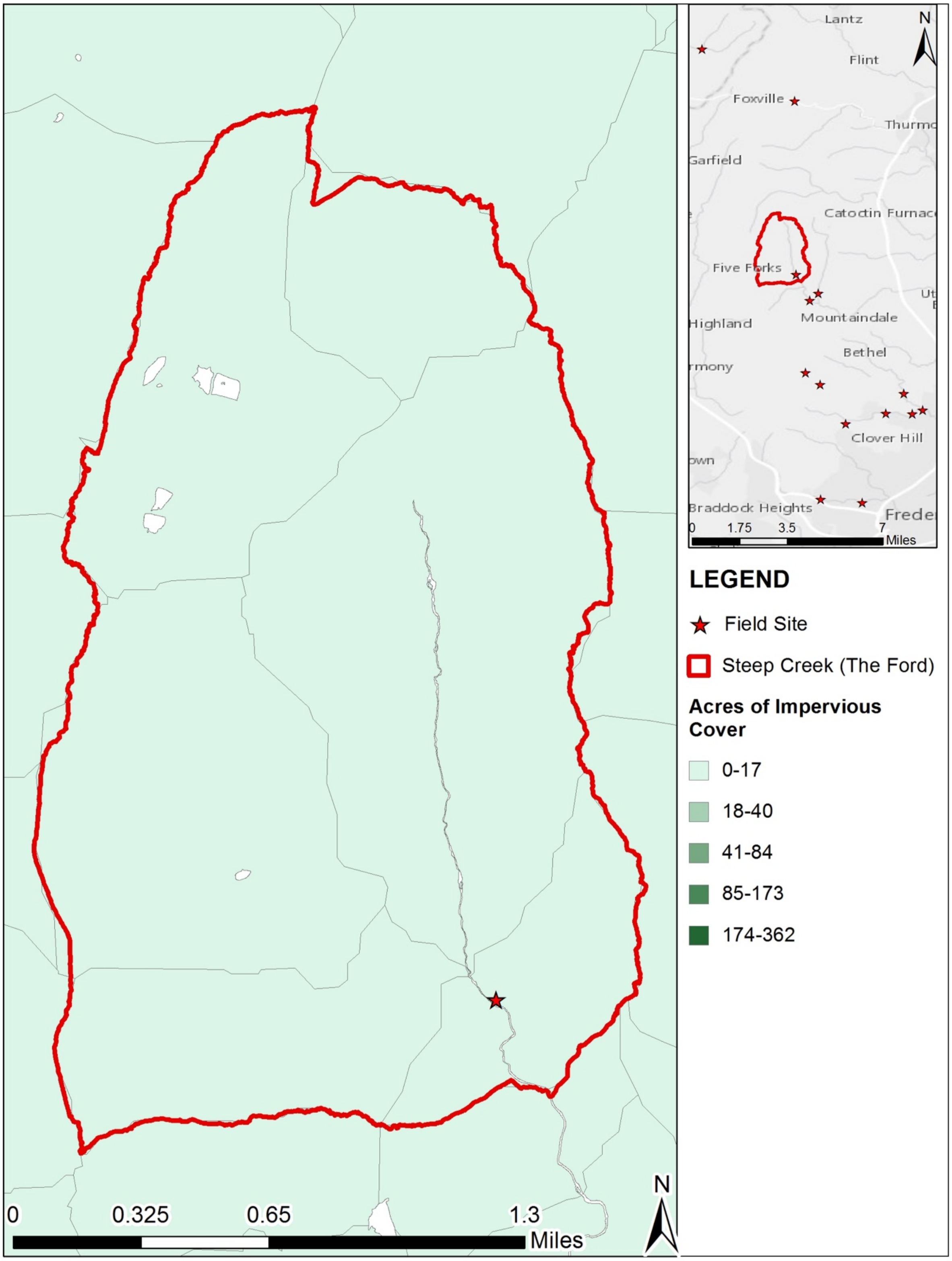

Figure 10. Map of Steep Creek watershed delineation and total acres of impervious cover.

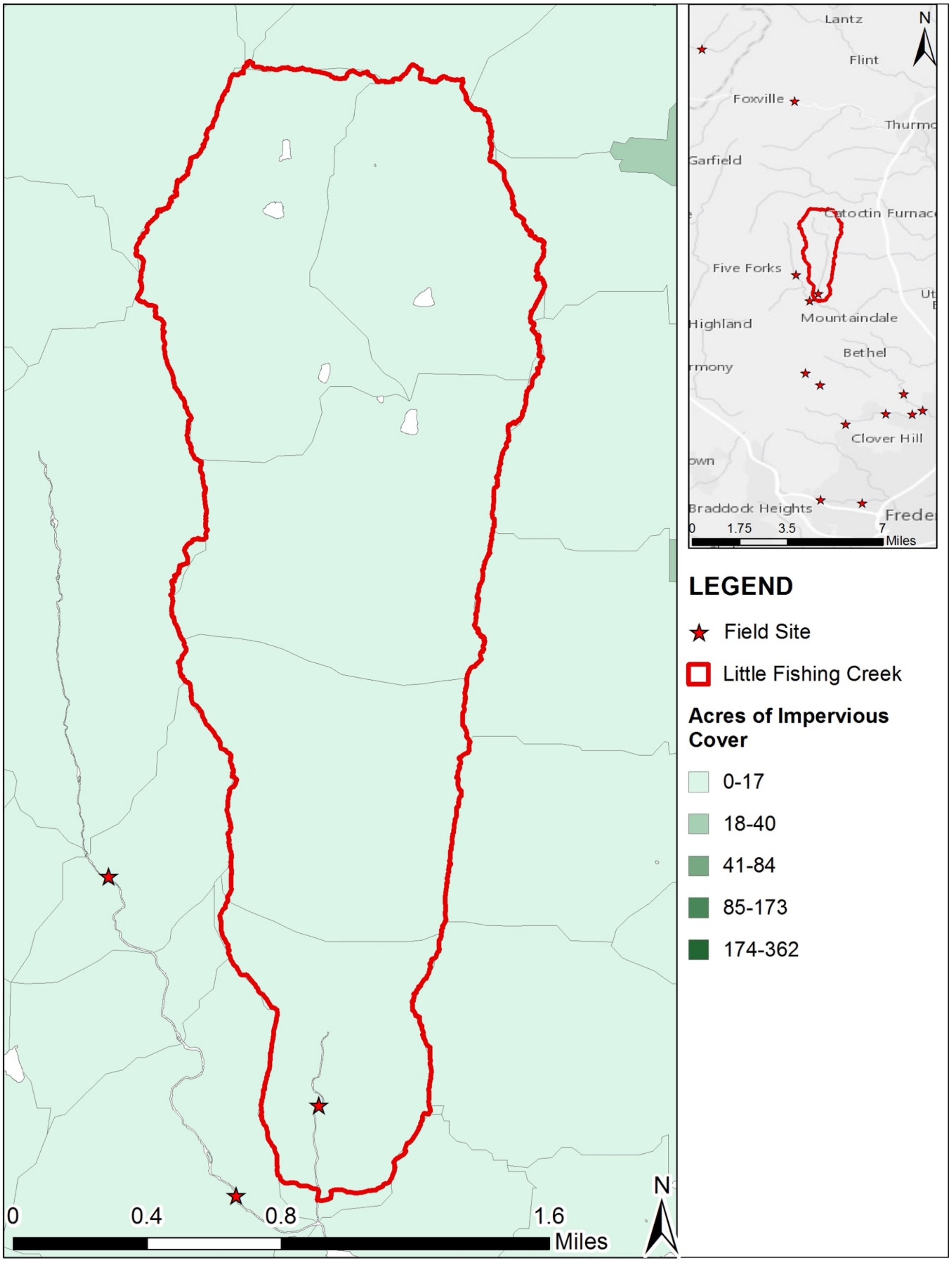

Figure 11. Map of Little Fishing Creek watershed delineation and total acres of impervious cover.

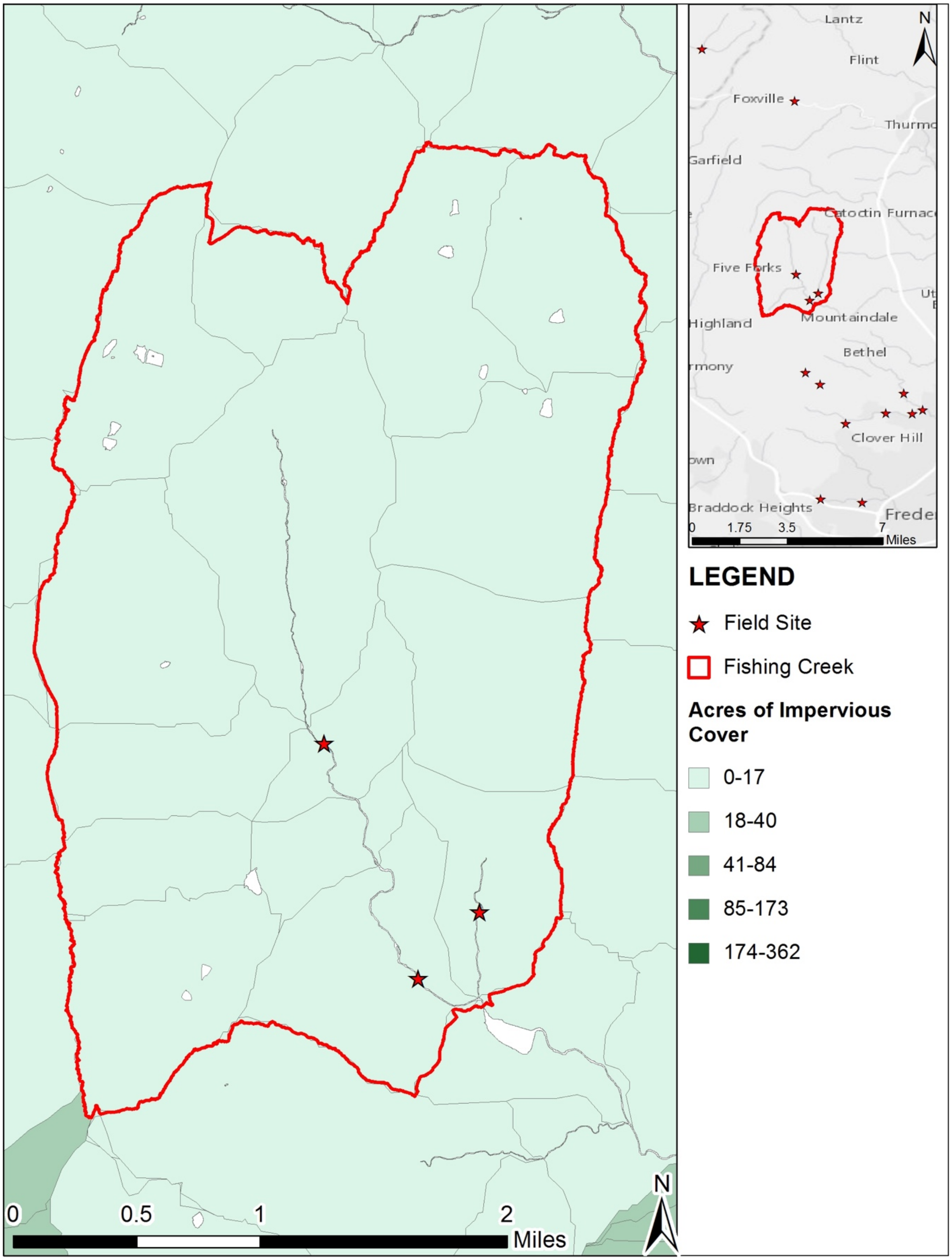

Figure 12. Map of Fishing Creek watershed delineation and total acres of impervious cover.

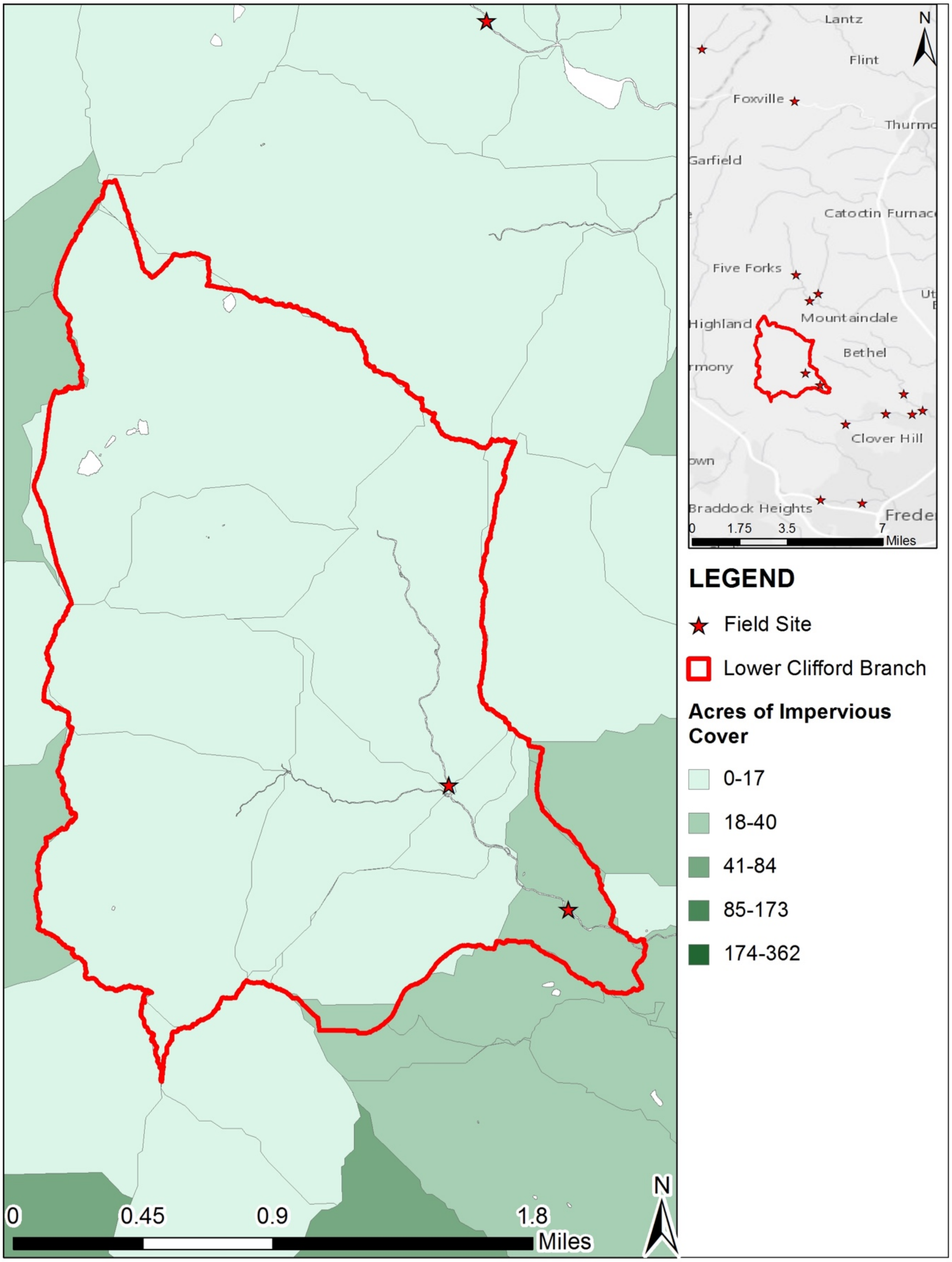

Figure 13. Map of Lower Clifford Branch watershed delineation and total acres of impervious cover.

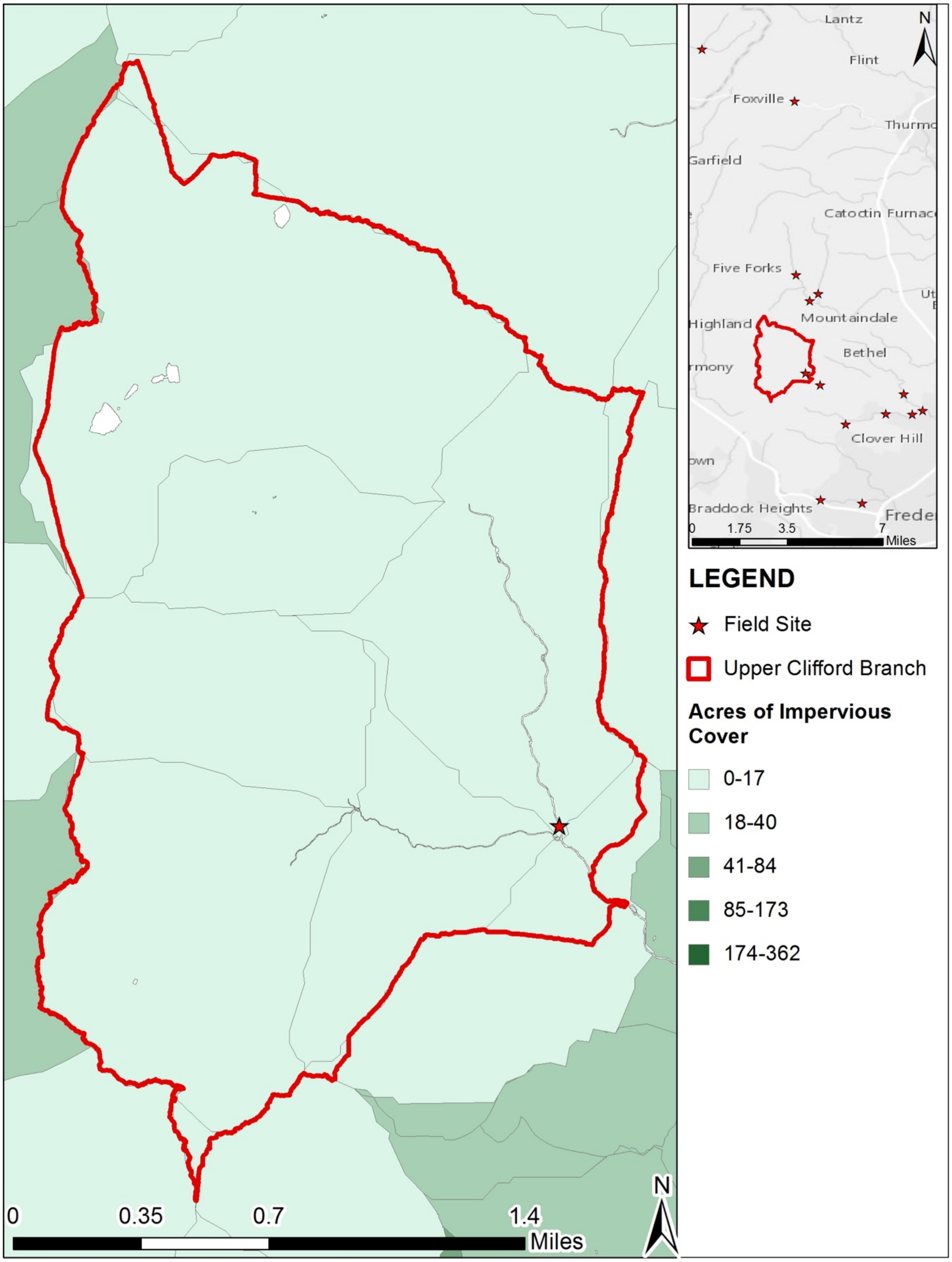

Figure 14. Map of Upper Clifford Branch watershed delineation and total acres of impervious cover.

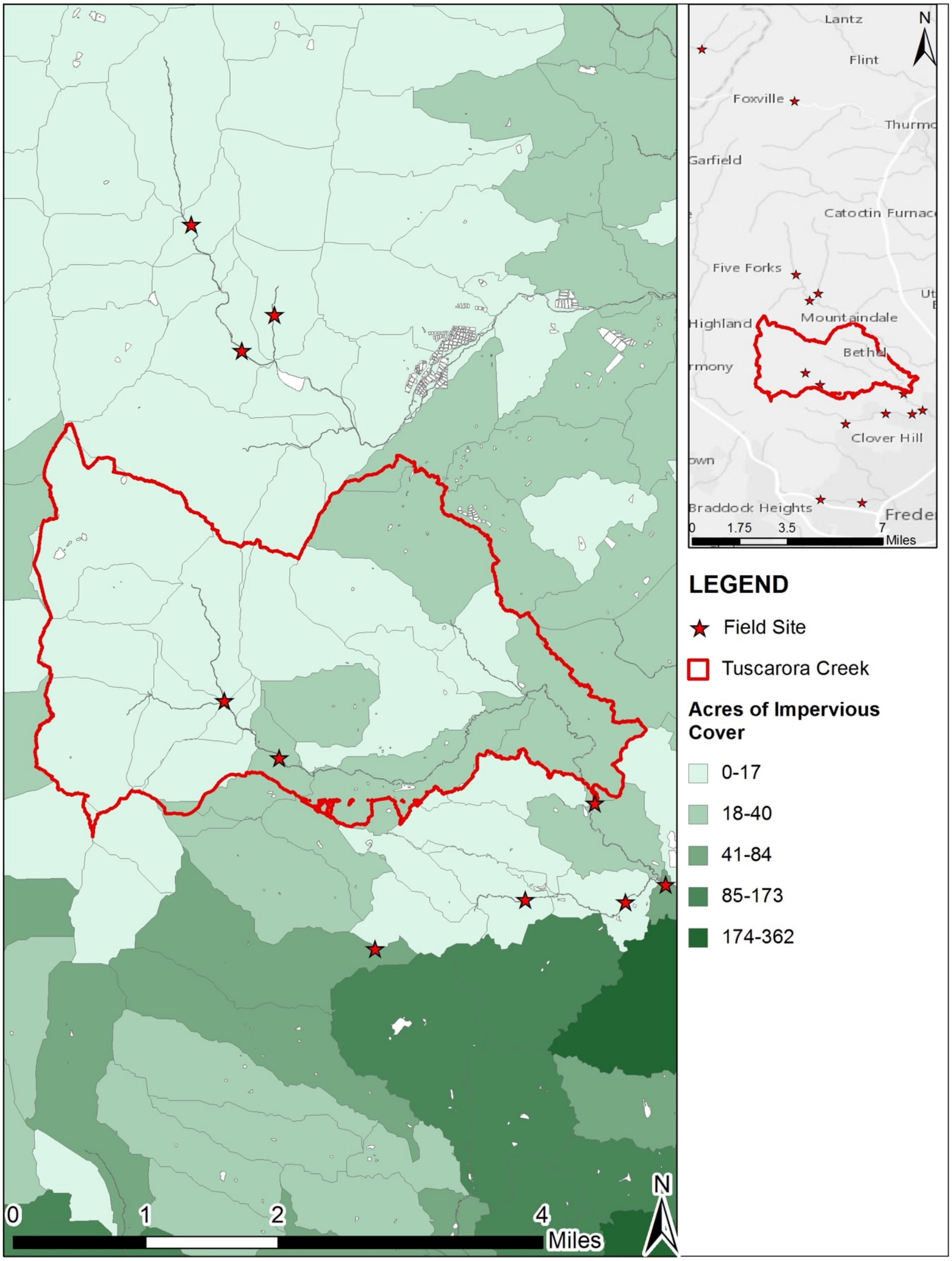

Figure 15. Map of Tuscarora Creek watershed delineation along Bloomfield Road and total acres of impervious cover.

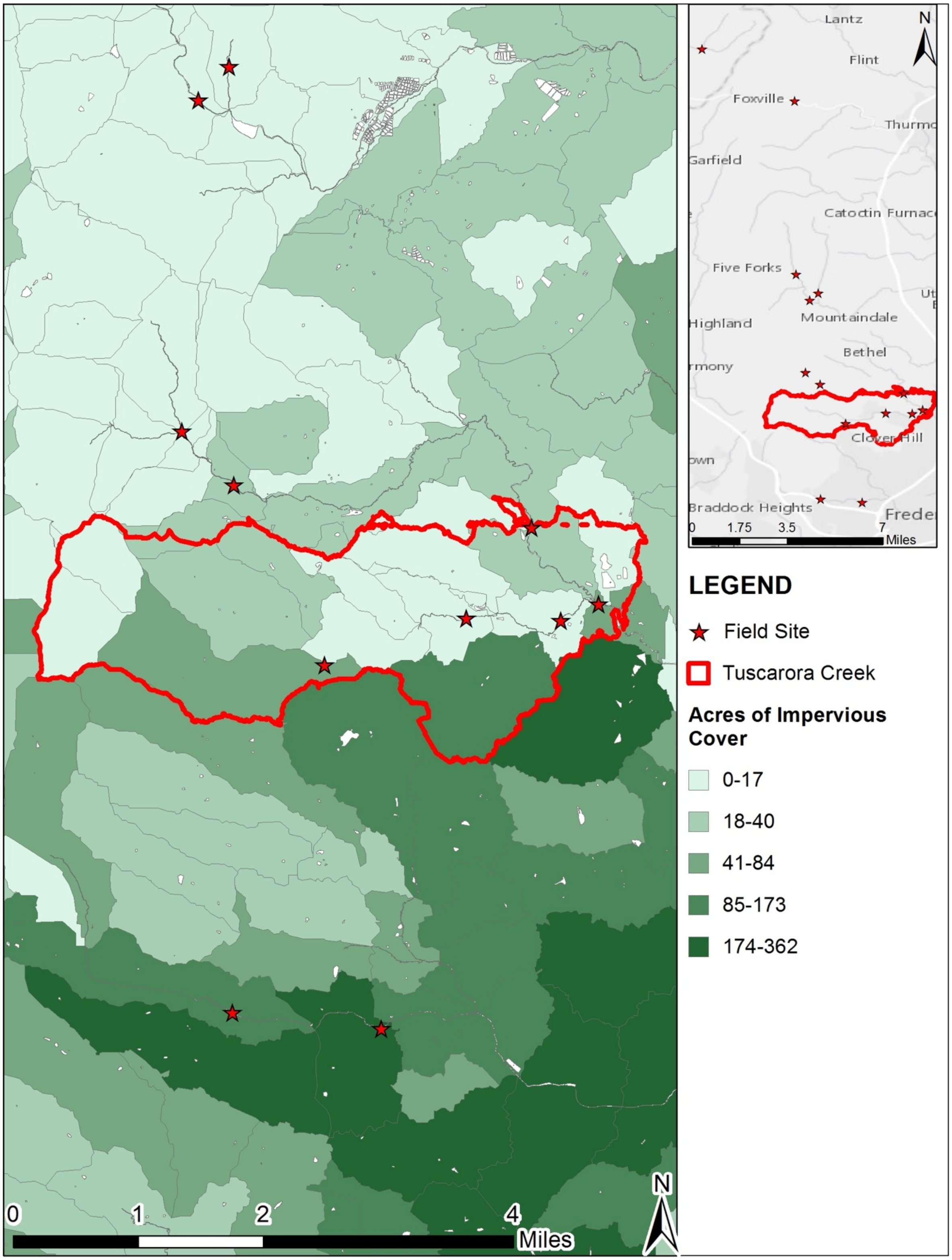

Figure 16. Map of Tuscarora Creek watershed delineation along Willowbrook Road and total acres of impervious cover.

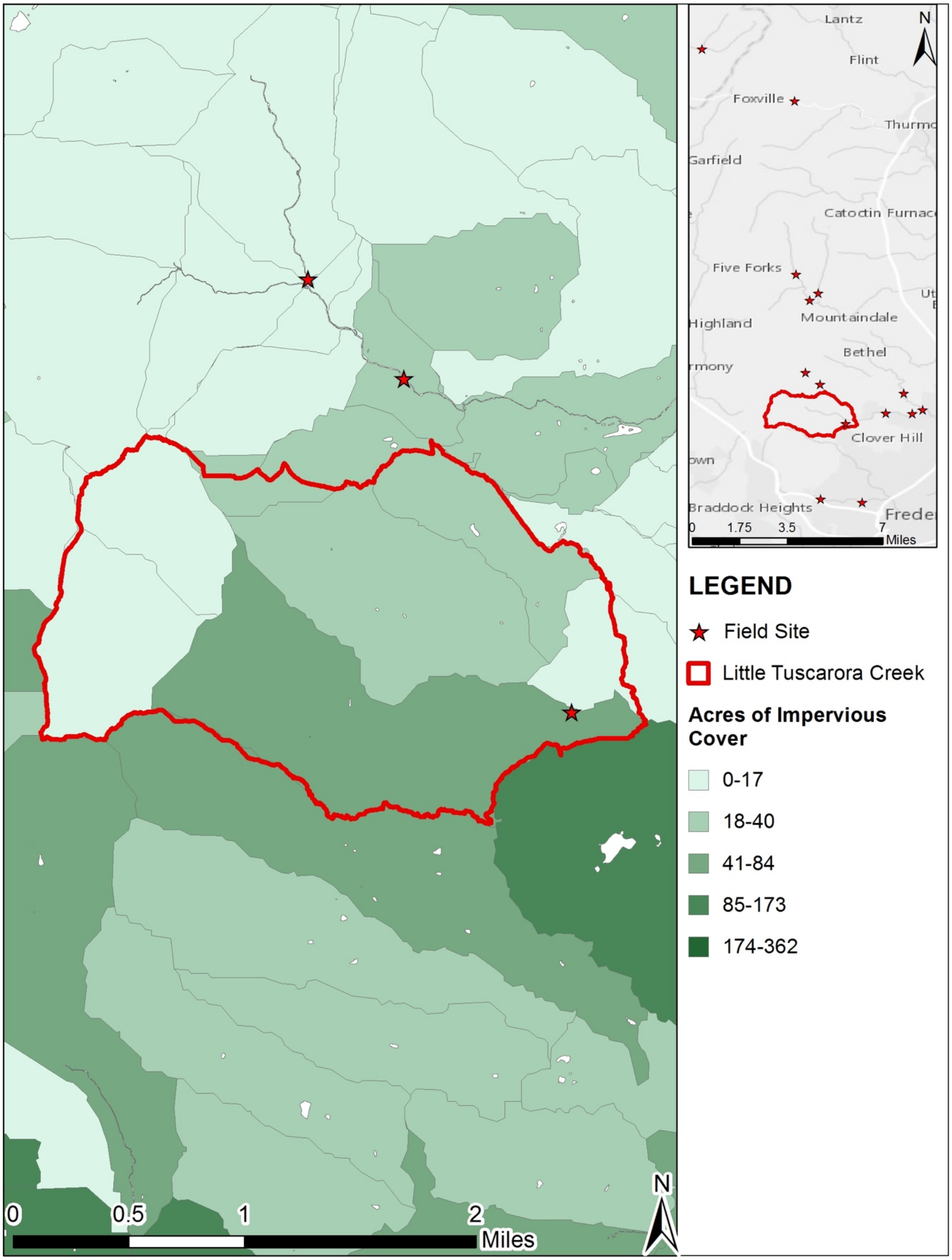

Figure 17. Map of Little Tuscarora Creek watershed delineation along Opossumtown Pike and total acres of impervious cover.

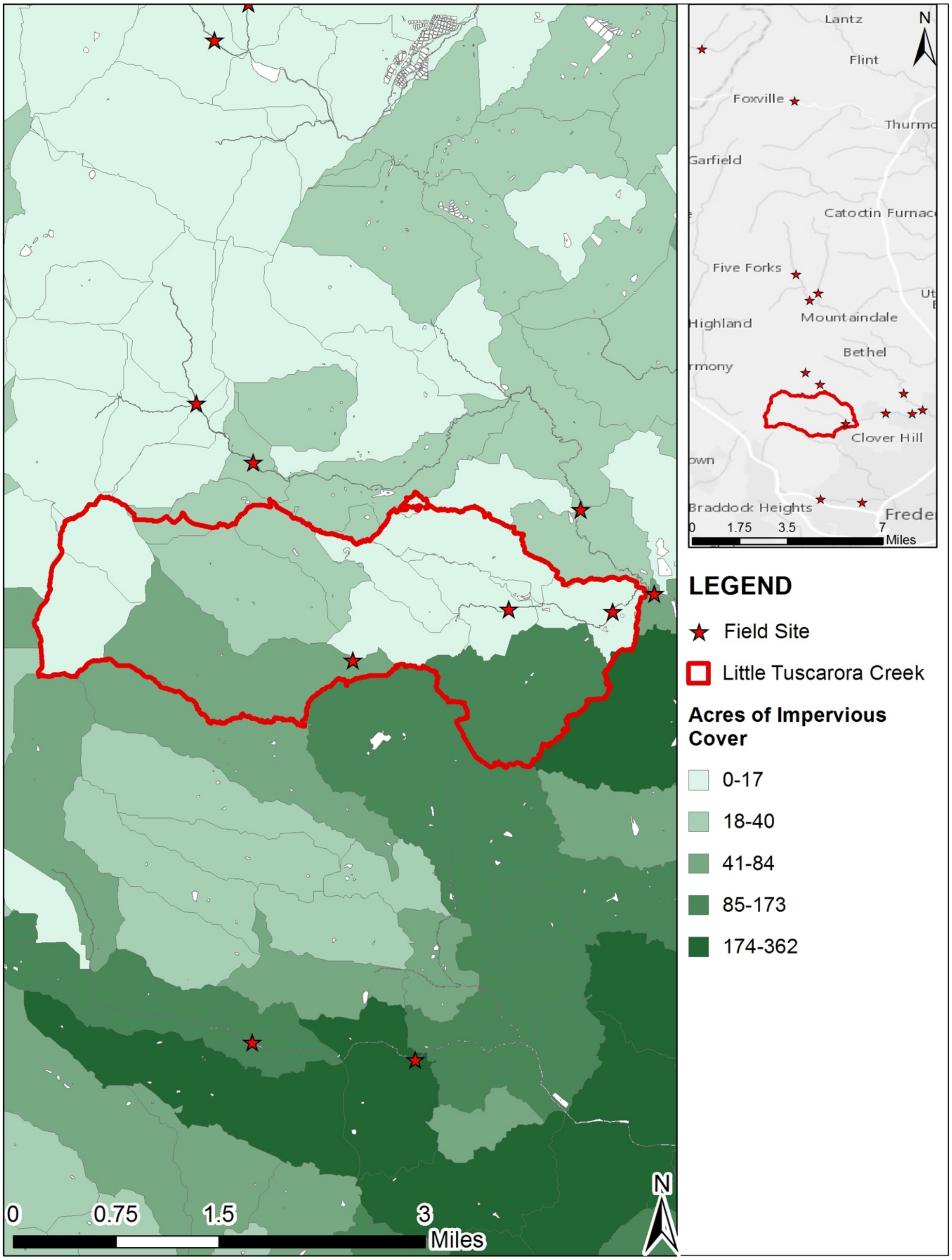

Figure 18. Map of Little Tuscarora Creek watershed delineation along Rocky Springs Road and total acres of impervious cover.

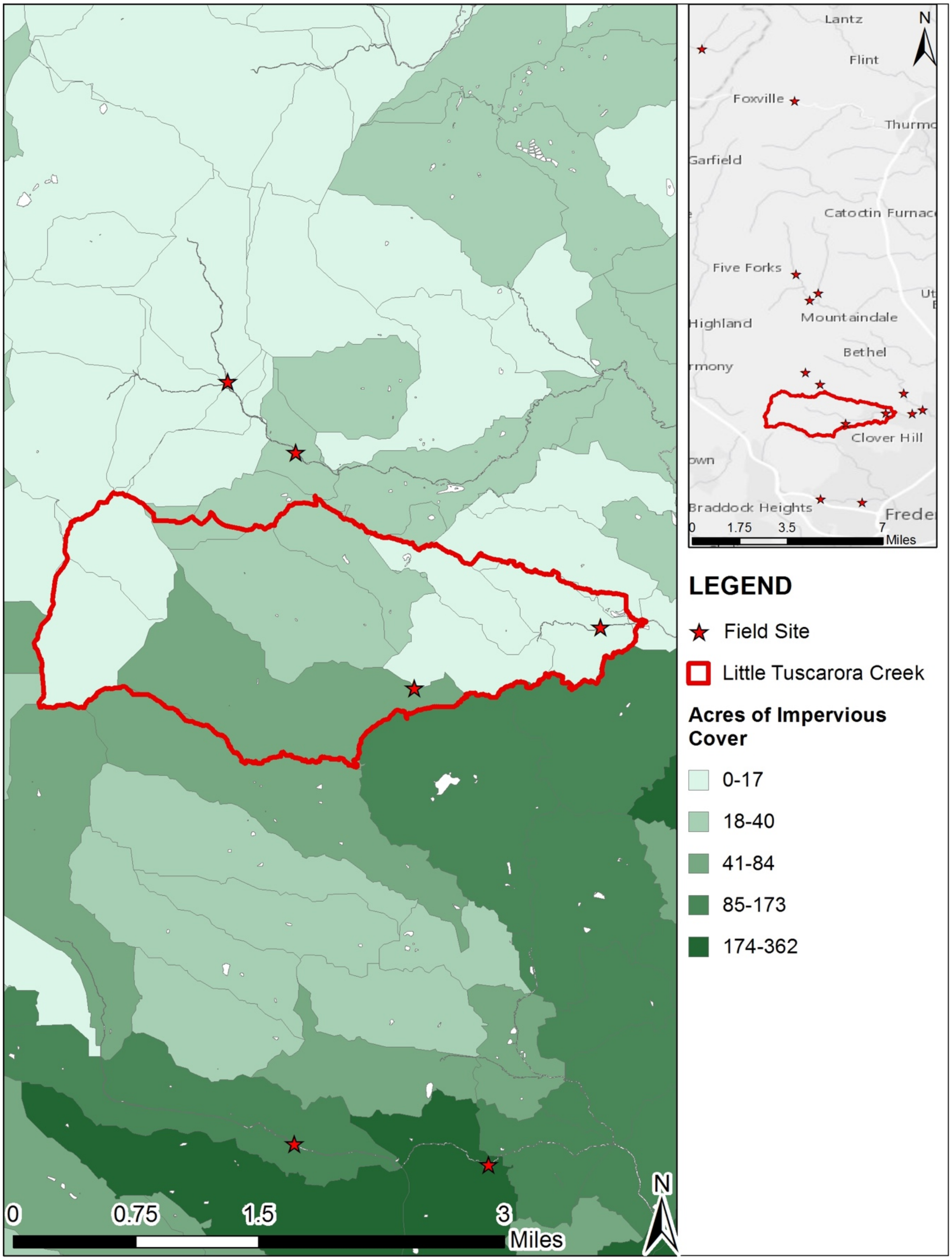

Figure 19. Map of Little Tuscarora Creek watershed delineation along Walter Martz Road and total acres of impervious cover.

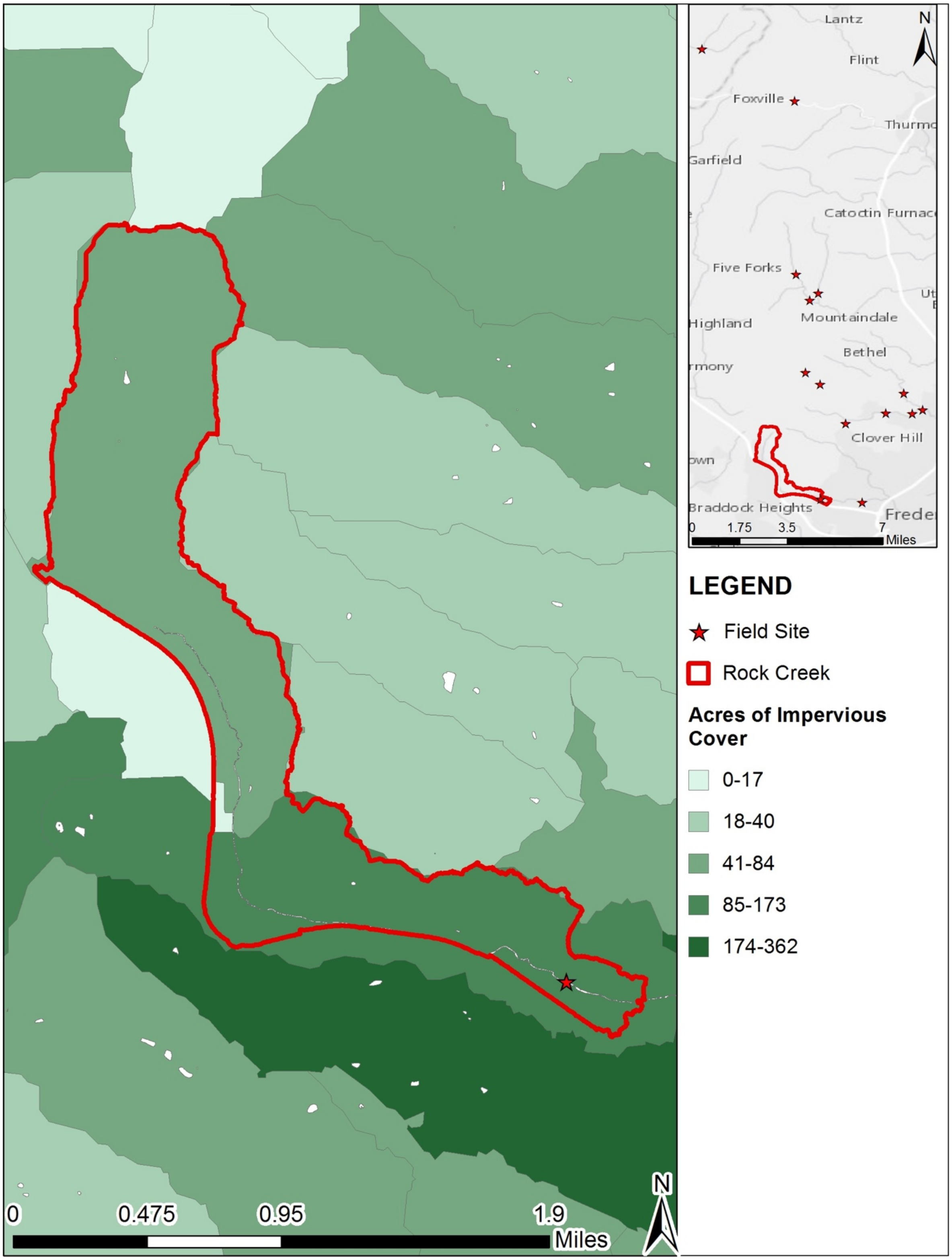

Figure 20. Map of Rock Creek watershed delineation within Stonegate Park and total acres of impervious cover.

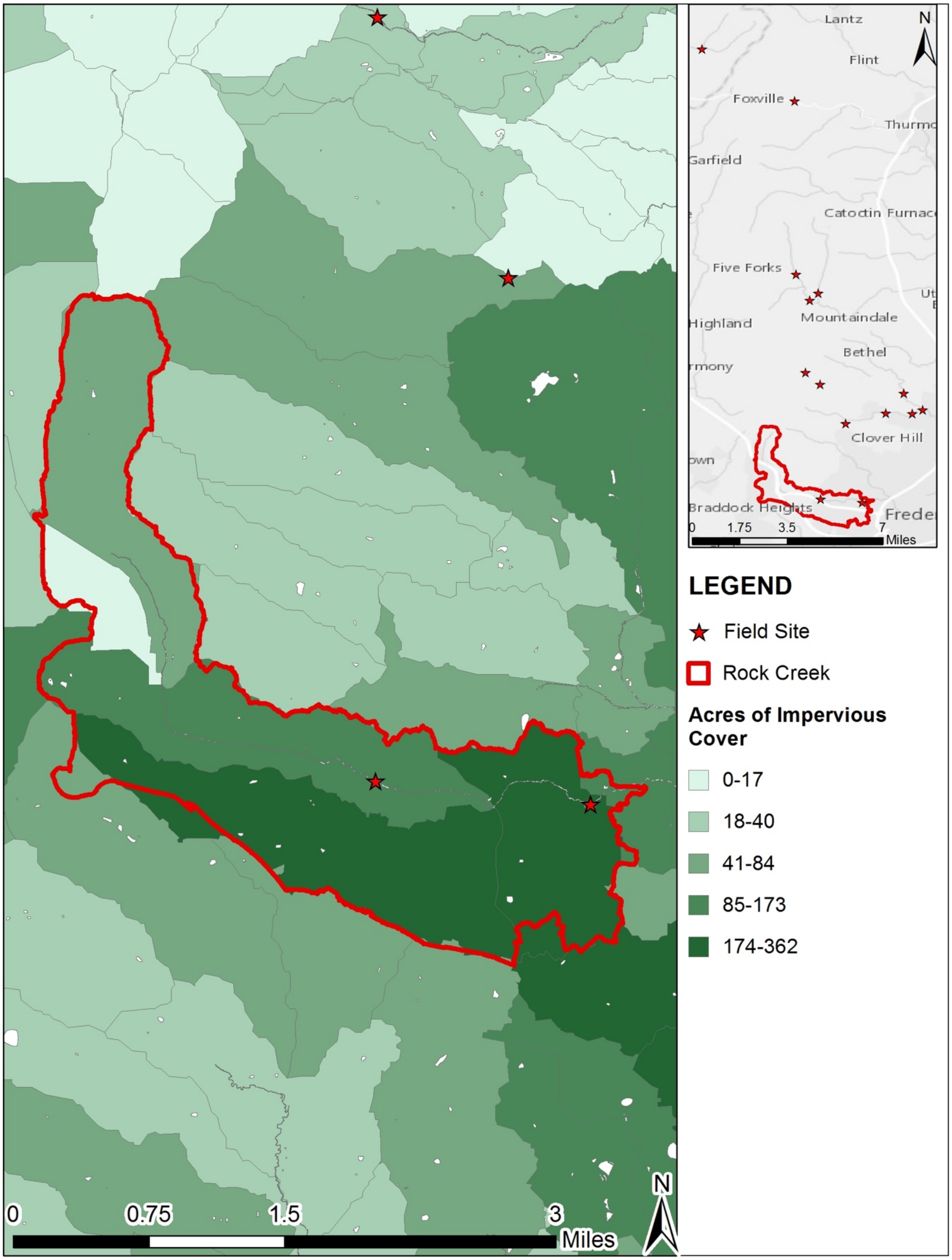

Figure 21. Map of Rock Creek watershed delineation within Willowdale Park and total acres of impervious cover.