Banisteria, Number 38, pages 38-59
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Decline of the Freshwater Mussel Fauna of the North Fork and South Fork Shenandoah Rivers, Virginia

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ABSTRACT

The North and South forks of the Shenandoah River in Virginia flow through predominantly agricultural areas and have been subjected to degradation by point and non-point source pollution (including mercury contamination from factory spills and potential arsenic contamination from pesticide use), sedimentation, alteration of hydrology by impoundments, and other alterations to their flows. The historical mussel fauna of both drainages has not been well documented. A review of published literature, museum collection data, and unpublished reports and field survey data reveals that seven species (*Alasmidonta undulata*, *Alasmidonta varicosa*, *Elliptio complanata*, *Elliptio fisheriana*, *Lampsilis ovata*, *Lasmigona subviridis*, and *Strophitus undulatus*) have been found in the North Fork Shenandoah River (NFSR) watershed. Six of these species (all except *E. fisheriana*) are also known from the South Fork Shenandoah River (SFSR) drainage, as is possibly *Lampsilis cariosa*. *Pyganodon cataracta*, a primarily lentic species, has been recorded once from each drainage, but it is not a member of the free-flowing riverine fauna.

Surveys conducted in the NFSR and SFSR in the 1990s and early 2000s suggested significant declines in mussel populations. During 2008-2009, 87 surveys were conducted at 84 unique sites in these drainages in an effort to assess the current status of the entire freshwater mussel community. Only one species (*E. complanata*) was observed alive in the NFSR drainage and the mainstem SFSR, whereas live individuals of three species (*A. undulata*, *E. complanata*, and *S. undulatus*) were found in headwater tributaries of the SFSR. Shell material was found for all lotic species previously recorded from these drainages with the exception of *L. subviridis.* The results of the 2008-2009 surveys suggest that there has been a near total loss of the mussel fauna of the Shenandoah River drainage in Virginia during the past century.

Key words: *Alasmidonta*, *Elliptio*, freshwater mussel, *Lampsilis*, *Lasmigona*, Shenandoah River, *Strophitus*, Unionidae, Virginia.

INTRODUCTION

Freshwater mussels (Order Unionoida) are of high conservation concern (Williams et al., 1993; Strayer et al., 2004). Approximately 40% (115 of 288) of the United States species are listed as critically imperiled or imperiled by NatureServe (Master et al., 2000). Thirty-seven species (about 12%) are presumed to be extinct or possibly extinct (Master et al., 2000). Twenty percent of the U.S. mussel fauna receives some federal protection under the Endangered Species Act (Master et al., 2000). Almost one quarter of Virginia's freshwater mussel species (20 of 81) are federally listed (Roble, 2010). The demise of many mussel species has been linked to the degradation of water quality and loss of aquatic habitats due to sedimentation or channel alteration (Helfrich & Neves, 2003; Strayer et al., 2004).

In 2006, the Shenandoah River was ranked as the fifth most "endangered" river in the United States by the conservation group American Rivers (2006). High population growth, suburban development, and recent evidence of fish kills within the drainage contributed to this ranking. With regard to the freshwater mussel fauna, historical chemical (i.e., mercury) pollution essentially extirpated mussel populations of the South Fork Shenandoah River (SFSR; Carter, 1977), but the North Fork Shenandoah River (NFSR) was thought to

be unaffected. Mercury, in the form of methyl mercury, has been shown to bioaccumulate in freshwater mussel tissue and may cause both hormonal changes and potential shifts in energy allocation in affected individuals (Kernaghan et al., 2011). The impacts of mercury on freshwater fish are also well documented, and include reduced reproductive success, behavioral changes that may increase mortality, and direct mortality (Schweiger et al., 2006). Since fish are hosts for mussel glochidia, it is plausible that mercury pollution may indirectly impact mussel reproduction; however, further studies are needed to examine this.

Additionally, there was heavy use of lead arsenate as a pesticide throughout the Shenandoah Valley from the late 1800s to the 1950s (VDCR-DSW, 2009). High levels of arsenic have been measured in fish tissue samples taken from the Shenandoah Valley. It is hypothesized that these high levels may be related to the pesticide, or to the use of arsenic as an additive to poultry feeds and subsequent excretion in poultry manure (VDCR-DSW, 2009). Arsenic can bioconcentrate in an organism, but it does not bioaccumulate up the food chain (Eisler, 1988). The impacts of arsenic on an organism are variable even between closely related species (Eisler, 1988). There is little published data concerning the effects of arsenic on freshwater mussel species, but marine mussels have been shown to bioconcentrate arsenic and exhibit slower growth rates (Eisler, 1988). It is unknown if the presence of arsenic in the Shenandoah River system impacted the mussel fauna either directly or indirectly.

Historically, the NFSR and SFSR drainages were sampled on several occasions (1912-1968) by a number of eminent malacologists, including Arnold E. Ortmann, Joseph P. E. Morrison, William J. Clench, and David H. Stansbery (see details below). More recently, surveys of selected sites in the NFSR by biologists from the Virginia Department of Conservation and Recreation – Division of Natural Heritage (DCR-DNH) during the early to mid-1990s suggested that mussel populations had seriously declined based on encounters with high numbers of fresh dead and relict shell material and few live individuals. In an effort to assess the current status of the entire freshwater mussel community of the NFSR and SFSR drainages, surveys were conducted during 2008-2009 by DCR-DNH. In particular, species of state concern were targeted, including the Brook Floater (*Alasmidonta varicosa*, state endangered), Green Floater (*Lasmigona subviridis*, state threatened), and Yellow Lampmussel (*Lampsilis cariosa*, state special concern [category subsequently abolished]).

STUDY AREAS

North Fork Shenandoah River

The NFSR mainstem flows through the Valley and Ridge physiographic province of Virginia for approximately 107 miles (172 km), draining an area of 1033 mi^2 (2675 km^2; Krstolic et al., 2006). The watershed is characterized by rolling hills and valleys and is bordered to the east by the Massanutten Mountains. The watershed drains all of Shenandoah County and portions of Frederick, Page, Rockingham, and Warren counties, Virginia and Hardy County, West Virginia (Fig. 1). The headwaters of the mainstem NFSR are in Hardy County, West Virginia and Rockingham County, Virginia. From the headwaters, the river flows east before turning northeast in Timberville, roughly paralleling Interstate 81 as far as Strasburg. At Strasburg, the NFSR turns east again, paralleling Interstate 66, until joining the SFSR in Front Royal to form the Shenandoah River.

The ridges of the physiographic region are formed by resistant materials such as quartzite and sandstone, while the valleys are comprised of more highly erodible limestone, shale, and dolomite (Krstolic et al., 2006). The upper (headwater) section of the NFSR cuts through primarily sandstone formations and forms wide meanders along the eastern edge of the valley. After the NFSR passes Edinburg, the meanders become very narrow (called the Seven Bends area), where it follows fracture zones in the Martinsburg shale (Hack & Young, 1959). In the middle and lower reaches, the NFSR has cut down to the bedrock, thus the channel is wide and shallow (Krstolic et al., 2006).

Alteration of the NFSR channel began in the early 1800s with wing dams and cut-throughs of bedrock ledges built to facilitate river navigation (Trout, 1997). Today, the NFSR is crossed by several low-water bridges. In addition, six dams, ranging in height from 5 to 16 ft (1.5-4.8 m), were built between 1900 and the 1920s, primarily for hydroelectric power and water supply sources for surrounding cities.

South Fork Shenandoah River

The SFSR mainstem flows through the Valley and Ridge physiographic province of Virginia for approximately 95 miles (153 km), draining an area of 1671 mi^2 (4328 km^2). Similar to the NFSR, rolling hills and valleys characterize the watershed, which is bordered to the east by the Blue Ridge Mountains. The northern portion of the drainage is bordered to the west

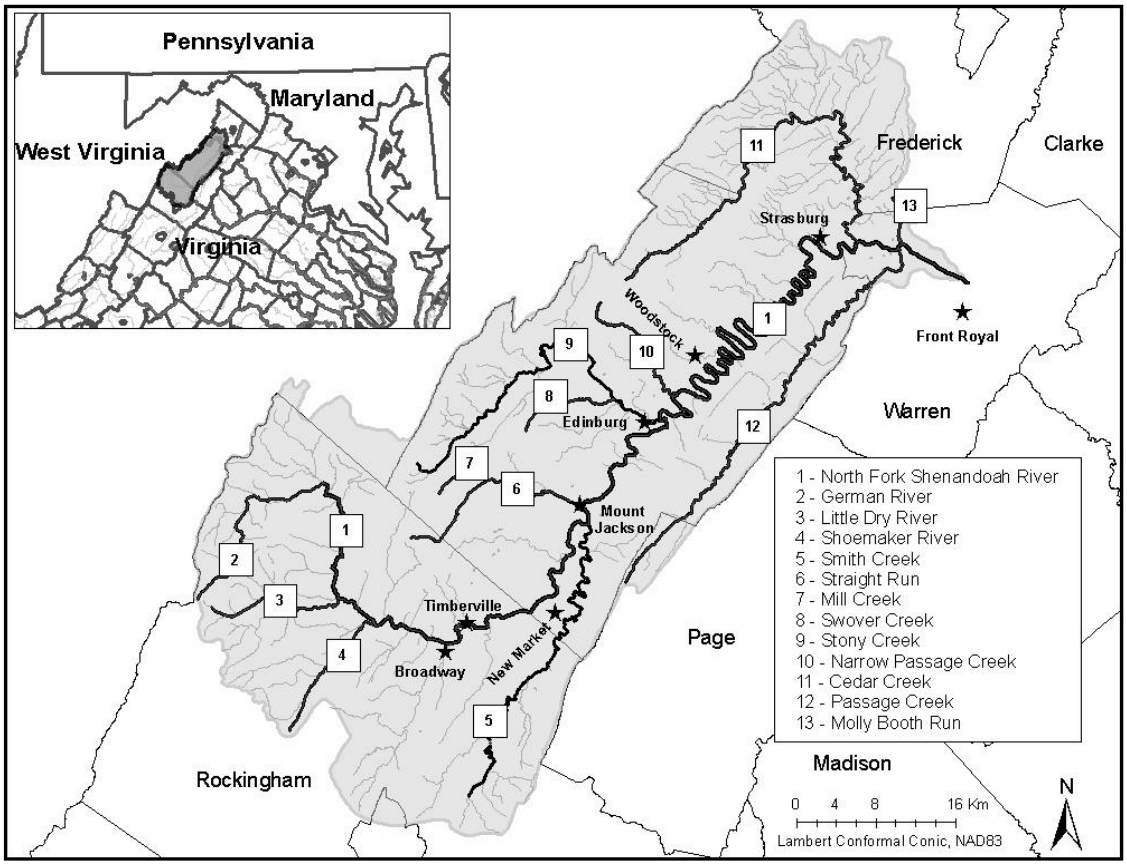

Fig. 1. Drainage area (gray shaded) of the North Fork Shenandoah River, Virginia.

by the Massanutten Mountains. The watershed drains portions of Augusta, Rockingham, Page, and Warren counties, Virginia (Fig. 2). The SFSR begins in Port Republic, Virginia at the confluence of the North and South rivers. It flows generally to the northeast, roughly parallel to U.S. Route 340. It meets the NFSR at Front Royal, Virginia to form the Shenandoah River.

The upper reaches of the SFSR and its main headwater tributaries (i.e., North, Middle, and South rivers) flow through the Massanutten Mountain syncline, which extends for about 30 miles (48 km) from the southwest end of the mountain to near the junction of U.S. Routes 340 and 11 (Frye, 1986). The core of the syncline here is the erodible Martinsburg shale. As the SFSR continues north, tight meanders are common where it follows the fracture zones of the Martinsburg shale (Hack, 1965). Similar to the NFSR, the middle and lower reaches of the SFSR have cut down to the bedrock, thus the channel is wide and shallow.

The SFSR from Port Republic to Front Royal was open to navigation in 1807 (Trout, 1997). This included construction of wing dams, cut-throughs of bedrock ledges, and mill-shoots (Trout, 1997). Today, there are four dams, constructed in the 1920s, primarily for hydroelectric power. They range from 15 to 28 feet (4.6-8.5 m) high. In addition, the SFSR is crossed by several low-water bridges.

HISTORICAL MUSSEL FAUNA OF THE SHENANDOAH RIVER DRAINAGE

The historical mussel fauna of the Shenandoah River drainage is not well documented, although Ortmann (1919) reported seven species and Johnson (1970) nine species from this drainage (Table 1). To supplement these reports, we searched eight online mollusk collection databases for specimen records from the Shenandoah River drainage. Collectively, the databases from the Academy of Natural Sciences of Philadelphia (ANSP, 22 records, 1916-1980, six others without dates) Carnegie Museum of Natural History (CMNH, 21 records, 1911-1937, two others without dates), Museum of Comparative Zoology, Harvard University (MCZ, 14 records, 1934-1968), National Museum of Natural History (NMNH, 14 records, 1934-

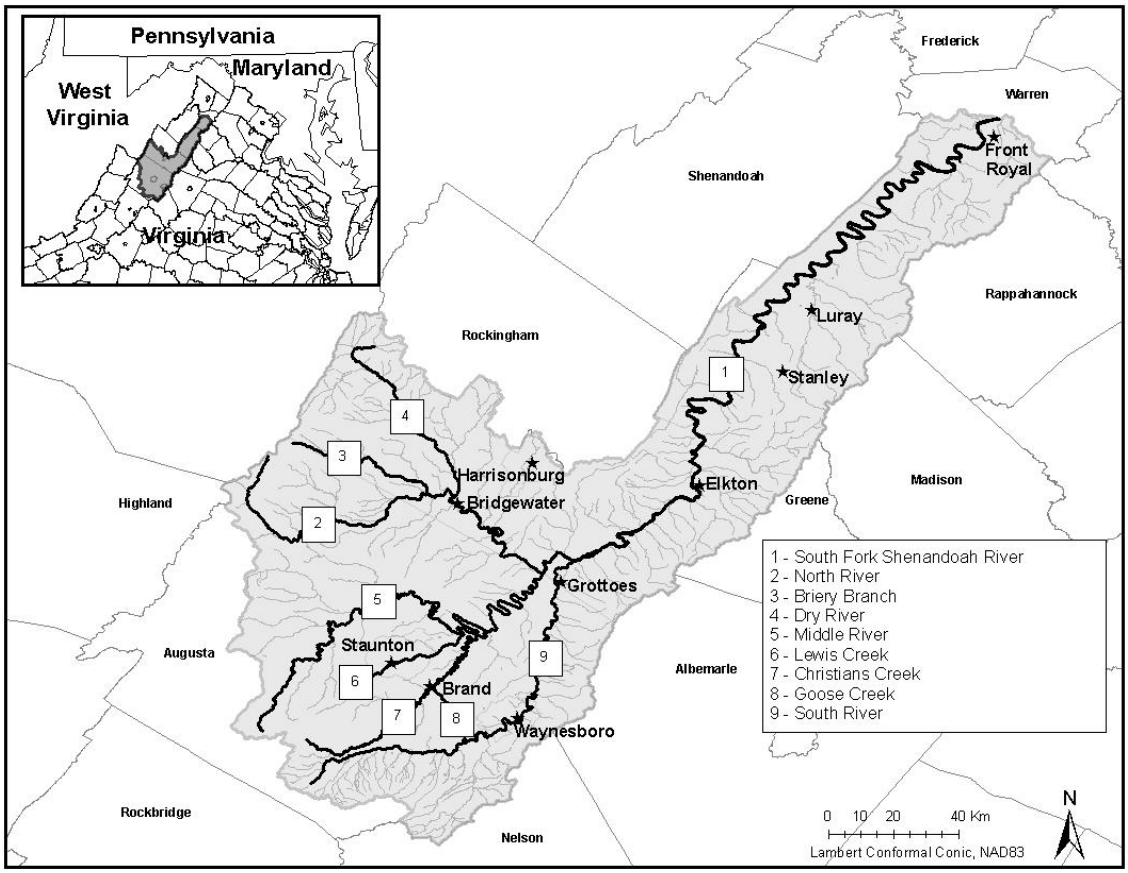

Fig. 2. Drainage area (gray shaded) of the South Fork Shenandoah River, Virginia.

1970, 10 others without dates), Museum of Biological Diversity, Ohio State University (OSUM, 11 records, 1968-1979), and the Museum of Zoology, University of Michigan (UMMZ, six records, 1928-1950, four others without dates), yielded records for nine mussel species (Table 1; no records were found in the online databases of the Illinois Natural History Survey or the Florida Museum of Natural History). Based on these sources (specimens not examined), seven species are recorded from the NFSR drainage, represented by 26 records spanning collection dates from 1912 to 1970 (plus eight collections without dates). These species are *Alasmidonta undulata* (Triangle Floater), *Alasmidonta varicosa*, *Elliptio complanata* (Eastern Elliptio), *Elliptio fisheriana* (Northern Lance), *Lampsilis ovata* (Pocketbook), *Lasmigona subviridis*, and *Strophitus undulatus* (Creeper). Available records for the Shenandoah River mainstem indicate a similar species composition. A search of museum and literature records revealed the historical presence of a similar mussel fauna in the SFSR drainage, including all of the NFSR species except *E. fisheriana* and the addition of *Lampsilis cariosa* (but see below).

Pyganodon cataracta (Eastern Floater) has been recorded from each drainage once. Ortmann collected this species (CMNH #61.5919) in 1912 along the South River at Waynesboro, noting (Ortmann, 1919: 157) that the specimens were "thin-shelled creek-form from a quiet pool." In 2005, two live individuals were found in Stony Creek above Lake Laura in the NFSR drainage (The Catena Group, 2006). This species thrives in nutrient-rich, often man-made impoundments and is not a member of the free-flowing riverine fauna.

In addition to the review of museum collection databases for historical records, we obtained field survey information from more recent literature, unpublished reports and field survey data, personal communications with malacologists, and recent collections (specimens examined) in the Virginia Museum of Natural History (Table 2). Fifteen total sources were found, collectively accounting for 84 surveys conducted between 1990 and 2007. The following is a brief summary of the known occurrences for each species in the NFSR and SFSR based on this historical information (Table 1) and known recent (herein defined as 1990-2007) surveys (Table 2).

Table 1. Historical (pre-1990) museum records of freshwater mussels from the Shenandoah River drainage. Records are taken from the following sources: Academy of Natural Sciences of Philadelphia (ANSP, Philadelphia, PA), Carnegie Museum of Natural History (CMNH, Pittsburgh, PA), Museum of Comparative Zoology (MCZ, Harvard University, Cambridge, MA), National Museum of Natural History (NMNH, Smithsonian Institution, Washington, DC), Ohio State University Museum of Biological Diversity (OSUM, Columbus, OH), University of Michigan Museum of Zoology (UMMZ, Ann Arbor, MI), Ortmann (1919), Johnson (1970), Clarke (1981), and the personal collection of A. Gerberich (via R. Neves, pers. comm.). 1 - same as CMNH record; 2 - cites Ortmann (1919); 3 - cites 'USNM' = NMNH; 4 - same as MCZ record. Locations or collection events that are known or likely to be equivalent are indicated with the same superscript letter.

River **Location**	***Alasmidonta undulata***	***Alasmidonta varicosa***	***Elliptio complanata***	***Elliptio fisheriana***	***Lampsilis cariosa***	***Lampsilis ovata***	***Lasmigona subviridis***	***Pyganodon cataracta***	***Strophitus undulatus***
North Fork Shenandoah River (NFSR) Drainage									
NFSR Broadway	CMNH Ortmann[1] Johnson[2] Clarke[2]		CMNH Ortmann[1] as *E. violaceus*						CMNH Ortmann[1]
NFSR Mt. Jackson			UMMZ						
NFSR E of Woodstock (possibly Burnshire Bridge, Rt. 758)		MCZ NMNH Johnson[4]	MCZ Johnson[4] Clarke[4]	MCZ as *E. productus* Johnson as *E. lanceolata*		MCZ as *L. ovata ventricosa*			MCZ as *S. rugosus* Johnson
NFSR Stonewall Mill (= Rt. 663)		NMNH							
NFSR 'on 5th bend of 7 bends' ca. 3 mi E Woodstock		OSUM	OSUM	OSUM as *E. producta*					OSUM
NFSR VA Rt. 55 bridge, ca. 2 mi SE Strasburg		MCZ [c] OSUM [c] Gerberich	NMNH MCZ [c] OSUM [c]	NMNH as *E. angustatus* MCZ [c] as *E. lanceolata* OSUM [c] as *E. producta*		NMNH as *L. ventricosa* MCZ [c] as *L. ovata ventricosa* OSUM [c] as *L. cardium*	NMNH MCZ [c] OSUM [c]		NMNH
NFSR Riverton			UMMZ as *E. dilatata*						
Passage Creek 2 mi SW Seven Fountains	NMNH		Johnson[3]						
South Fork Shenandoah River (SFSR) Drainage									
Christians Creek ca. 4 mi SE Staunton, at Brand	MCZ [d] OSUM [d]								MCZ [d] OSUM [d]
North River Weyers Cave			Johnson						
South River Waynesboro	CMNH Ortmann[1] Johnson[2]	CMNH Ortmann[1]	ANSP CMNH Ortmann[1] as *E. violaceus*					CMNH Ortmann[1] Johnson[2]	CMNH Ortmann[1] Johnson[2]
SFSR Elkton	CMNH Ortmann[1] Johnson[2] Clarke[2]	CMNH Ortmann[1]	CMNH Ortmann[1] as *E. violaceus*				CMNH Ortmann[1] Johnson[2]		CMNH Ortmann[1] Johnson[2]

Table 1 (continued).

River Location	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis cariosa*	*Lampsilis ovata*	*Lasmigona subviridis*	*Pyganodon cataracta*	*Strophitus undulatus*
South Fork Shenandoah River (SFSR) Drainage									
SFSR US Rt. 211 W of Luray							NMNH UMMZ		UMMZ
SFSR below Luray			ANSP			ANSP			ANSP
SFSR 2 mi W Compton		ANSP as *A. marginata*	ANSP			ANSP	ANSP		ANSP
SFSR Hazard Mill Rec. Area, 1.5 mi W Bentonville			ANSP			ANSP			
SFSR Rt. 613 near Bentonville [a]		ANSP as *A. marginata*	ANSP NMNH UMMZ			NMNH	ANSP		ANSP NMNH
SFSR ca. 8 mi SW Front Royal [a]			NMNH [e] UMMZ [e]		NMNH				NMNH
SFSR 2 mi NW Limeton		ANSP as *A. marginata*	ANSP			ANSP as *L. cardium*			
SFSR Front Royal			UMMZ						
SFSR Riverton		MCZ Johnson							
Shenandoah River (SR) Mainstem									
SR Front Royal							NMNH		
SR 7.0 mi SE Berryville (=US Rt. 17/50)				UMMZ as *E. shepardiana*		UMMZ			
SR ESE Berryville [b]						MCZ			
SR VA Rt. 7 [b]			UMMZ			NMNH as *L. ventricosa* UMMZ			
SR Ashby Gap to Snickers Gap (= US Rt. 17 to VA Rt. 7)	NMNH	NMNH				NMNH as *L. ventricosa*	NMNH		NMNH
SR Harpers Ferry, Jefferson Co., West Virginia	ANSP CMNH Ortmann[1] Johnson Clarke[2]	ANSP CMNH UMMZ Ortmann[1]	CMNH UMMZ	ANSP as *E. fisherianus* & *E. lanceolatus* CMNH as *E. producta* Ortmann as *E. cupreus*	CMNH	CMNH & UMMZ as *L. cardium* Johnson	CMNH Ortmann[1] Johnson		ANSP
SR Jefferson Co., West Virginia				ANSP, MCZ, & UMMZ as *E.producta/us* Johnson as *E. lanceolata*					

Alasmidonta undulata, Triangle Floater

The first known NFSR record of *A. undulata* is a specimen collected by Ortmann in 1912 from Broadway (CMNH #61.5932). Presumably, this is the record cited by Ortmann (1919), Johnson (1970), and Clarke (1981). There is a 1938 collection from Passage Creek by J. P. E. Morrison (2 mi SW of Seven Fountains, NMNH #529660).

More recently within the NFSR drainage, DCR-DNH reported a few relict shells from Chapman Landing in 1995 (Roble, 1998), and Johnson & Neves (2004) reported one shell from Rt. 667, just east of Woodstock in 2004. The last known live specimens were observed by DCR-DNH in Smith Creek in 1990 (Rt. 620 and Mt. Airy) and 1991 (U.S. Rt. 211). Eleven additional surveys in 1990 (DCR-DNH field surveys), 1994 (VDGIF, 2009), 1995 (Roble, 1998; Winston, 1995), 1996 (Winston, 1996), 2005 (The Catena Group, 2006; VDGIF, 2009), and 2006 (VDGIF, 2009) along Smith Creek, including U.S. Rt. 211, found only shell material at eight locations (Table 2). There is no evidence that this species has been found in other tributaries to the NFSR.

In the SFSR drainage, *A. undulata* is recorded from the mainstem at Elkton based on a 1912 collection by Ortmann (CMNH #61.5931; Ortmann, 1919; Johnson, 1970; Clarke, 1981). Ortmann (1919) and Johnson (1970) also cite a 1912 collection (by Ortmann) from the South River, a main tributary to the SFSR, at Waynesboro (CMNH #61.5925). Material collected on 8 September 1968 by W. J. Clench and D. H. Stansbery from Christians Creek (a tributary to the Middle River) at Brand (ca. 4 mi SE Staunton) is housed at MCZ (#266575) and OSUM (#20528).

More recent observations of *A. undulata* have been made in the SFSR drainage (Table 2). Live individuals were observed in Christians Creek at Rt. 831 (Neves, 2003) and the South River downstream of Rt. 657 (DCR-DNH 2000 survey; only shells were found in the same area during a 2007 survey by DCR-DNH). Single shells were reported from both the South River at Rt. 652 (Neves, 2003) and the Middle River SW of Spring Hill (B. Watson, pers. comm.). We are not aware of any recent mussel surveys in the North River.

Alasmidonta undulata was also collected historically from the Shenandoah River mainstem in Virginia between U.S. Rt. 17 and VA Rt. 7 in Clarke County (NMNH #515742 [collector/year: Bartsch/ 1934]). It is also documented from the Shenandoah River in West Virginia (ANSP #115148 [Fowler/1916] and #365839 [collector unknown/pre-1890]; CMNH #61.5379 [Ortmann/1911]; Ortmann, 1919; Johnson, 1970; Clarke, 1981).

Alasmidonta varicosa, Brook Floater

The first dated collection of *A. varicosa* in the NFSR was obtained "East of Woodstock" in 1957 by J. P. E. Morrison and J. Rosewater (MCZ #216721; same collection presumably cited by Johnson [1970] and Clarke [1981]). Morrison collected *A. varicosa* at the same location in 1963 (NMNH #791515). Three specimens were collected in 1979 "on 5th bend of the 7 bends, about 3 mi. E of Woodstock" (OSUM #45513, collector unknown). Material collected in 1968 by W. J. Clench and D. H. Stansbery from NFSR at VA Rt. 55, 2 mi SE of Strasburg is housed at MCZ (#266346) and OSUM (#20522). Three live specimens were also collected at this site in 1984 by A. Gerberich et al. (R. J. Neves, pers. comm.; disposition of specimens unknown). In 1970, the limnologist E. W. Surber collected *A. varicosa* in NFSR at Rt. 663 (NE of Woodstock) (NMNH #756713). Ortmann collected *A. varicosa* in 1912 at both the SFSR at Elkton (CMNH #61.5935) and the South River at Waynesboro (CMNH #61.5934) (Ortmann, 1919). Johnson (1970) cited the MCZ specimen (#103869) collected by Clench in 1934 from the SFSR at Riverton. ANSP has specimens of *A. varicosa* from three sites (Table 1) along the SFSR between Compton and Limeton (ANSP #390194-96 [all R. Dillon/1976-80], catalogued as *A. marginata*).

We found no evidence of live *A. varicosa* being documented during surveys conducted from 1990-2007 in the NFSR or SFSR drainages (Table 2). Fresh dead specimens were observed on the NFSR at Rt. 600 (DNH field survey, 27 June 1990) and VA Rt. 55 (DNH field survey 26 June 1990, "fresh dead of all ages"). Shells are reported from NFSR for 18 of 20 sampling events at 11 unique locations downstream of and including river mile 52.7 (near Chapman Landing). There is one shell record from Cedar Creek (ca. 0.8 miles from the confluence with NFSR; Neves, 2003) and from eight locations along Smith Creek (Winston, 1996; Roble, 1998; The Catena Group, 2006; VDGIF, 2009).

Reports of *A. varicosa* shells in the SFSR drainage are limited to the South River at Rt. 658 (Neves, 2003) and the SFSR mainstem at Andy Guest/Shenandoah River State Park (1993 DCR-DNH survey; n = 1).

Alasmidonta varicosa was also collected from the Shenandoah River mainstem in Virginia between U.S. Rt. 17 and VA Rt. 7 in Clarke County (NMNH #515741 [George Washington University/1934]). It was also documented from the mainstem in West Virginia (ANSP #41054 [Tryon/no date (probably ca. 1860)]; ANSP #115149 [Fowler/1916]; CMNH #61.5387 [Ortmann/1911]; CMNH #70784 and UMMZ #130185 [both Richmond/1937]; Ortmann, 1919).

Elliptio complanata, Eastern Elliptio

Ortmann (1919) reported *E. complanata* (as *E. violaceus*) from Broadway (ca. NFSR mile 86; CMNH #61.5897). Four other NFSR sites are documented by museum specimens or literature references: Mt. Jackson (UMMZ #44985 [Hobbs/1928]), east of Woodstock (MCZ #216719 [Morrison & Rosewater/1957]; Johnson, 1970), the 5th of 7 bends, ca. 3 mi E of Woodstock (OSUM #45514 [collector unknown/ 1979]), and the VA Rt. 55 bridge, 2 mi SE of Strasburg (MCZ #266269 and OSUM #20525 [both Clench & Stansbery/1968]; NMNH #837327 [no data]). There is one specimen (UMMZ #246060 [Wood/1950]) from the NFSR at Riverton, Virginia, which is catalogued as *E. dilatata*, an Interior Basin species (its range includes southwestern Virginia), but presumably it is referable to *E. complanata* and thus has been included with records of this species in Table 1. There is one historical record of *E. complanata* from Passage Creek, a tributary to the NFSR, from 2 mi SW of Seven Fountains (Johnson, 1970 cites USNM = NMNH, but this record is lacking from the online NMNH database).

More recent surveys (Table 2) recovered shell material from NFSR beginning at river mile 70.8 (Rt. 720, S of Mt. Jackson) downstream through Passage Creek (river mile 5). Live *E. complanata* were observed at 12 of 13 locations between Woodstock and Passage Creek (Roble, 1998; Neves, 2003; Johnson & Neves, 2004). Live specimens were also recently reported for four of ten surveys conducted in Smith Creek during 1990-91 (DCR-DNH field surveys) and 1996 (Winston, 1996). Shell material was observed at all ten survey locations (Winston, 1996; Roble, 1998; The Catena Group, 2006). Live *E. complanata* were observed in good numbers at four locations in Passage Creek in 2007 (Ostby et al., 2008). Shell material only was observed in Cedar Creek (Roble, 1998; Neves, 2003).

Elliptio complanata was collected historically from at least seven locations on the SFSR: Elkton (CMNH #61.5896 [Ortmann/1912]), "below Luray" (ANSP #389143 [Dillon/1974]), Rt. 613 near Bentonville (ANSP #389144 [Dillon/1976] and #353170 [Dillon/ 1980]; NMNH #837332 [no data]), which may be the same locality as collections from "about 8 miles SW of Front Royal" made by Morrison and Rosso (1954; both NMNH #853600 and UMMZ #216399), Hazard Mill Recreation Area, 1.5 mi W of Bentonville (ANSP #389145 [Dillon/1976]), 2 mi W of Compton (= 3 mi below Goods Falls) (ANSP #389148 [Dillon/1976]), 2 mi NW of Limeton (ANSP #389141 [Dillon/1976]), and Front Royal (UMMZ #246100 [Wood/1950]). Johnson (1970) reported an MCZ record from the North River at Weyers Cave, but an online search of the MCZ database did not confirm this. Ortmann (1919) reported his 1912 South River collection (as *E. violaceus*) from Waynesboro (CMNH #61.5887); there is also a more recent collection from this site (ANSP #390106 [Worsely/1977]).

There are several museum records from the Shenandoah River mainstem in Virginia (ANSP #42815 [Tryon/no date (probably ca. 1860)]; UMMZ #246075 [collector unknown/1946]) and at Harpers Ferry, West Virginia (UMMZ #94128 [Allen/no date]); CMNH #61.5353 [Ortmann/1911]; CMNH #70785 and UMMZ #130184 [both Richmond/1937]).

Only one live *E. complanata* has been reported during recent surveys in the SFSR. Beaty & Neves (1998) observed this species at the Rt. 613 crossing near Bentonville. Two live individuals were observed by DCR-DNH in the South River downstream of Rt. 657 and shells were collected from Christians Creek (Neves, 2003).

Elliptio fisheriana, Northern Lance

The taxonomy of Atlantic Slope *Elliptio* species is not resolved and in need of genetic study (NatureServe, 2009). Johnson (1970) lumped many nominal lanceolate species into *Elliptio lanceolata*, including *E. fisheriana* and *E. producta*. For the purposes of this report, a narrower definition is used where *E. lanceolata* does not occur north of the Rappahannock River drainage in Virginia (Alderman, 2003; Bogan et al., 2009). The name *Elliptio producta* is reported in early museum collections (Table 1), and *E. angustata*, *E. producta*, and *E. fisheriana* were used inter-changeably by various biologists in the 1990s and early 2000s to apply to the same taxon (Table 2). According to recent genetic research on lanceolate *Elliptio* species in Virginia, "all black, shiny black, yellowish green with rays lanceolate *Elliptio*s from Virginia with and without a sharp posterior ridge and with straight or curved margins are all considered *Elliptio fisheriana* at this time pending addition of other topotypic lanceolate taxa from South Carolina and Georgia" (Bogan et al., 2009). Therefore, all previous records of lanceolate *Elliptio* specimens and field observations from the Shenandoah River drainage are treated as *E. fisheriana* in this report. However, the records are presented in the tables and appendices using the original determinations.

Elliptio fisheriana is known from two NFSR sites based on museum collections: 5th of 7 bends, ca. 3 mi E of Woodstock (OSUM #45515 [collector unknown/ 1979], catalogued as *E. producta*) and VA Rt. 55, 2 mi SE of Strasburg (NMNH #837328 [no data], catalogued as *E. angustatus*; OSUM #20524 [Clench &

Table 2. Summary of mussel surveys conducted in the North Fork Shenandoah River (NFSR) and South Fork Shenandoah River (SFSR) drainages between 1990 and 2007. Tributaries to NFSR and SFSR are listed in upstream to downstream order. All river miles are estimated from the mouth. An 'L' or a number (if recorded) indicates that live animals were reported, and precedes an 'S' or a number, which indicates if shell material was reported. Numbers for the exotic Asiatic clam, *Corbicula fluminea*, are not given here. VMNH = Virginia Museum of Natural History. 1 = reported as *Elliptio* sp.; 2 = reported as *Elliptio producta*; 3 = reported as *Elliptio lanceolata;* 4 = reported as *Lampsilis* sp. * = No mussels (live or shell) observed.

River	Location	River Mile	Year	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis cariosa*	*Lampsilis ovata*	*Lasmigona subviridis*	*Strophitus undulatus*	*Corbicula fluminea*	Reference and Comments
North Fork Shenandoah River Drainage													
NFSR	VA Rt. 259	88.7	1990*										DNH field survey
NFSR	Rt. 617	86.3	1990*										DNH field survey
NFSR	Rt. 953/617	78.0	1990									L/S	DNH field survey
NFSR	Rt. 767	73.5	1995									L/S	Roble, 1998
NFSR	Rt. 720	70.8	1990			0/S							DNH field survey
NFSR	US Rt. 11	69.8	2002									L/S	Neves, 2003
NFSR	Off Rt. 698	67.1	2002			0/5						L/S	DNH field survey
NFSR	Off Rt. 698	67.1	2002	0/S	0/S	0/3							Catena Group, 2007
NFSR	Rt. 675	57.5	2002									L/S	DNH field survey
NFSR	Rt. 672	52.7	1995	0/S	0/S	0/S	0/S					L/S	Roble, 1998
NFSR	Chapman Dam	48.5	1990			-/3	-/1						VMNH collection
NFSR	Rt. 667	45.2	2004	0/1	0/2	6/S	0/3		0/1			L/S	Johnson & Neves, 2004
NFSR	Rt. 758	41.7	1990		0/S	0/S[1]		0/S		0/S		L/S	DNH field survey
NFSR	Rt. 758	41.7	2003		0/1	0/8					0/2	L/S	Neves, 2003
NFSR	Rt. 663	36.5	1990			0/S	0/1[2]	0/1				L/S	DNH field survey
NFSR	Rt. 663	36.5	2003		0/1	0/6		0/2[4]				L/S	Neves, 2003
NFSR	0.5 mi downstream Pugh Run	36.2	1992			-/3	-/1						VMNH collection
NFSR	Farmer's Mill near Rt. 661	32.2	1990		0/34	4/25+	1/9[2]	0/5			0/1	L/S	DNH, VMNH, Hoffman, 2001
NFSR	Rt. 600	28.4	1990		0/S	L/S	1/S[2]	0/5		1/S	0/1	L/S	DNH field survey
NFSR	Rt. 600	28.4	1995		0/4	0/200	0/30+	0/1			0/2	L/S	Roble, 1998
NFSR	Rt. 600	28.4	2002		0/1	3/S	0/S[3]					L/S	Neves, 2003
NFSR	Rt. 744	17.0	2002*										Hartman, 2002
NFSR	Rt. 744	17.0	2007		0/3	0/S[1]						L/S	Hartman, 2007
NFSR	Rt. 648	12.6	1990		0/S	L/S	0/S[2]	0/4		0/4	0/1	L/S	DNH field survey
NFSR	Rt. 648	12.6	1995		0/S	18/S	0/S[2]					0/S	DNH field survey
NFSR	Rt. 648	12.6	2002		0/2	19/S	0/S[3]	0/1		0/1		L/S	Neves, 2003
NFSR	VA Rt. 55	10.1	ca. 1990			-/6							VMNH collection
NFSR	VA Rt. 55	10.1	1990		0/50	L/10+	0/3[2]	0/S		0/12	0/1	L/S	DNH, VMNH
NFSR	VA Rt. 55	10.1	1995		0/S	14/10+		0/S			0/S	L/S	Roble, 1998
NFSR	VA Rt. 55	10.1	2002		0/2	1/S	0/S[3]					L/S	Neves, 2003
NFSR	Rt. 610	5.2	1990		0/S	L/S	0/S[2]	0/S		0/S	0/S	L/S	DNH field survey
NFSR	Off Rt. 612	5.0	2002		0/1	3/S	0/1[3]				0/1	L/S	Neves, 2003
Holman's Creek	VA Rt. 42	5.2	2005*										Catena Group, 2006
Smith Creek	Downstream Rt. 811	27.8	2006								4/0		VDGIF, 2009
Smith	Rt. 811	27.0	1995	0/3							14/8		Winston, 1995b
Smith	Rt. 793	17.2	1995	0/S	0/1	0/S						L/S	Roble, 1998
Smith	Off Rt. 620	16.8	2005	0/5	0/1						0/1		VDGIF, 2009

Table 2 (continued).

River	Location	River Mile	Year	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis cariosa*	*Lampsilis ovata*	*Lasmigona subviridis*	*Strophitus undulatus*	*Corbicula fluminea*	Reference and Comments
Smith	Rt. 794	16.1	1995	0/1		0/10						L/S	Roble, 1998
Smith	Rt. 620	15.9	2005	0/S	0/S	0/S					0/S		Catena Group, 2006
Smith	Rt. 823	14.1	1990		-/2	-/3							VMNH collection
Smith	US Rt. 211	11.3	1991	L/S	0/2	L/S						L/S	DNH field survey
Smith	US Rt. 211	11.3	1995	0/S	0/S	0/S	0/S					L/S	Roble, 1998
Smith	Rt. 620	6.3	1995	0/1		0/S						0/S	Roble, 1998
Smith	Rt. 620	5.5	1996	0/5	0/5	7/1+					0/1		Winston, 1996
Smith	Rt. 620	4.4	1990	1/S	0/S	3/S					1/3	L/S	DNH, VMNH
Smith	Rt. 730	1.4	1990			1/-						L/S	DNH field survey
Smith	Rt. 730	1.4	1994		0/7						0/1		VDGIF, 2009
Smith	Private road	0.6	1990	1/-	0/S	1/-					0/S	L/S	DNH field survey
Smith	Private road	0.1	1994								0/1		VDGIF, 2009
Mill Creek	Rt. 612	9.5	2005*										Catena Group, 2006
Straight Run	Rt. 724	-	2005*										Catena Group, 2006
Stony Creek	Rt. 723	19.0	2005										2 live *Pyganodon cataracta*; Catena Group, 2006
Stony	Rt. 710	3.8	1995*										Winston, 1995a
Stony	Off Rt. 675	2.0										0/S	Neves, 2003
Swover Creek	Rt. 691	-	1995*										Winston, 1995a
Cedar Creek	Rt. 628	13.3	2003									L/S	Neves, 2003
Cedar	Rt. 622	8.0	1990*										DNH field survey
Cedar	US Rt. 11	2.6	1996			0/1						0/S	Roble, 1998
Cedar	Rt. 635	0.8	1990*										DNH field survey
Cedar	Rt. 635	0.8	2003		0/1	0/43						L/S	Neves, 2003
Passage Creek	Rt. 730	30.0	2007*										Ostby et al., 2008
Passage	Rt. 775	22.2	2007									L/S	Ostby et al., 2008
Passage	Seven Fountains Rd	16.5	2007			6/0						L/S	Ostby et al., 2008
Passage	Rt. 772	13.1	2007			14/0						L/S	Ostby et al., 2008
Passage	Off Rt. 678	8.0	2007			81/0						L/S	Ostby et al., 2008
Passage	Elizabeth Furnace	6.7	1996			0/1						-/S	DNH field survey
Passage	Elizabeth Furnace	6.5	2007			31/0						L/S	Ostby et al., 2008
Passage	VA Rt. 55	1.3	2007									L/S	Ostby et al., 2008
Passage	Rt. 610	0.1	2007									L/S	Ostby et al., 2008
South Fork Shenandoah River Drainage													
Middle River	Rt. 742	35.5	2005	0/1									B. Watson, pers. comm.
Christians Creek	US Rt. 340	22.8	2003									0/S	Neves, 2003
Christians	Rt. 831	21.3	2003	8/0		0/11					2/0	0/S	Neves, 2003
South River	Rt. 658	43.5	2003		0/1						0/1	0/0	Neves, 2003
South	Rt. 652	42.2	2003	0/1								0/S	Neves, 2003

Table 2 (continued).

River	Location	River Mile	Year	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis cariosa*	*Lampsilis ovata*	*Lasmigona subviridis*	*Strophitus undulatus*	*Corbicula fluminea*	Reference and Comments
South Fork Shenandoah River Drainage													
South River	Rt. 657 (Cowbane Prairie Nat. Area Preserve)	39.8	2000	25-30/ 5-6							100+/ 10+	L/S	DNH field survey
South	Rt. 657 (Cowbane Prairie NAP)	39.8	2007	0/15		2/0					1/20+	L/S	DNH field survey
South	Shenandoah Wetland Mitigation Bank site	39.1	2003									L/S	DNH field survey
South	Rt. 664	29.8	1990									L/S	DNH field survey
South	Rt. 664	29.8	2003			0/7						L/S	Neves, 2003
South	Waynesboro	25.9	2003									L/S	Neves, 2003
Back Creek	Rt. 624	-	2003									0/S	Neves, 2003
SFSR	Rt. 675	44.1	1990			0/S							DNH field survey
SFSR	Rt. 613	18.2	1998			1/35							Beaty & Neves, 1998
SFSR	Rt. 613	18.2	2002			0/S							Neves, 2003
SFSR	Shen. River State Park	15	1993		0/1	0/S		0/S					DNH field survey, Roble, 1998
SFSR	Shen. River State Park	15	1995			0/100's		0/S					DNH field survey, Roble, 1998
Indian Hollow	Rt. 613	-	1998*										Beaty & Neves, 1998

Stansbery/1968], catalogued as *E. producta*; MCZ #266270 [Clench & Stansbery/1968], catalogued as *E. lanceolata*). Johnson (1970) reported this species (as *E. lanceolata*) from 'E Woodstock' presumably based on material in the MCZ (#216720 [Morrison & Rosewater/ 1957], catalogued as *E. productus*). The last known records of live *E. fisheriana* in the NFSR are of one individual each at two sites observed in 1990 during DCR-DNH field surveys (both recorded in field notes as *E. producta*). Shell material of *E. fisheriana* (identified variously as *E. producta*, *E. fisheriana*, and *E. lanceolata*) has been found from Chapman Landing (Rt. 672) to Passage Creek. There is only one record of shell material of *E. fisheriana* in Smith Creek (Roble, 1998), and no evidence of its presence in any other NFSR tributary. There are no historical or recent records of *E. fisheriana* from the SFSR. It is unknown if this species is absent from this drainage, or if it has been overlooked due to infrequent surveys.

There are historical records of a lanceolate *Elliptio* species from the Shenandoah River mainstem in Virginia and West Virginia that are variously catalogued as *E. fisherianus* (ANSP #41562 [Tryon/no date (probably ca. 1860)]; reported as *E. cupreus* by Ortmann, 1919), *E. lanceolata* (Johnson, 1970; ANSP #365823 [collector unknown/pre-1890]), *E. producta/ productus* (ANSP #127138 [collector unknown/pre-1918]), CMNH #61.12360 [Ortmann/1911]; UMMZ #94547 [Hartman/no date (probably ca. 1870)]), and *E. shepardiana* (UMMZ #22810 [Tryon/no date (probably ca. 1860)]). Presumably, all of these specimens are referable to *E. fisheriana*.

Lampsilis cariosa, Yellow Lampmussel
and *Lampsilis ovata*, Pocketbook

Johnson (1970) reported that *Lampsilis ovata* was accidentally introduced into the Shenandoah River system in 1889 as larvae on bass and other fishes transplanted from the Interior Basin and St. Lawrence

River system where *L. ovata* naturally occurs. Morrison (1972) believed that *L. cariosa* did not occur in the Potomac River basin significantly above the Fall Line, and that the specimens from the Shenandoah were *L. ovata*. *Lampsilis cariosa*, which is native to Atlantic Slope drainages (Johnson, 1970), can be distinguished from *L. ovata* by the sharp posterior ridge and dull olivaceous tint of the shell, often completely rayed in the latter species. *Lampsilis cariosa* usually has a distinct bright yellow, glossy periostracum, with rays usually confined to the posterior slope (Johnson, 1970). Relict shell material may be difficult to distinguish. Records under both names are provided here, but all may in fact refer to *L. ovata*.

Museum records of *Lampsilis* species (MCZ specimens catalogued as *L. ovata ventricosa*) are available from three sites on the NFSR: east of Woodstock (MCZ #216708 [Morrison & Rosewater/ 1957], Farmer's Mill near Rt. 661, 2 mi S Mauertown (VMNH #329 [Lipford/1990], two relict valves reported as *L. cariosa* by Hoffman, 2001), and VA Rt. 55, 2 mi SE of Strasburg (MCZ #266274 and OSUM #20526 [both Clench & Stansbery/1968], latter catalogued as *L. cardium*; NMNH #837329 [no data], catalogued as *L. ventricosa*). Only one recent survey on the NFSR (Rt. 667) identified shell material as *L. ovata* (Johnson & Neves, 2004). There are museum records for *L. ovata* from four sites on the SFSR: below Luray (ANSP #389202 [Dillon/1974], Rt. 613 near Bentonville (NMNH #83733 [no data]), Hazard Mill Recreation Area, 1.5 mi W of Bentonville (ANSP #389207 [Dillon/1976], and 2 mi W of Compton (ANSP #389211 [Dillon/1976]). We are not aware of any recent survey observations of *L. ovata* in the SFSR drainage. A collection from the SFSR 2 mi NW of Limeton is catalogued as *L. cardium* (ANSP #389214 [Dillon/1976]). Online database searches yielded several museum records of *L. ovata* (NMNH specimens catalogued as *L. ventricosa*) from the Shenandoah River mainstem in Virginia: NMNH #466824-25 [Morrison/ 1936]; NMNH #515740 [no data]; MCZ #192906 and UMMZ #247324 [both Athearn & Athearn/1950]; UMMZ #246030 [no data]).

Lampsilis cariosa is not recorded from the NFSR prior to Johnson's 1970 publication, and there is only one record from the SFSR (NMNH #853596 [Morrison & Rosso/1954]). Surveys in the 1990s by DCR-DNH (unpublished field notes) recorded *L. cariosa* from seven locations in the NFSR and Neves (2003) reported *L. cariosa* during a 2002 survey at one of these same locations. DCR-DNH reported *L. cariosa* shells in the SFSR at Shenandoah River Raymond R. "Andy" Guest, Jr. State Park in 1995. No live *L. cariosa* were found in either drainage.

Lasmigona subviridis, Green Floater

Lasmigona subviridis is known from three museum collections obtained at the VA Rt. 55 crossing of the NFSR, 2 mi SE of Strasburg: MCZ #266275 and OSUM #20523 [both Clench & Stansbery/1968]; NMNH #837331 [no data]; Clarke (1981). There are museum records of *L. subviridis* from the SFSR at Elkton (CMNH #61.5911 [Ortmann/1912]; Ortmann, 1919; Johnson, 1970) the U.S. Rt. 211 bridge near Luray (NMNH #837335 [no data]), Rt. 613 near Bentonville (ANSP #390203 [Dillon/1976]), and 2 mi W of Compton (ANSP #390204 [Dillon/1976]). A collection record for "Page County" (UMMZ #104151 [Bryant/no date]) is probably from the vicinity of Luray. Museum records for the Shenandoah River mainstem in Virginia exist for Front Royal (NMNH #251566 [Cooke/no date]) and between U.S. Rt. 17 and VA Rt. 7 in Clarke County (NMNH #427267 [Bartsch/ 1934]), and there is at least one collection from Harpers Ferry, West Virginia (CMNH #61.5361 [Ortmann/ 1911]).

One live *L. subviridis* was observed by DCR-DNH in 1990 at the Rt. 600 bridge crossing of the NFSR (ca. river mile 28.4). Otherwise, only shell material was observed at five locations between Burnshire Dam (Rt. 758, ca. river mile 41.7) and the mouth of Passage Creek. This species has not been documented from any NFSR tributaries. There are no recent survey observations of *L. subviridis* from the SFSR.

Strophitus undulatus, Creeper

There are four historical records of *Strophitus undulatus* from the NFSR: Broadway (CMNH #61.5947 [Ortmann/1912]; Ortmann, 1919), east of Woodstock (MCZ #216718 [Morrison & Rosewater/ 1957]; Johnson, 1970), 5th of 7 bends, ca. 3 mi E of Woodstock (OSUM #45512 [collector unknown/ 1979]), and VA Rt. 55, 2 mi NE of Strasburg (NMMH #837330 [no data]). Museum records of *S. undulatus* from the SFSR drainage are available from Elkton (CMNH #61.5946 [Ortmann/1912]; Ortmann, 1919; Johnson, 1970), below Luray (ANSP #390166 [Dillon/ 1974], Rt. 613 near Bentonville (ANSP #403506 [Dillon/1980]; NMNH #837334 [no data]), ca. 8 miles SW of Front Royal (NMNH #853597 [Morrison & Rosso/1954]), and 2 mi W of Compton (ANSP #390165 [Dillon/1976]). A Page County record (UMMZ #74651 [Bryant/no date]) is probably from the vicinity of Luray. There are also records from the South River at Waynesboro (CMNH #61.5937 [Ortmann/ 1912]; Ortmann, 1919; Johnson, 1970) and Christians Creek at Brand (MCZ #266671 and OSUM #20527

[both Clench & Stansbery/1968]). Museum collections exist for the Shenandoah River mainstem between U.S. Rt. 17 and VA Rt. 7 in Clarke County, Virginia (NMNH #515743 [Bartsch/no date]) and from Harpers Ferry, West Virginia (ANSP #115150 [Fowler/1916]).

Recent surveys documented *S. undulatus* at seven locations along the NFSR (shells only) and at eight sites in Smith Creek. Live individuals were observed in Smith Creek in 1990 (DCR-DNH; n = 1), 1995 (Winston, 1995; n = 14), and 2006 (VDGIF, 2009; n = 4, site just upstream of the Winston record). There are no recent observations of *S. undulatus* in the mainstem of the SFSR, but there have been reports of live individuals in Christians Creek (Rt. 831; Neves, 2003) and in the South River (downstream of Rt. 657; DCR-DNH field surveys in 2000 and 2007).

FIELD SURVEY METHODS

We evaluated existing survey data, including museum specimens, published literature, unpublished reports, and unpublished field notes, to determine the locations of previous survey sites and potential areas of mussel species of conservation concern. Recent information on physical attributes and fish communities of the NFSR (Krstolic et al., 2006) and SFSR (J. L. Krstolic, pers. comm.) were also considered in the site selection process. In addition, *de novo* survey sites were selected by identifying reaches of the NFSR and selected tributaries (e.g., Cedar, Passage, and Smith creeks) and the SFSR and selected tributaries (e.g., North, Middle, and South rivers, and Christians Creek) that had not been previously surveyed. Field surveys took place between 28 July 2008 and 7 October 2009.

Survey crews used snorkel and/or viewscope techniques to locate live mussels and shell material. Muskrat middens were examined for discarded shell material. Data were recorded on physical attributes such as stream width, substrate types, water temperature, turbidity, relative degree of sedimentation, and weather conditions, as well as length of survey (time and distance) and conservation concerns.

Due to the difficulty in distinguishing *Lampsilis cariosa* from *L. ovata* based solely on relict shell material, the designation *Lampsilis* sp. is used here, although literature and museum records suggest that only *L. ovata* occurs in the study area. Live or fresh material, if found during this study, would have been determined to species.

Initially, surveys focused on the NFSR and its tributaries; however, as work progressed, few live mussels were found and thus inventory efforts were expanded to include the SFSR drainage. In particular, sections of the South River upstream of Waynesboro that may have escaped historical chemical pollution (Carter, 1977) were targeted for survey, as were the Middle and North Rivers, which had minimal available survey data. Surveys were also conducted in the SFSR mainstem. The locations of freshwater mussel surveys conducted by DCR-DNH staff during 2008-2009 in the NFSR and SFSR drainages are shown in Figs. 3 and 4, respectively.

RESULTS

During 2008-2009, we conducted 87 surveys at 84 unique sites (Table 3). Only five of 26 locations on the NFSR yielded observations of live native mussels, all of which were identified as *Elliptio complanata* (n = 26), a common species throughout the Atlantic Slope. All five locations are downstream of Woodstock, Shenandoah County, Virginia. Live *E. complanata* (n = 5) also were observed at one of eight survey sites in Smith Creek, a tributary to the NFSR. Only two live *E. complanata* were found at seven sampling sites along the SFSR mainstem. Live *Alasmidonta undulata*, *Strophitus undulatus*, and *E. complanata* were found in the South River, a tributary to the SFSR. These observations include high numbers of *A. undulata* (25-30 and 77 in 2000 and 2009, respectively) and *S. undulatus* (100-105 and 104 in 2000 and 2009, respectively) occurring syntopically with moderate numbers of *E. complanata* (21 in 2009) below Rt. 657 along Cowbane Prairie Natural Area Preserve and extending into the adjacent Shenandoah Wetland Mitigation Bank property. One fresh dead specimen of *A. undulata* was found in Christians Creek.

Shell material of six mussel species was identified from the NFSR drainage: *A. undulata*, *A. varicosa*, *E. complanata*, *E. fisheriana*, *Lampsilis* sp., and *S. undulatus*. Shells of all of these species except *E. fisheriana* also were found in the SFSR drainage. No shells of *L. subviridis* (or *P. cataracta*) were found in either drainage.

DISCUSSION

Mussel Diversity and Distribution

Compared to the species-rich rivers of the Tennessee drainage (e.g., Clinch River: 60 species, Ortmann, 1918, Ahlstedt, 1991; Copper Creek: 25 species, Hanlon et al., 2009; Powell River: 41 species, Ortmann, 1918, Wolcott & Neves, 1994), the mussel diversity of Atlantic Slope rivers tends to be much lower (e.g., Rappahannock River system: 8 species, Ortmann, 1913, Johnson, 1970; Pamunkey River system: 10 species, Riddick, 1973, Blood & Riddick,

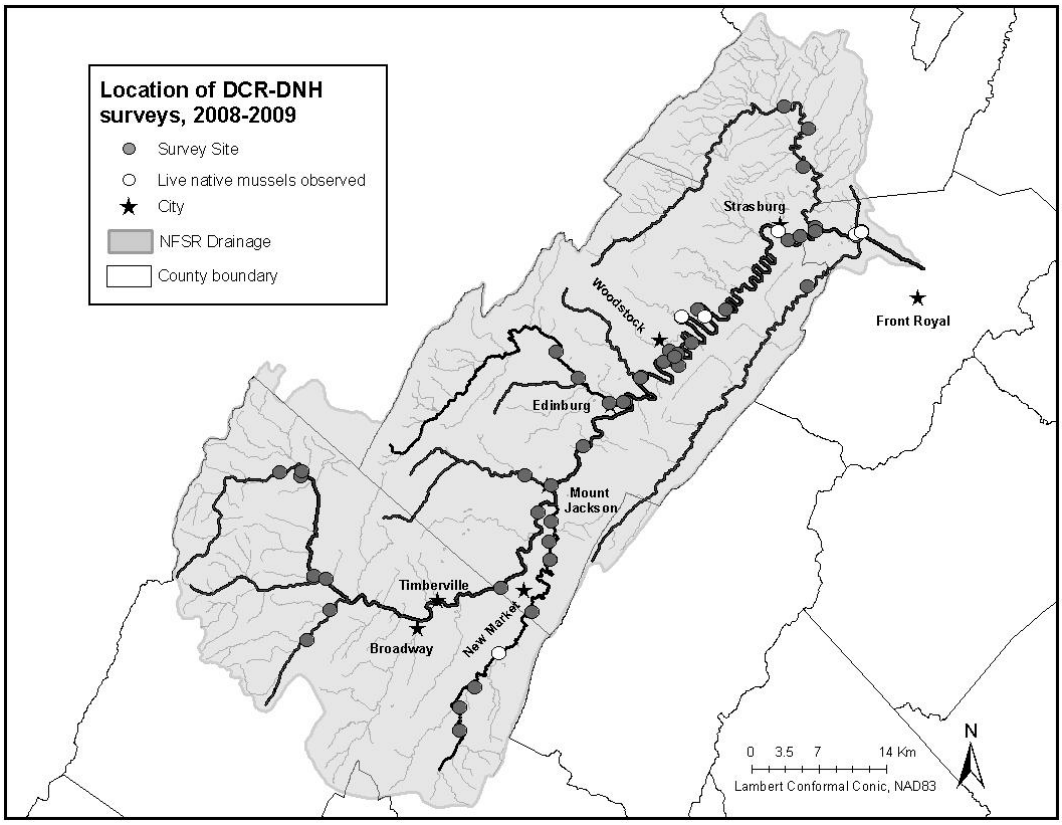

Fig. 3. DCR-DNH freshwater mussel survey locations in the North Fork Shenandoah River drainage, 2008-2009.

1974; Chowan River system [includes Blackwater, Nottoway, and Meherrin rivers in Virginia]: ca. 20 species, Johnson, 1970, Fuller, 1975, Alderman, 1995). Likewise, the historical mussel fauna of the Shenandoah River drainage in Virginia was characterized by low diversity. Only eight species have been documented from the NFSR and just seven from the SFSR, including the more lentic species, *Pyganodon cataracta*. Taylor (1985) documented the same eight species from the headwaters of the Potomac River in West Virginia. Johnson (1970) reported only five additional species from the entire Potomac drainage (*Alasmidonta heterodon*, *Anodonta implicata*, *Leptodea ochracea*, *Lampsilis radiata*, and *Ligumia nasuta*) and noted both *Lampsilis cariosa* and *Lampsilis ovata* (see species accounts above). Based on the results of the current study, the historically low diversity of the NFSR and SFSR may have declined to only one remaining species (*E. complanata*) confirmed from the NFSR and three species (*A. undulata*, *E. complanata*, and *S. undulatus*) confirmed as extant in the SFSR. Other species may persist in either or both drainages, but in such low numbers that they were not detected during this study. The lack of live or shell material of *L. subviridis* during our surveys may indicate that this species has been extirpated from the Shenandoah River drainage (last live specimen found in 1990).

In addition to an apparent reduction in the number of surviving species, there also seems to be a reduced distribution of the mussel fauna in the NFSR and SFSR. Museum records indicate that mussels once occurred in the NFSR upstream as far as Broadway in Rockingham County, Virginia (ca. river mile 86; Ortmann, 1919) (Table 1). Recent surveys (1990-2007) reported live mussels (mostly *E. complanata*, but also *E. fisheriana* and *L. subviridis*) at most sampling locations between NFSR river miles 0 and 45.2, but in 2008-2009, only live *E. complanata* were found at five (all between river miles 4.5 and 36.5) of 26 survey sites. Live mussels were found at several sites in Smith Creek during past surveys (DCR-DNH field survey, 1990; Winston, 1995; VDGIF, 2009), but at only one of our eight survey sites. Ostby et al. (2008) also reported live *E. complanata* from several sites along Passage Creek in 2007.

Museum records reveal that mussels were collected historically from three headwater tributaries of the SFSR (North River, South River, and Christians Creek) (Table 1) and from the mainstem extending from Elkton (river mile 80.4) to Front Royal (river mile 0). Recent surveys (Table 2) and the current survey (Table 3)

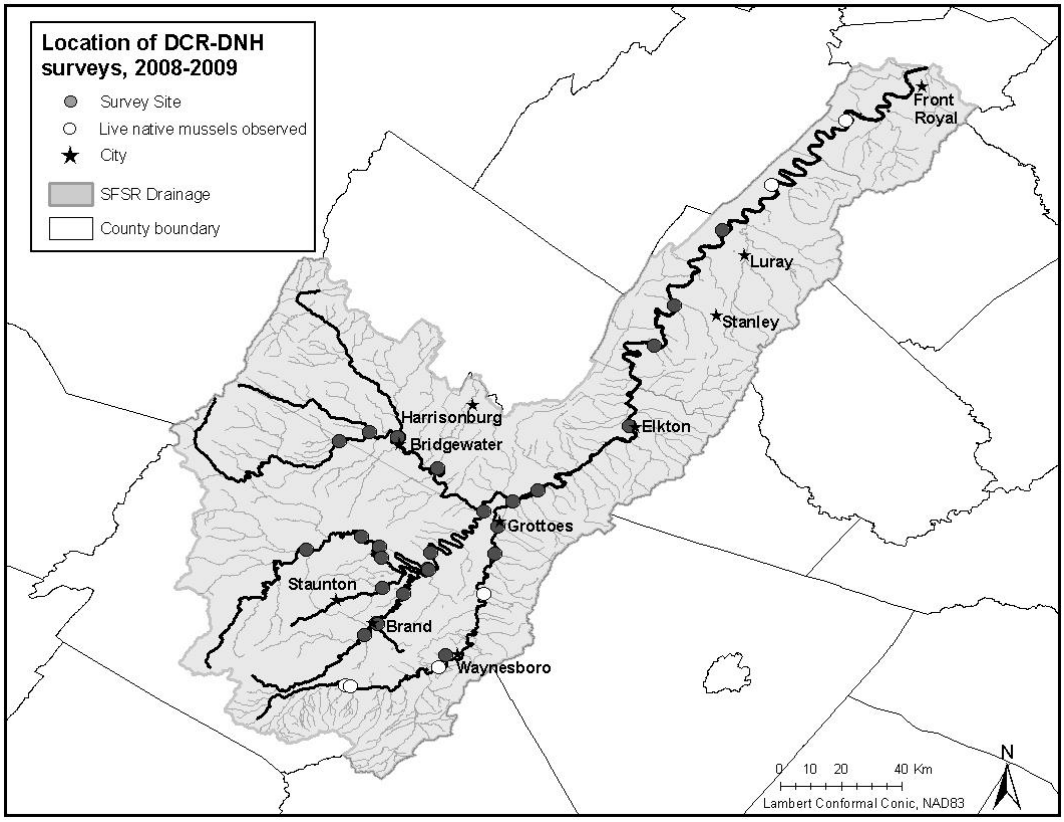

Fig. 4. DCR-DNH freshwater mussel survey locations in the South Fork Shenandoah River drainage, 2008-2009.

documented live native mussels in two headwater tributaries (South River and Christians Creek), but only three live *E. complanata* were observed in the SFSR mainstem (one each at river miles 15.0, 18.2, and 34.5).

The pattern of mussel populations becoming scarcer in the mainstem of a river and viable populations being limited to its tributaries is documented in other areas (Alderman, 1994; Chazal, 2005). This fragmented distribution may increase the risk of a mussel population becoming genetically isolated or extirpated due to localized events such as drought, chemical spills, or impounding.

Habitat Conditions and Threats

The NFSR and SFSR both flow through predominantly agricultural areas, with livestock, poultry, and crops (mostly corn) common and contributing to non-point source pollution. Twelve tributaries to NFSR have been identified by the Virginia Department of Environmental Quality (VDEQ) as impaired waters (VDEQ, 2008b). The NFSR mainstem is classified as impaired in two sections: 1) between Turley Creek and Holmans Creek, primarily due to non-point source pollution and the presence of fecal coliforms and *Escherichia coli*; and 2) from the Passage Creek confluence downstream to the confluence of the NFSR and SFSR (beginning of Shenandoah River mainstem), due to high mercury loads. Large portions of all three major tributaries to the SFSR (North, Middle, and South rivers) are listed as impaired waters, as is the entire SFSR (VDEQ, 2008b). Causes of the impaired classification include high mercury levels, the presence of fecal coliforms and *E. coli*, and poor benthic macroinvertebrate ratings (VDEQ, 2008b). Eggleston (2009) estimated that mercury input into the South River, largely emanating from contaminated floodplain sediments, needs to be reduced by 98.9% (from 189 to 2 kg per year) to prevent fish tissue methyl mercury concentrations from rising above acceptable levels for human consumption. Similar reductions are estimated for the SFSR and the Shenandoah River mainstem.

General observations of the sediments throughout all study reaches indicate that embedded substrates are common. Embedded substrates are problematic for the survival of macroinvertebrates, including mussels, because they reduce the availability of suitable microhabitats in the hyporheic zone (Box & Mossa, 1999; Ostby, 2005). However, it should be noted that embeddedness was not quantified during this study.

Table 3. Summary of mussel surveys conducted in the North Fork Shenandoah River (NFSR) and South Fork Shenandoah River (SFSR) drainages by DCR-DNH in 2008 and 2009. Tributaries to NFSR and SFSR are listed in upstream to downstream order. All river miles are estimated from the mouth of listed river. An 'L' or a number indicates that live animals were observed, and precedes an 'S' or a number, which indicates if shell material was observed. Numbers for the exotic Asiatic clam, *Corbicula fluminea*, are not given here. All *Lampsilis* shells were relict and thus not identified to species (see text for further discussion). No live individuals or shells of *Lasmigona subviridis* (or *Pyganodon cataracta*) were found during the surveys. "7BSP" = the future site of Seven Bends State Park; "NC" = Not Calculated.

River	Location	Date	River Mile	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis* sp.	*Strophitus undulatus*	*Corbicula fluminea*	Comments
German	Rt. 826	5-Aug-08	1.4								No mussels
NFSR	Rt. 820	5-Aug-08	103.3								No mussels
NFSR	at "Blue Hole"	5-Aug-08	103.0								No mussels
Little Dry	at NFSR	5-Aug-08	0								No mussels
NFSR	at Little Dry	5-Aug-08	94.9								No mussels
NFSR	Rt. 612	6-Aug-08	92.9								No mussels
Shoemaker	Rt. 612	6-Aug-08	4.9								No mussels
Shoemaker	off Rt. 612	6-Aug-08	1.8								No mussels
NFSR	Rt. 617 (Plains Mill)	6-Aug-08	78.0	0/1		0/1				L/S	Live *Corbicula* only
NFSR	Rt. 720	6-Aug-08	70.8			0/1				L/S	Live *Corbicula* only
NFSR	Rt. 720	9-Oct-08	70.8							L/S	Live *Corbicula* only
Smith	Rt. 811	10-Sep-08	28.0							0/S	No live mussels
Smith	Rt. 717 (E of Lacey Springs)	15-Sep-09	26.2							L/S	Live *Corbicula* only
Smith	Rt. 608 (SE of Mauzy)	15-Sep-09	22.8							L/S	Live *Corbicula* only
Smith	Rt. 796	15-Sep-09	18.8	0/1		5/10-15				L/S	1 live native species
Smith	Rt. 823 (at jct w/ Rt. 620)	15-Sep-09	14.0	0/1		0/7-9				L/S	Live *Corbicula* only
Smith	Rt. 620 (NW of Alpine)	10-Sep-08	6.3	0/1		0/10+			0/3	L/S	Live *Corbicula* only
Smith	Rt. 732/Rt. 620	10-Sep-08	4.4	0/2	0/1	0/20+				L/S	Live *Corbicula* only
Smith	Rt. 730	9-Oct-08	1.4			0/10+				L/S	Live *Corbicula* only
Mill	Rt. 614	25-Aug-08	2.1							0/S	No live mussels
NFSR	Rt. 698 (E of Mt. Jackson)	25-Aug-08	68.0			0/1				L/S	Live *Corbicula* only
NFSR	Rt. 707	9-Sep-08	63.8	0/2	0/2	0/40+				L/S	Live *Corbicula* only
Stony	Rt. 675	25-Aug-08	6.8							L/S	Live *Corbicula* only
Stony	Rt. 682	25-Aug-08	4.5							L/S	Live *Corbicula* only
Stony	Hwy. 11	25-Aug-08	1.3							L/S	Live *Corbicula* only
Stony	at NFSR	9-Oct-08	0							L/S	Live *Corbicula* only
NFSR	at Stony	9-Oct-08	57.5			0/6-7				L/S	Live *Corbicula* only
Narrow Passage	at NFSR	9-Sep-08	0			0/6-7				L/S	Live *Corbicula* only

Table 3 (continued).

River	Location	Date	River Mile	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis* sp.	*Strophitus undulatus*	*Corbicula fluminea*	Comments
NFSR	at Narrow Passage Creek	9-Sep-08	52.7							L/S	Live *Corbicula* only
NFSR	Rt. 609	25-Sep-08	47.8		0/1	0/50+	0/20+	0/4-5		L/S	Millions of *Corbicula*
NFSR	7BSP - downstream Rt. 609	7-Oct-08	46.9			0/6		0/1		L/S	Live *Corbicula* only
NFSR	7BSP - Camp Lupton	7-Oct-08	46.0			0/36	0/1	0/1		L/S	Live *Corbicula* only
NFSR	Rt. 667	29-Jul-08	45.2			0/100+	0/5	0/1		L/S	Live *Corbicula* only
NFSR	7BSP - downstream Rt. 667	7-Oct-08	44.8		0/1	0/30-40	0/2			L/S	Live *Corbicula* only
NFSR	Rt. 758 (Burnshire Dam)	25-Sep-08	41.7			0/5	0/1			L/S	Millions of *Corbicula*
NFSR	Rt. 663	28-Jul-08	36.5			0/4-5	0/1			L/S	Live *Corbicula* only
NFSR	Rt. 663	23-Sep-08	36.5		0/1	4/100+	0/10	0/1		L/S	1 live native species
NFSR	off Rt. 661	23-Sep-08	32.2			1/1000's	0/50+	0/3-4	0/2	L/S	1 live native species
NFSR	Rt. 661	29-Jul-08	31.6			0/30	0/2			L/S	Live *Corbicula* only
NFSR	Rt. 600	29-Jul-08	28.4			0/35	0/1			L/S	Live *Corbicula* only
NFSR	downstream Rt. 648	24-Sep-08	12.4		0/2	13/100's	0/100's	0/1	0/1	L/S	1 live native species
NFSR	off Rt. 1201	30-Jul-08	11.5			0/60+	0/2			L/S	Live *Corbicula* only
NFSR	Hwy. 55	24-Sep-08	10.1		0/2-3	0/100's	0/20+	0/2		L/S	Live *Corbicula* only
Cedar	Rt. 606	30-Jul-08	17.3							L/S	Live *Corbicula* only
Cedar	Rt 628 (Stephens Fort)	30-Jul-08	13.3							L/S	Live *Corbicula* only
Cedar	Rt. 622 (Minebank Ford)	30-Jul-08	8.0							L/S	Live *Corbicula* only
Cedar	at NFSR	8-Oct-08	0			0/S				L/S	Live *Corbicula* only
NFSR	at Cedar Creek	8-Oct-08	7.9		0/2	0/100's	0/2	0/1	0/1	L/S	Live *Corbicula* only
Passage	Elizabeth Furnace	30-Jul-08	6.7			0/1				L/S	Live *Corbicula* only
Passage	at NFSR	24-Sep-08	0							0/S	No live mussels
NFSR	at Passage Creek	24-Sep-08	5.0			3/100's	0/2-3	0/1		L/S	1 live native species
Molly Booth	at NFSR	8-Oct-08	0							0/S	No live mussels
NFSR	boat landing off Rt. 626	8-Oct-08	4.5		0/2	5/100's	0/1	0/1	0/2	L/S	1 live native species
North	Rt. 766	26-Aug-08	NC								No mussels
Briery Branch	Rt. 748	12-Aug-09	NC								No mussels
Dry River	at North River	12-Aug-09	0							0/S	No live mussels
North	at Dry River	12-Aug-09	21.1							0/S	No live mussels
North	Rt. 993	10-Sep-09	13.9							L/S	Live *Corbicula* only
North	Rt. 668 (NW of Grottoes)	11-Aug-09	4.4	0/1		0/20+				L/S	Live *Corbicula* only

Table 3 (continued).

River	Location	Date	River Mile	*Alasmidonta undulata*	*Alasmidonta varicosa*	*Elliptio complanata*	*Elliptio fisheriana*	*Lampsilis* sp.	*Strophitus undulatus*	*Corbicula fluminea*	Comments
Middle	Rt. 728 (W of Franks Mill)	16-Sep-09	44.0							L/S	Live *Corbicula* only
Middle	Rt. 742 (SW of Mt. Pisgah)	16-Sep-09	35.6							L/S	Live *Corbicula* only
Middle	Rt. 781 (near Bald Rock)	11-Aug-09	32.7			0/4				L/S	Live *Corbicula* only
Middle	Rt. 781 (W of Verona)	16-Sep-09	29.3			0/2				L/S	Live *Corbicula* only
Lewis Creek	Rt. 931 (off Rt. 790)	11-Aug-09	3.0							L/S	Live *Corbicula* only
Christians	Rt. 635 (SW of Brand)	16-Sep-09	16.3							L/S	Live *Corbicula* only
Christians	Rt. 637/250	11-Sep-08	14.1	0/1		0/1				L/S	Fresh dead *A. undulata*
Goose	at Christians Creek	11-Sep-08	0							L/S	Live *Corbicula* only
Christians	Rt. 795	11-Sep-08	7.2			0/3-4				L/S	Live *Corbicula* only
Christians	at Middle River	7-Aug-08	0	0/3	0/1	0/30				L/S	Live *Corbicula* only
Christians	at Middle River	26-Aug-08	0		0/1	0/S			0/1	L/S	Live *Corbicula* only
Middle	at Christians Creek	26-Aug-08	17.8		0/2	0/S				L/S	Live *Corbicula* only
Middle	Rt. 926	26-Aug-08	15.0	0/1		0/S				L/S	Live *Corbicula* only
South	Cowbane Nat. Area Preserve	4-Aug-09	39.8	68/S		6/2-3			78/S	L/S	3 live native species
South	Shenandoah Wetland Mitigation Bank site, ca. 1.5 km upstream Rt. 608	9-Sep-09	39.1	9/10-20		15/0			26/0	L/S	3 live native species
South	Rt. 631 (SE of Oak Hill)	5-Aug-09	27.6			1/5				L/S	1 live native species
South	Riverview Park, Waynesboro	5-Aug-09	25.4							L/S	Live *Corbicula* only
South	Rt. 612 (Crimora)	10-Sep-09	13.8			1/0				L/S	1 live native species
South	Rt. 778 (Harriston)	10-Sep-09	7.5							L/S	Live *Corbicula* only
South	Rt. 844 (Grand Caverns)	10-Sep-09	4.2							L/S	Live *Corbicula* only
South	at SFSR	7-Aug-08	0							L/S	Live *Corbicula* only
SFSR	Rt. 708 (Lynnwood)	7-Oct-09	94.6							L/S	Live *Corbicula* only
SFSR	Bus. Hwy. 33 (Elkton)	7-Oct-09	80.4							L/S	Live *Corbicula* only
SFSR	Rt. 650 (Grove Hill)	7-Aug-08	65.0							L/S	Live *Corbicula* only
SFSR	Bus. Hwy. 340 (Alma)	7-Oct-09	57.2			0/1				L/S	Live *Corbicula* only
SFSR	Rt. 675 (Bixler's Landing)	7-Oct-09	44.1			0/3		0/1		L/S	Live *Corbicula* only
SFSR	off Rt. 684 (Fosters Landing)	6-Oct-09	34.5			1/10-12				L/S	1 live native species
SFSR	Shenandoah River State Park	6-Oct-09	15.0			1/10				L/S	1 live native species
Total live individuals (# of sites)	87 total surveys at 84 sites	2008-2009	---	77 (2)	0	56 (12)	0	0	104 (2)	---	Total of 3 live native species at 12 sites

Livestock and human use (including driving trucks and/or all terrain vehicles in the river) were noted on several occasions. These can cause high disturbances in the sediments and directly kill mussels by trampling or crushing. Additionally, livestock may introduce coliforms directly into the water. Human use also includes lower-impact activities such as swimming, canoeing, and fishing.

Currently, there are five small dams along the NFSR. The 5 ft (1.5 m) dam near Riverton (NFSR mile 0.5) is now demolished (Cooley, 2010). Dams can prevent the free passage of fish, which serve as hosts to the larval stage (glochidia) of freshwater mussels. This hampers the distribution of mussels and may restrict their recolonization of an area (Watters, 1996). The 6.5 ft (2 m) Winchester water supply dam east of Strasburg (river mile 6.5) likely prevents free movement of fish during normal river flows, but fish may be able to move upstream during high flood events. The dam at Burnshire Bridge (NFSR mile 41.7) is higher (ca. 13 ft [4 m]), likely preventing the passage of fish. All live mussels found in the NFSR during 2008 were downstream of this dam. However, live *E. complanata* were observed about 3.5 river miles above the dam in 2004 (Johnson & Neves, 2004). Surveys by DCR-DNH at the same location in 2008 did not yield any live mussels. The remaining dams are: Chapman Dam (13 ft [4 m], river mile 48.6), Edinburg Dam (16 ft [4.9 m], river mile 58.8), and Timberville Dam (6 ft [1.8 m], river mile 84.9).

There are four dams along the SFSR (Luray Dam, river mile 46.2; Newport Dam river mile 60.6; Shenandoah Dam river mile 73.8; McGaheysville Dam river mile 89.8), all of which are 15 ft (4.5 m) or higher and likely prevent fish passage. There is a 9 ft (2.7 m) high dam along the Middle River at Damtown (approximately river mile 15.8) and farther upstream is a 22 ft (6.7 m) high dam south of Swoope, Virginia. All three live *E. complanata* observed in the SFSR during the past 15 years (one each at Rt. 613 [Beaty & Neves, 1998], Fosters Landing, and Andy Guest/Shenandoah River State Park [both DCR-DNH field surveys, 2009]) were found downstream of the Luray Dam.

Finally, both the NFSR and SFSR have experienced recent, large fish kills (VDEQ, 2008a). In 2004, an estimated 80 percent of the adult Smallmouth Bass (*Micropterus dolomieu*) and Redbreast Sunfish (*Lepomis auritus*) died due to undetermined stressors. It is unknown what impact, direct or otherwise, this may have on the mussel fauna of the Shenandoah Valley.

CONCLUSIONS

Overall, current mussel habitat quality of the NFSR and SFSR is poor, resulting from many conditions including pollution, habitat alteration, and water quality concerns. Reversing the impacts of any one of these threats would be a long-term project and require cooperation from every level of government and private sector agencies, as well as numerous private landowners. The benefits of any new management plans may not be realized for many years, but action should not be delayed because recolonization of mussels has been successful in other venues (Strayer et al., 2004).

By far, the best known extant mussel community (three species) in either the NFSR or SFSR drainage inhabits the South River along the boundary of DCR-DNH's Cowbane Prairie Natural Area Preserve, extending downstream to a wetland mitigation site held by the Shenandoah Wetland Bank. This river reach may be one of the best remaining sites for *Alasmidonta undulata* and *Strophitus undulatus* populations in Virginia (B. Watson, pers. comm.). It would be prudent to develop a monitoring protocol for these populations, as well as to seek conservation initiatives such as conservation easements and land acquisition.

In general, substrate conditions throughout the surveyed areas tended to be embedded with silt and evidence of large algal blooms was common. In conjunction with other impacts on the river habitats and water quality (e.g., dams, point and non-point source pollution, etc.), overall mussel habitat quality is poor. Except for one large mussel population in the South River, observations of live mussels were typically limited to 1-5 individuals. It is unknown if such small populations can reproduce effectively. All live mussels in the NFSR and SFSR mainstems were below high dams. It is unlikely that mussel populations will be able to spread beyond these dams, thus headwater populations may be isolated from any mainstem individuals. To improve conditions for freshwater mussels in the NFSR and SFSR drainages, both water quality improvements and habitat restoration must be made.

ACKNOWLEDGEMENTS

This work was completed with funds provided by the Virginia Department of Game and Inland Fisheries through an Endangered Species Act Section 6 grant from the U.S. Fish and Wildlife Service. Matching funds were provided by the Virginia Department of Conservation and Recreation, Division of Natural Heritage. We thank the many people who provided invaluable assistance to this project: John Holmes and Leslie Mitchell-Watson of the Friends of North Fork Shenandoah River were of great assistance with logistics and landowner contact, Jeff Kelbe, the

Shenandoah Riverkeeper, generously shared his knowledge of the river, Jennifer Krstolic (U.S. Geological Survey) generously shared river habitat locational information and answered numerous water quality-related questions, and Maureen Dougherty (DCR-DNH), Chris Hobson (DCR-DNH), Megan Bradley (VDGIF), and Brian Watson (VDGIF) participated in field surveys and helped with specimen identifications. Former and current DCR-DNH staff that participated in mussel surveys in the Shenandoah watershed in the early-mid 1990s include Tim Berry, Chris Hobson, Mike Lipford, Chris Pague, Dirk Stevenson, Phil Stevenson, and the second author. This paper benefited greatly from comments by the reviewers and we thank them for their time and comments. Last but not least, we thank Richard Hoffman for granting access to the VMNH collection and the curators of the various museums cited in the text that have made their collection databases available to the public online.

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