

## RESTORATION AND COLONIZATION OF FRESHWATER MUSSELS AND FISH IN A SOUTHEASTERN UNITED STATES TAILWATER<sup>†</sup>

JAMES B. LAYZER<sup>a\*</sup> and EDWIN M. SCOTT, Jr.<sup>b</sup>

<sup>a</sup> U.S. Geological Survey, Tennessee Cooperative Fishery Research Unit, Tennessee Technological University, Cookeville, TN 38505, USA

<sup>b</sup> Tennessee Valley Authority, Resource Stewardship, 17 Ridgeway Road, Norris, TN 37828, USA

### ABSTRACT

The French Broad River originates in North Carolina, flows west into Tennessee and at its confluence with the Holston River forms the Tennessee River. Douglas Dam, located on the French Broad River 52 km above its mouth, is operated primarily for peaking hydroelectric power and flood control. Prior to completion of the dam in 1943, the lower French Broad River contained about 53 species of freshwater mussels and 100 species of fish. By 1977, the fauna in the 52-km-long tailwater was reduced to 12 species of mussels and 42 native species of fish. Improvements in tailwater conditions occurred following initiation of minimum flows in 1987, and consistent reaeration of discharge in 1993. From 1988 to 2002, we sampled three sites (4, 28, and 39 km downstream of the dam) to monitor the fish assemblage. Each year since 1988, we have collected one or more additional species, indicating continued immigration. We collected 82 native and 9 exotic species of fish overall, but the maximum of 67 species in 1 year suggests that some species reside in the tailwater at low densities or all immigrants may not successfully colonize the tailwater. There is limited potential for most extirpated species of mussels to naturally recolonize the tailwater because source populations are isolated. Consequently, 19 754 adult mussels of 19 species were introduced between 1997 and 2000. Survival of translocated mussels has been high, and successful reproduction of at least one translocated species has occurred. Additionally, four mussel species are naturally colonizing the tailwater. Colonization and recruitment of additional mussel species is expected as populations of their host fishes increase. We believe that the improved conditions of the tailwater may allow for the re-establishment of sustaining populations of 30 mussel species of historic occurrence, but the continued operation of Douglas Dam as a peaking hydroelectric project will reduce the probability of successfully reintroducing some species. Published in 2006 by John Wiley & Sons, Ltd.

KEY WORDS: minimum flows; reaeration; dams; fish; mussels; recolonization; reintroduction

### INTRODUCTION

The Tennessee River is one of the most regulated drainages in the southeastern United States; the Tennessee Valley Authority (TVA) operates 11 dams on the Tennessee River, and 27 dams on major tributaries. Gehrke *et al.* (1999) defined four zones in regulated streams: a reach upstream of the impoundment where flows are unmodified; an impounded reach inundating lotic habitat; the immediate tailwater where flow alterations are greatest; and a reach further downstream where flow alterations are attenuated due to the influx of tributary inflows. Only two of these zones (the impounded and tailwater zones) occur in much of the Tennessee River system because distances between dams and impoundments are relatively short, and reaches upstream of impoundments are the tailwaters of other dams. Most dams in the Tennessee Valley are operated primarily to supply electrical power during daily peak demands, and for flood control. Daily and seasonal hydrographs below peaking hydroelectric projects bare little resemblance to preimpoundment conditions (Gore *et al.*, 1989). These altered hydrographs result in a state of constant flux in the amount and location of suitable habitat for aquatic biota in peaking project tailwaters (Nestler *et al.*, 1989). Moreover, profound changes in physical and chemical conditions can occur in these tailwaters

\* Correspondence to: James B. Layzer, U.S. Geological Survey, Tennessee Cooperative Fishery Research Unit, Tennessee Technological University, Cookeville, TN 38505, USA. E-mail: jim\_layzer@tntech.edu

<sup>†</sup>This article is a U.S. Government work and is in the public domain in the U.S.A.

Received 15 August 2003

Revised 9 August 2005

Accepted 17 August 2005

(Dortch and Martin, 1989; Gore *et al.*, 1989). The biodiversity of streams in the Tennessee River Valley was among the richest anywhere in the North Temperate Zone; however, inundation of riverine habitat and decades of operating dams in a peaking mode have devastated the fauna.

In the Tennessee River drainage, many of the fish species extirpated from tailwater areas have the potential to recolonize these waters because of the existence of tributary populations. In contrast, most species of mussels extirpated from tailwaters do not have the potential for recolonization because tributary populations either have been extirpated or they are isolated by impoundments (Anderson *et al.*, 1991; Layzer *et al.*, 1993). Furthermore, most species of mussels have a complex life history that includes a larva (glochidium) that is an obligate parasite on fish. Glochidia of many mussel species are host specific and can metamorphose into juveniles only on one or a few species of fish. Because adults are relatively immobile, recolonization by mussels is inextricably linked to successfully parasitizing a host and the subsequent movements of the infested host. Thus, even when there is connectivity between tailwaters and a source population, recolonization is likely to take decades. Consequently, re-establishment of mussel populations necessitates translocating adult or juvenile mussels; however, unsuitable tailwater conditions must first be ameliorated. Despite increasing electrical demands and offstream uses of water, there is a growing interest in modifying discharge regimes and water quality to restore biodiversity. In 1987, TVA initiated a major program to improve tailwater conditions below 16 dams. In most tailwaters, this program resulted in improvements in the fish and benthic macroinvertebrate assemblages (Scott *et al.*, 1996), suggesting that re-establishment of mussel populations might be successful.

Re-establishing mussel populations is critical because freshwater mussels are considered to be the most imperiled group of organisms in North America (Strayer *et al.*, 2004). Moreover, the introduction of zebra mussels (*Dreissena polymorpha*) to North America in the 1980s confounded efforts to conserve remaining populations of unionids. Zebra mussels established dense populations soon after their introduction, and extirpated local populations of native unionids in the Laurentian Great Lakes (Gillis and Mackie, 1994; Schloesser and Nalepa, 1994). Their subsequent invasion of the Ohio River system, including the Tennessee River, was of particular concern because this drainage contains many critically endangered unionid species. Consequently, efforts were initiated to locate and evaluate potential refugia (Dunn and Layzer, 1997; Sickel *et al.*, 1997; Nichols *et al.*, 2000).

The improvements in discharge from Douglas Dam located on the lower French Broad River in eastern Tennessee provided a potential opportunity for re-colonization by fish and restoration of mussel populations in the tailwater. The tailwater also has a low potential for zebra mussel invasion via commercial and recreational boats. The goal of our study was to evaluate the 52-km-long tailwater of Douglas Dam for re-establishment of endangered species of mussels. Specific objectives were to document the historical fish and mussel assemblages, monitor fish recolonization, evaluate the present composition of the fish assemblage with respect to the presence of glochidial hosts, evaluate sites for reintroducing mussels, and determine the likelihood of establishing self-sustaining mussel populations.

## STUDY AREA

The 351-km-long French Broad River originates near Rosman, North Carolina and at its confluence with the Holston River in Knoxville, Tennessee, forms the Tennessee River (Figure 1). Douglas Dam is the largest (61 m high, 519 m long) of the four dams on the mainstem of the French Broad River and is located 52 km upstream from its mouth. The dam, completed in 1943, created a 12 788 ha reservoir that inundated 69 km of the French Broad River. The dam and reservoir are operated primarily for hydroelectric peaking power and flood control. During peak generation, the powerhouse discharges 510 m<sup>3</sup>/s. Prior to October 1987, there was no discharge during periods of nongeneration; thus, prolonged periods of nongeneration resulted in aerial exposure of shoals and increased water temperatures in the 52-km-long tailwater. Each of the four powerhouse turbines is fed by an individual penstock that draws from the hypolimnion. During periods of lake stratification, water discharged frequently contained <4 mg/L of dissolved oxygen (DO). In October 1987, discharge regime was modified to include pulsing one of the four turbines for 30–45 min every fourth hour to maintain a minimum flow of 16.6 m<sup>3</sup>/s at Saffell Island located 4 km downstream (rkm 48). Various configurations of surface water pumps and injection of liquid oxygen were tested between 1987 and 1993. After reaeration techniques became fully operational in 1993, nearly all water discharged contained >4 mg DO/L (Scott, 1999).

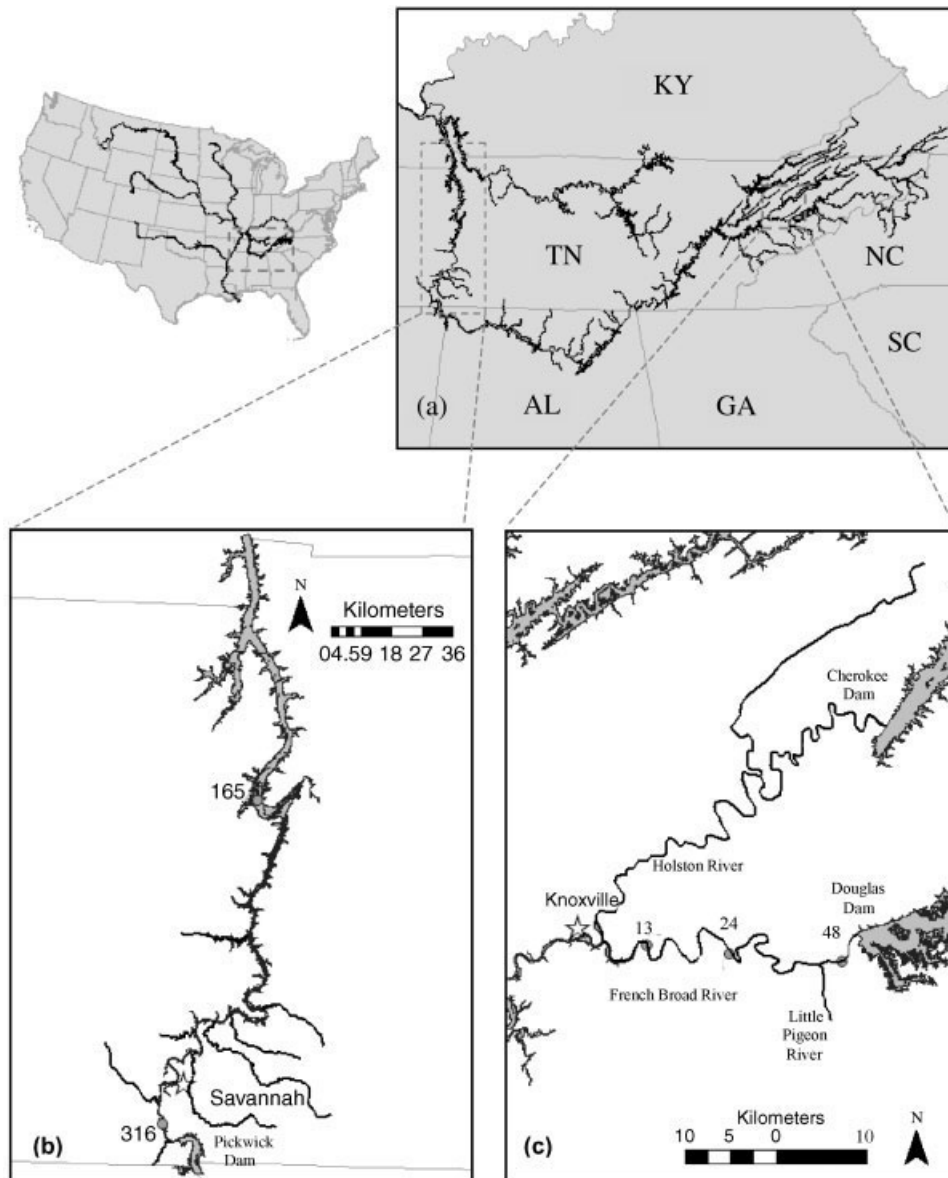


Figure 1. (a) Location map of the Tennessee and French Broad rivers. (b) Locations of mussel collection sites in the lower Tennessee River. (c) Map of the French Broad River below Douglas Dam showing fish sampling sites

### HISTORICAL FAUNA

The historical fish fauna of the French Broad River is poorly known. Although Cope (1870) collected fish in several of its tributaries, there were no extensive surveys of the mainstem, particularly in the lower 52 km, prior to completion of Douglas Dam in 1943. To reconstruct the likely composition of the historical fish assemblage, we relied heavily on the synopsis of collection records provided in Etnier and Starnes (1993), reviewed unpublished fish collections of the mainstem made since the construction of Douglas Dam, examined records for the resident fish fauna in the lower portion of the Holston River, and augmented these data with our judgment based on extensive personal collecting in the upper Tennessee River system. In all, the historical fish fauna likely consisted of 100 species (Table I). Additionally, nine introduced species have been collected from the lower French Broad River.

Table I. Historical (pre-impoundment of the Tennessee River) and recent fish fauna of the lower French Broad River

Family species	Common name	Historical <sup>a</sup>	1977 <sup>b</sup>	1988–1993 <sup>c</sup>	1994–2002 <sup>c</sup>
Petromyzontidae	Lampreys				
<i>Ichthyomyzon bdellium</i>	Ohio lamprey	X			X
<i>Ichthyomyzon castaneus</i>	Chestnut lamprey	X			X
<i>Lampetra appendix</i>	American brook lamprey	X			X
Acipenseridae	Sturgeons				
<i>Acipenser fulvescens</i>	Lake sturgeon	X			X*
<i>Scaphirhynchus platyrhynchus</i>	Shovelnose sturgeon	X			
Polyodontidae	Paddlefishes				
<i>Polyodon spathula</i>	Paddlefish	X			
Lepisosteidae	Gars				
<i>Lepisosteus oculatus</i>	Spotted gar	X	X	X	X
<i>Lepisosteus osseus</i>	Longnose gar	X	X	X	X
Clupeidae	Herring				
<i>Alosa alabamiae</i>	Alabama shad	X			
<i>Alosa chrysochloris</i>	Skipjack herring	X		X	X
<i>Dorosoma cepedianum</i>	Gizzard shad	X	X	X	X
<i>Dorosoma petenense</i>	Threadfin shad	X	X	X	X
Hiodontidae	Mooneyes				
<i>Hiodon tergisus</i>	Mooneye	X	X	X	X
Anguillidae	Freshwater eels				
<i>Anguilla rostrata</i>	American eel	X			
Cyprinidae	Minnows				
<i>Camptostoma oligolepis</i>	Largescale stoneroller	X	X	X	X
<i>Carassius auratus</i> *	Goldfish				X
<i>Ctenopharyngodon idella</i> *	Grass carp				X
<i>Cyprinus carpio</i> *	Common carp		X	X	X
<i>Cyprinella galactura</i>	Whitetail shiner	X	X	X	X
<i>Cyprinella spiloptera</i>	Spotfin shiner	X	X	X	X
<i>Cyprinella whipplei</i>	Steelcolor shiner	X			
<i>Erimonax monachus</i>	Spotfin chub	X			
<i>Erimystax insignis</i>	Blotched chub	X			
<i>Hybognathus nuchalis</i>	Mississippi silvery minnow	X			
<i>Hybopsis amblops</i>	Bigeye chub	X	X	X	X
<i>Luxilus chrysocephalus</i>	Striped shiner	X			X
<i>Luxilus coccogenis</i>	Warpaint shiner	X			
<i>Macrhybopsis aestivalis</i>	Speckled chub	X	X	X	X
<i>Macrhybopsis storeriana</i>	Silver chub	X			X
<i>Nocomis micropogon</i>	River chub	X	X	X	X
<i>Notemigonus crysoleucas</i>	Golden shiner	X	X		X
<i>Notropis atherinoides</i>	Emerald shiner	X	X		X
<i>Notropis leuciodus</i>	Tennessee shiner	X	X		X
<i>Notropis photogenis</i>	Silver shiner	X	X		X
<i>Notropis rubellus</i>	Rosyface shiner	X		X	X
<i>Notropis stramineus</i>	Sand shiner	X			X
<i>Notropis telescopus</i>	Telescope shiner	X		X	
<i>Notropis volucellus</i>	Mimic shiner	X	X	X	X
<i>Phenacobius uranops</i>	Stargazing minnow	X			X
<i>Pimephales notatus</i>	Bluntnose minnow	X		X	X
<i>Pimephales promelas</i>	Fathead minnow				X
<i>Pimephales vigilax</i>	Bullhead minnow	X		X	
Catostomidae	Suckers				
<i>Carpodes carpio</i>	River carpsucker	X		X	X
<i>Carpodes cyprinus</i>	Quillback	X			X
<i>Carpodes velifer</i>	Highfin carpsucker	X			
<i>Catostomus commersoni</i>	White sucker	X			X

Continues

Table I. Continued

Family species	Common name	Historical <sup>a</sup>	1977 <sup>b</sup>	1988–1993 <sup>c</sup>	1994–2002 <sup>c</sup>
<i>Cycleptus elongatus</i>	Blue sucker	X			X
<i>Hypentelium nigricans</i>	Northern hogsucker	X	X	X	X
<i>Ictiobus bubalus</i>	Smallmouth buffalo	X	X	X	X
<i>Ictiobus cyprinellus</i>	Bigmouth buffalo	X			
<i>Ictiobus niger</i>	Black buffalo	X		X	X
<i>Lagochila lacera</i>	Hairlip sucker	X			
<i>Minytrema melanops</i>	Spotted sucker	X			X
<i>Moxostoma anisurum</i>	Silver redhorse	X			X
<i>Moxostoma carinatum</i>	River redhorse	X	X	X	X
<i>Moxostoma duquesnei</i>	Black redhorse	X	X	X	X
<i>Moxostoma erythrurum</i>	Golden redhorse	X	X	X	X
<i>Moxostoma macrolepidotum</i>	Shorthead redhorse	X	X	X	X
Ictaluridae	Catfishes				
<i>Ameiurus melas</i>	Black bullhead	X			X
<i>Ameiurus natalis</i>	Yellow bullhead	X	X		X
<i>Ameiurus nebulosus</i>	Brown bullhead	X			X
<i>Ictalurus furcatus</i>	Blue catfish	X		X	
<i>Ictalurus punctatus</i>	Channel catfish	X	X	X	X
<i>Noturus eleutherus</i>	Mountain madtom	X		X	X
<i>Noturus flavus</i>	Stonecat	X			
<i>Pylodictis olivaris</i>	Flathead catfish	X	X	X	X
Esocidae	Pikes				
<i>Esox masquinongy</i>	Muskellunge	X			
Salmonidae	Trout				
<i>Oncorhynchus mykiss</i> *	Rainbow trout				X
<i>Salmo trutta</i> *	Brown trout				X
Fundulidae	Topminnows				
<i>Fundulus catenatus</i>	Northern studfish	X			X
<i>Fundulus notatus</i>	Blackstripe topminnow	X	X	X	X
Poeciliidae	Livebearers				
<i>Gambusia affinis</i> *	Western mosquitofish	X	X	X	X
Atherinidae	Silversides				
<i>Labidesthes sicculus</i>	Brook silverside	X	X	X	X
Cottidae	Sculpins				
<i>Cottus caroliniae</i>	Banded sculpin	X	X	X	X
Moronidae	Temperate basses				
<i>Morone chrysops</i>	White bass	X	X	X	X
<i>Morone mississippiensis</i>	Yellow bass	X		X	X
<i>Morone saxatilis</i> *	Striped bass				X
Centrarchidae	Sunfishes				
<i>Ambloplites rupestris</i>	Rock bass	X	X	X	X
<i>Lepomis auritus</i> *	Redbreast sunfish		X	X	X
<i>Lepomis cyanellus</i>	Green sunfish	X		X	X
<i>Lepomis gulosus</i>	Warmouth	X		X	X
<i>Lepomis macrochirus</i>	Bluegill	X	X	X	X
<i>Lepomis megalotis</i>	Longear sunfish	X		X	
<i>Lepomis microlophus</i>	Redear sunfish	X		X	X
<i>Micropterus dolomieu</i>	Smallmouth bass	X	X	X	X
<i>Micropterus punctulatus</i>	Spotted bass	X	X	X	X
<i>Micropterus salmoides</i>	Largemouth bass	X	X	X	X
<i>Pomoxis annularis</i>	White crappie	X	X	X	X
<i>Pomoxis nigromaculatus</i>	Black crappie	X		X	X
Percidae	Perches				
<i>Etheostoma blennioides</i>	Greenside darter	X	X	X	X
<i>Etheostoma camurum</i>	Bluebreast darter	X			X
<i>Etheostoma jessiae</i>	Blueside darter	X		X	X

Continues

Table I. Continued

Family species	Common name	Historical <sup>a</sup>	1977 <sup>b</sup>	1988–1993 <sup>c</sup>	1994–2002 <sup>c</sup>
<i>Etheostoma kennicotti</i>	Stripetail darter	X			X
<i>Etheostoma Rufilineatum</i>	Redline darter	X	X	X	X
<i>Etheostoma simoterum</i>	Snubnose darter	X	X	X	X
<i>Etheostoma vulneratum</i>	Wounded darter	X			
<i>Etheostoma zonale</i>	Banded darter	X	X	X	X
<i>Perca flavescens</i> *	Yellow perch			X	X
<i>Percina aurantiaca</i>	Tangerine darter	X			X
<i>Percina burtoni</i>	Blotchside logperch	X			
<i>Percina caprodes</i>	Logperch	X	X	X	X
<i>Percina evides</i>	Gilt darter	X			X
<i>Percina sciera</i>	Dusky darter	X		X	X
<i>Percina shumardi</i>	River darter	X			
<i>Percina squamata</i>	Olive darter	X			
<i>Percina tanasi</i>	Snail darter	X		X	X
<i>Sander canadense</i>	Sauger	X	X	X	X
<i>Sander vitreus</i>	Walleye	X		X	X
Sciaenidae	Drums				
<i>Aplodinotus grunniens</i>	Freshwater drum	X	X	X	X
Total native species		100	42	56	78
Introduced species			3	4	9

\*Introduced species.

<sup>a</sup>Primarily based on Etnier and Starnes (1993).

<sup>b</sup>Data from Harned (1979).

<sup>c</sup>Our study.

The historical mussel fauna in the mainstem of the French Broad River, particularly in the lower 52 km, also is poorly known. To reconstruct the likely composition of this assemblage, we used taxonomic composition of shells from an aboriginal site (unpublished data, P. Parmalee), a collection of relic shells from a presumed muskrat midden (unpublished data, J.R. Shute and P. Rakes), reviewed pertinent literature, especially the extensive species distribution records in Parmalee and Bogan (1998), and our own collection records. We assumed that most species recorded from the Little Pigeon River (Parmalee, 1988), a major tributary to the lower French Broad River, also once occurred in the French Broad River. Boepple and Coker (1912) reported the occurrence of the ebonyshell (*Fusconaia ebena*) in the French Broad River, but Hughes and Parmalee (1999) found no evidence in their examination of aboriginal middens that this species occurred in the upper Tennessee River system prior to damming of the mainstem. Morrison (1942), however, suggested that the absence of ebonyshells in aboriginal middens was a result of the deeper habitat occupied by this species and therefore not collected for food. Due to the lack of unequivocal evidence of its occurrence, we conservatively choose not to include the ebonyshell as part of the historical fauna of the French Broad River. From the above records, we estimated that at least 53 species of mussels once occurred in the mainstem of the lower French Broad River (Table II). It is possible that additional species such as the deertoe (*Truncilla truncata*) which has been recorded both upstream (Ahlstedt, 1991) and downstream (Hughes and Parmalee, 1999) of the study area also occurred in the lower French Broad River.

## METHODS

### Fish sampling

We selected 3 of the 12 sites sampled by Harned (1979) to monitor the fish assemblage over time. The sites were located 4, 28, and 39 km below Douglas Dam (Figure 1). These sites were selected to evaluate possible changes in the fish assemblage with respect to distance from the dam; each site included riffle, run, and pool habitats. All fish



Table II. Historical and present mussel fauna of the lower French Broad River, and prognosis for re-establishing self-sustaining populations. Limiting factor: H, known hosts are mid-water column species or, if hosts are unknown, hosts for congeneric species are mid-water column species; P, potential donor populations are small, functionally extinct, or subspecies may be extinct

Species	Common name	Source <sup>a</sup>	Current status <sup>b</sup>	Prognosis (limiting factor)
<i>Actinonaias ligamentina</i>	Mucket	1, 2, 3	Extirpated	Good
<i>Actinonaias pectorosa</i>	Pheasantshell	2	Extirpated	Good
<i>Alasmodonta marginata</i>	Elktoe	1	Extirpated	Good
<i>Amblema plicata</i>	Threeridge	1, 3, 4, 5	Resident	Good
<i>Cyclonaias tuberculata</i>	Purple wartyback	1, 3, 4, 5	Resident	Good
<i>Cyprogenia stegaria</i> *	Fanshell	1, 2, 3	Extirpated	Good
<i>Dromus dromas</i> *	Dromedary pearlymussel	1, 2, 3	Extirpated	Good
<i>Ellipsaria lineolata</i>	Butterfly	5	Extirpated	Good
<i>Elliptio crassidens</i>	Elephantear	1, 3, 4, 5	Resident	Poor (H)
<i>Elliptio dilatata</i>	Spike	1, 3, 5	Extirpated	Good
<i>Epioblasma arcaeformis</i>	Sugarspoon	1, 3	Extinct	—
<i>Epioblasma brevidens</i> *	Cumberlandian combshell	1	Extirpated	Good
<i>Epioblasma capsaeformis</i> *	Oyster mussel	1, 3	Extirpated	Good
<i>Epioblasma cf. florentina</i> *		1, 3	Extirpated	Poor (P)
<i>Epioblasma haysiana</i>	Acornshell	1, 3	Extinct	—
<i>Epioblasma lewisii</i>	Forkshell	3	Extinct	—
<i>Epioblasma propinqua</i>	Tennessee riffleshell	3	Extinct	—
<i>Epioblasma stewardsoni</i>	Cumberland leafshell	1, 3	Extinct	—
<i>Epioblasma torulosa gubernaculum</i> *	Green blossom	1, 2	Extirpated	Poor (P)
<i>Fusconaia barnesiana</i>	Tennessee pigtoe	1, 3, 4	Resident	Poor (H)
<i>Fusconaia subrotunda</i>	Longsolid	1, 2, 3	Extirpated	Poor (H)
<i>Hemistena lata</i> *	Crackling pearlymussel	1, 3	Extirpated	Poor (H)
<i>Lampsilis abrupta</i> *	Pink mucket	4	Resident	Good
<i>Lampsilis fasciola</i>	Wavyrayed lampmussel	1, 3	Extirpated	Good
<i>Lampsilis ovata</i>	Pocketbook	1, 3, 4	Resident	Good
<i>Lasmigona costata</i>	Flutedshell	1, 3	Extirpated	Good
<i>Lemiox rimosus</i> *	Birdwing pearlymussel	1, 3	Extirpated	Good
<i>Leptodea fragilis</i>	Fragile papershell	3, 4	Resident	Good
<i>Lexingtonia dolabelloides</i>	Slabside pearlymussel	1, 3, 4	Extirpated	Poor (H)
<i>Ligumia recta</i>	Black sandshell	1, 2, 4, 5	Resident	Good
<i>Medionidus conradicus</i>	Cumberland moccasinshell	1, 3	Extirpated	Good
<i>Obovaria retusa</i> *	Ringpink	2	Extirpated	Poor (P)
<i>Obovaria subrotunda</i>	Round hickoryshell	1, 3	Extirpated	Unknown
<i>Plethobasus cooperianus</i> *	Orangefoot pimpleback	1, 2, 3	Extirpated	Unknown
<i>Plethobasus cyphus</i>	Sheepnose	1, 2, 3	Extirpated	Good
<i>Pleurobema cordatum</i>	Ohio pigtoe	2, 3, 4	Resident	Poor (H)
<i>Pleurobema oviforme</i>	Tennessee clubshell	1, 3	Extirpated	Poor (H)
<i>Pleurobema plenum</i> *	Rough pigtoe	1, 2, 3	Extirpated	Poor (H)
<i>Pleurobema rubrum</i>	Pyramid pigtoe	1, 2, 3	Extirpated	Poor (H)
<i>Pleurobema sintoxia</i>	Round pigtoe	3	Extirpated	Poor (H)
<i>Potamilus alatus</i>	Pink heelsplitter	1, 3, 4, 5	Resident	Good
<i>Ptychobranhus fasciolaris</i>	Kidneyshell	1, 2, 3	Extirpated	Good
<i>Ptychobranhus subtentum</i>	Fluted kidneyshell	1, 3	Extirpated	Good
<i>Pyganodon grandis</i>	Giant floater	1, 3	Resident	Good
<i>Quadrula cylindrica</i>	Rabbitsfoot	1, 2, 3	Extirpated	Poor (H)
<i>Quadrula intermedia</i> *	Cumberland monkeyface	3	Extirpated	Poor (H)
<i>Quadrula metanevra</i>	Monkeyface	2	Extirpated	Good
<i>Quadrula pustulosa</i>	Pimpleback	1, 2, 3, 4, 5	Resident	Good
<i>Quadrula sparsa</i> *	Appalachian monkeyface	1, 3	Extirpated	Poor (H, P)

Continues

Table II. Continued

Species	Common name	Source <sup>a</sup>	Current status <sup>b</sup>	Prognosis (limiting factor)
<i>Quadrula verrucosa</i>	Pistolgrip	4	Nonindigenous	Not applicable
<i>Toxolasma lividus</i>	Purple lilliput	1	Extirpated	Good
<i>Villosa iris</i>	Rainbow	1, 3	Extirpated	Good
<i>Villosa trabalis</i> * (or <i>V. perpurpurea</i> *)	Cumberland bean (or purple bean)	1, 3	Extirpated	Good
<i>Villosa vanuxemensis</i>	Mountain creekshell	1, 3	Extirpated	Good

<sup>a</sup>Source of record of occurrence: 1, Parmalee (1988); 2, Shute and Rakes (unpublished data, 1998); 3, Parmalee (unpublished data, 1990); 4, this study; 5, Harned (1979).

<sup>b</sup>Excluding mussels translocated in this study.

\* = Listed as endangered by the U.S. Fish and Wildlife Service.

samples were collected over a 3-day period during daylight hours in spring or summer while discharge from Douglas Dam was either zero or at minimum levels. In shallow water throughout the river channel and along the shorelines, a crew of five persons collected fish using a backpack electro-shocker, dip nets, and a 6.1-m-long seine with 4.8 mm mesh. The seine was routinely positioned perpendicular to the river's flow at a distance of 6 m downstream from the person operating the backpack shocker. As direct current (DC) was applied to an area approximately equal to the width of the seine, the operator moved downstream to the stationary seine. Fish stunned by the electric field were collected as they drifted into the stationary seine or were dip-netted. Each seine set and electro-fishing pass constituted one unit of sampling effort. An effort was made to sample all habitat types with respect to depth, current velocity, and substrate. In areas of little or no current (e.g., backwaters), seine hauls were made. Additional backpack shocking along shorelines sampled brush, boulder, undercut bank, and tree root habitats; each 5-min-long sample was counted as one unit of effort. Sampling was repeated in each habitat until three successive passes produced no additional new species. We used boat electrofishing to sample along shorelines and channel sections of deep pools. Shocking runs, in a downstream direction, continued until two successive runs failed to collect any additional species in a given habitat. Each 10-min-long boat-shocking run was counted as two units of sampling effort. All captured fish, except young-of-the-year fishes were identified, counted, and examined for anomalies (parasites, deformities, etc.). Some fish were preserved in 10% formalin and kept as voucher specimens or for later laboratory verification. Temporal changes in the fish assemblage were assessed with the Tailwater Fish Index (TFI) (Scott, 1999). The TFI is a modification of the Index of Biotic Integrity (Karr *et al.*, 1986), and is composed of 12 metrics (Table III). Scores of all metrics are summed and the integrity of the fish assemblage is based on the total score (58–60 = excellent; 48–52 = good; 40–44 = fair; 28–34 = poor;  $\leq 22$  = very poor).

Table III. Metrics and scoring criteria used to calculate the Tailwater Fish Index (TFI)

Metric	Score		
	1	3	5
1. Total number of species	<19	19–37	>37
2. Number of darter species	<4	4–6	>6
3. Number of sunfish species	<3	3–4	>4
4. Number of sucker species	<3	3–5	>5
5. Number of intolerant species	<4	4–8	>8
6. Tolerant species (%)	>40	20–40	<20
7. Omnivores + generalists (%)	>50	25–50	<25
8. Specialist insectivores (%)	<15	15–30	>30
9. Piscivores (%)	<2	2–5	>5
10. Catch-per-unit-effort	<6	6–11	>11
11. Hybrids (%)	>1	0.5–1	<0.5
12. Anomalies (%)	>5	2–5	<2



*Mussel translocations and sampling*

All species selected for translocation occur in the Tennessee River system; most species were historically found in the lower French Broad River, but a few species were not part of the historic fauna. Historically, ecological barriers (but not geomorphic or physical) existed in the Tennessee River that limited the upstream distribution of these species; following impoundment of the Tennessee River, these barriers no longer seem to exist as several species (including those we translocated) originally restricted to the lower Tennessee River have established populations several hundred kilometers upstream of their historical occurrence (Hughes and Parmalee, 1999). At least one of these species, the pistolgrip (*Quadrula verrucosa*), had colonized the French Broad River prior to our study. After consultation with state and federal agencies, a joint decision was made to translocate the few species not historically found in the French Broad River because of their ongoing upstream movement within the Tennessee River and because of the threat posed by the invasion of zebra mussels in the Tennessee River System. The French Broad River will likely remain a refuge for mussels from the zebra mussel invasion because barge traffic, a primary vector for upstream movement of zebra mussels in the Tennessee River, is restricted to the lower 3 km of the French Broad River.

Prior to translocating mussels and periodically thereafter, we conducted qualitative searches by snorkeling to determine species composition of the resident mussel fauna. To establish populations of unlisted mussel species and evaluate conditions for reintroducing endangered mussels, we collected mussels periodically from the lower Tennessee River in western Tennessee (Figure 1) while wading in shallow water or by SCUBA diving in deeper areas. Mussels were placed in coolers, covered with wet burlap, and transported to the laboratory where they were hand-scrubbed with wire brushes to remove any zebra mussels, and then quarantined for 30 days. In 1997, we translocated mussels that had been quarantined for 30 days in 1136 L tanks under static conditions, and then maintained in long-term holding facilities for  $\geq 1$  year as part of another study (Quinn, 2002). Subsequently, mussels translocated were quarantined for 30 days in a re-circulating system consisting of two 1136 L tanks, a sump, a biofilter, and pump. About 2 weeks before quarantining mussels, we inoculated the biofilter with filter material from a similar recirculating system used for maintaining fish. At the same time, we introduced about 50 fish (mixed species) into the quarantine tanks to maintain the bacterial culture; all fish were removed from the system when mussels were introduced. Mussels were fed live algae (*Bracteococcus grandis*) at an average rate of 1.4 mg (dry weight) per mussel every 2–3 days. Following quarantine, mussels were visually examined for zebra mussels before they were translocated to the French Broad River. Subsamples were moved to Center Hill Lake in central Tennessee where they were held in pocket nets for 12–17 months to monitor post-quarantine survival. Prior to translocation, mussels were marked with a power rotary tool (Morgan *et al.*, 1997), or shellfish tags were attached with cyanoacrylate glue (Lemarié *et al.*, 2000).

In 1997, we established two rectangular plots (250 m<sup>2</sup> and 120 m<sup>2</sup>) located adjacent to Campbell Island (rkm 13). Corners of each plot were marked for the duration of the study by concrete blocks. Prior to translocating mussels, we drove steel rods into the substrate adjacent to the blocks, attached tape measures, and then delineated a grid consisting of 1-m<sup>2</sup>. We inserted mussels into the substrate in nearly equal numbers into each 1 m<sup>2</sup> within each plot.

From 1998 through 2000, mussels were translocated to five rectangular plots established at the head of Seven Islands (rkm 24). Plot sizes varied from 170 to 250 m<sup>2</sup> and were determined by the number of mussels available and our desire to achieve a density of 10–12 mussels/m<sup>2</sup>. We marked out 1-m-wide lanes the length of each plot and translocated nearly an equal number of mussels throughout each lane. In 1999, we used these same methods to translocate mussels to one plot (180 m<sup>2</sup>) at Johnson Island (rkm 18) where plot size was limited by accessibility to suitable habitat.

We evaluated mussel survival at 1-year intervals following translocation with a stratified random sampling design. We drove steel rods into the substrate adjacent to each of the concrete blocks marking the plot corners and attached tape measures. A random numbers table was used to generate sampling points. At each point, a quadrat (1 m<sup>2</sup> for plots 1 and 2; 0.25 m<sup>2</sup> for plots 3–8) was laid on the substrate by snorkelers, the substrate was hand-excavated, and all mussels were identified and examined for marks before returning them to the river; unmarked individuals were considered to be resident mussels. On several occasions, we qualitatively searched the substrate downstream of each plot for dead and live mussels.

Between 1999 and 2003, we attempted to introduce three species of mussels by stream-side infestations of their glochidia on host fishes. Gravid pheasantshell (*Actinonaias pectorosa*), Cumberland moccasinshell (*Medionidus conradicus*), and fluted kidneyshell (*Ptychobranthus subtentum*) were collected from the Clinch River, Tennessee, and transported in coolers to the French Broad River. A hypodermic syringe filled with water was inserted into the marsupial gills and glochidia were flushed out (Waller *et al.*, 1985). Host fishes were collected by electrofishing at Seven Islands on the French Broad River. Glochidia were then poured into a bucket containing the fish and about 4 L of river water. Fish were exposed to the glochidia for 30–45 min, and then released at the collection site. Each year after the initial infestations, we searched for juveniles at the site by snorkeling and hand-digging the substrate to a depth of 2–3 cm.

## RESULTS

### *Fish assemblage*

The construction and operation of Douglas Dam devastated the fish assemblage of the lower French Broad River. In 1977, only 42 of the original 100 species were collected at 12 sites (Harned, 1979; Table I). Lampreys, sturgeon, and paddlefish were not collected, and relatively few species of cyprinids, catostomids, and percids were collected in 1977. Following initiation of minimum flows and testing of aeration techniques (1988–1993), species richness increased; during this time, 14 species of fish colonized the tailwater (Figure 2). After 1993 when the aeration techniques became fully operational, native fish diversity continued to increase. Between 1994 and 2002, we collected 78 native species (78% of the historical fauna), and 9 introduced species in the tailwater (Table I). Although sampling effort varied among years, effort was not correlated with species richness ( $r = 0.24$ ;  $p = 0.17$ ); however, species richness was positively correlated with year ( $r = 0.97$ ;  $p < 0.0001$ ). Many of the species colonizing the tailwater during this period included those that we considered to be relatively intolerant of low DO and zero minimum flows such as lampreys, catostomids, and percids. Re-colonization of darters (*Etheostoma* spp. and *Percina* spp.) at the site closest to the dam (rkm 48) was slow. At this site, no darters were collected in 1988, and only one species was found in 1992; however, seven darter species were collected in 2002. Although we collected many of

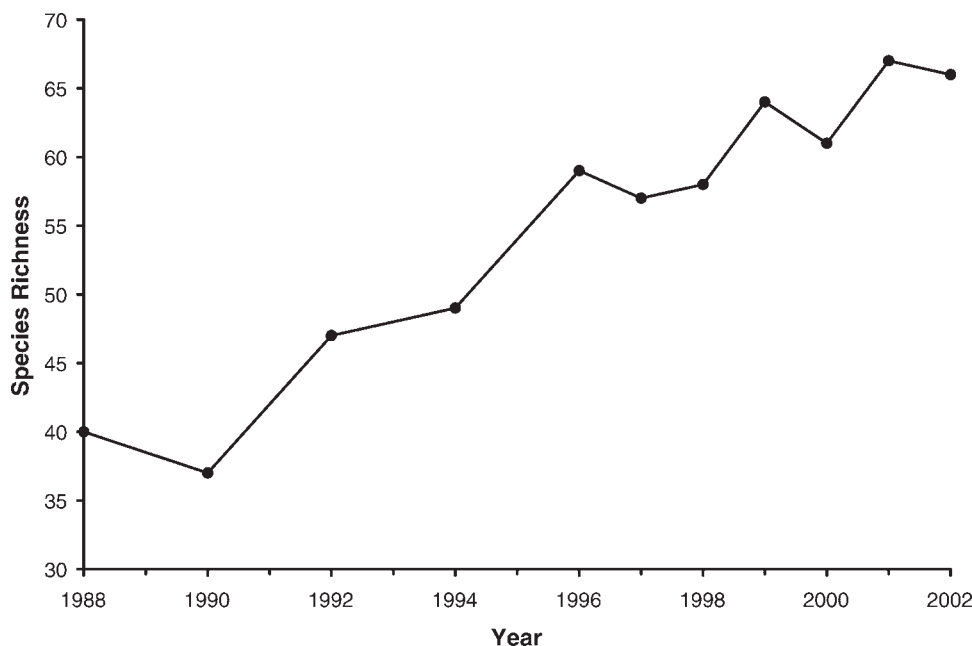


Figure 2. Changes in fish species richness in the lower French Broad River following institution of a minimum flow and oxygenation of the discharge from Douglas Dam

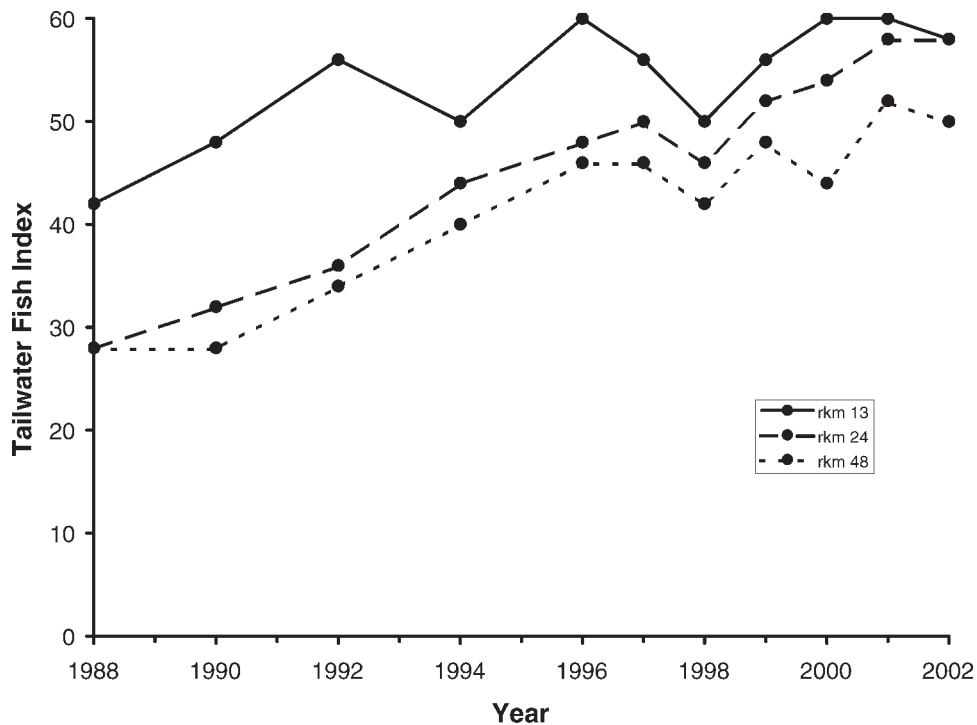


Figure 3. Tailwater Fish Index (TFI) scores for three sites on the lower French Broad River downstream of Douglas Dam following institution of a minimum flow and oxygenation of the discharge

the cyprinid species that occurred historically in the French Broad River, only a few individuals represented several of these species.

The TFI showed a dramatic improvement in the overall fish assemblage at our three permanent sampling sites (Figure 3). Increases in TFI values were temporally associated with distance from Douglas Dam. At the site farthest from the dam (rkm 13), TFI values improved from 42 (fair) in 1988 to 60 (excellent) in 8 years and have remained in the excellent range. At rkm 24, TFI values increased from poor in 1988 to excellent in 2001. At rkm 48, improvements in the fish assemblage increased from poor to good.

#### *Resident mussel fauna*

During qualitative searches and in our quadrat sampling for translocated mussels, we found 12 species of mussels alive, including the federally-listed endangered pink mucket (*Lampsilis abrupta*), and a fresh-dead shell of an additional species, the Tennessee pigtoe (*Fusconaia barnesiana*) (Table II). At Campbell Island (rkm 13), few live or dead indigenous mussels were found. In contrast, extensive mussel beds occurred over a 2.5 km stretch of river at Seven Islands (rkm 28). These extant mussel beds consisted primarily of very large (121–170 mm long) elephantears (*Elliptio crassidens*). The size and eroded condition of the elephantears and most other species found suggest they were living when Douglas Dam was constructed; however, recent (<5 years) recruitment was evident for the fragile papershell (*Leptodea fragilis*), pink heelsplitter (*Potamilus alatus*), pimpleback (*Quadrula pustulosa*), and the nonindigenous pistolgrip. Additionally, we judged the single fresh-dead Tennessee pigtoe that we collected to be about 5 years old. Throughout our study we did not see any evidence that zebra mussels had colonized the river.

#### *Mussel translocations*

Prior to quarantine, infestations of zebra mussels on native mussels collected from the lower Tennessee River were rare (~1 zebra mussel/1000 unionids). Mean survival during quarantine varied from 87% to 100% among species (Table IV). Following quarantine, no zebra mussels were found on any unionid. Long-term (12–17 months)

Table IV. Numbers and percent survival of mussels following quarantine in recirculating systems

Species	Number quarantined	Mean percent survival ( $\pm$ SE)	
		30 days	12–17 months
<i>Amblema plicata</i>	1433	98.0 $\pm$ 1.5	88.0 $\pm$ 0.0
<i>Cyclonaias tuberculata</i>	2188	98.7 $\pm$ 0.4	96.3 $\pm$ 1.8
<i>Ellipsaria lineolata</i>	45	87.5 $\pm$ 12.5	50.0 $\pm$ 0.0
<i>Elliptio crassidens</i>	1	100	100
<i>Fusconaia ebena</i>	2916	92.0 $\pm$ 5.0	77.0 $\pm$ 0.2
<i>Fusconaia flava</i>	173	99.0 $\pm$ 0.0	—
<i>Megalonaias nervosa</i>	192	100	100
<i>Obliquaria reflexa</i>	168	91.3 $\pm$ 6.3	40.5 $\pm$ 15.5
<i>Quadrula metanevra</i>	1422	99.7 $\pm$ 0.2	97.3 $\pm$ 1.2
<i>Quadrula pustulosa</i>	3308	89.5 $\pm$ 2.6	82.0 $\pm$ 4.6
<i>Quadrula verrucosa</i>	11	100	100
<i>Truncilla truncata</i>	9	89.0 $\pm$ 0.0	—

survival of mussels held at Center Hill Reservoir ranged from 77% to 100% for eight species, but was  $\leq 50\%$  for two species. In all, we translocated 19 754 adult mussels of 18 species into the 8 plots (Table V). At rkm 13, 12 mussels were introduced into every 1 m<sup>2</sup> of plot 1, and either 11 or 12 individuals were translocated into each 1 m<sup>2</sup> in plot 2. One year after translocation, estimated densities of live mussels within these plots were 55% (plot 1) and 52% (plot 2) of the densities translocated (Table VI). Mean density ( $\pm$  SE) of dead mussels in plot 1 was 0.76  $\pm$  (0.18)/m<sup>2</sup>, and 1.00 ( $\pm$  0.25)/m<sup>2</sup> in plot 2. Thus, recovery of translocated mussels averaged 61% for both plots.

In contrast to the initial equal distribution of mussels (12/m<sup>2</sup>) translocated into plot 1, the distribution of mussels in 1 m<sup>2</sup> quadrats samples was highly contagious; samples contained 0–19 individuals, indicating active or passive movement. Moreover, the distribution of mussels in quadrat samples continued to change in subsequent years ( $\chi^2$ ,  $p < 0.05$ ), indicating that mussels continued to move after the first year. This movement was not confined to the translocation plots. Four years after translocation, we found 76 live and 62 dead mussels in qualitative searches immediately downstream of plots 1 and 2. In both plots, estimated densities of live resident mussels were  $\leq 0.01/\text{m}^2$ .

Table V. Numbers of each species of mussel translocated to plots on the lower French Broad River

Species	Plot and number of mussels							
	1	2	3	4	5	6	7	8
<i>Amblema plicata</i>	410	140	293	134	—	1354	18	329
<i>Cyclonaias tuberculata</i>	550	155	542	687	419	16	592	365
<i>Ellipsaria lineolata</i>	—	—	—	—	—	21	—	201
<i>Fusconaia ebena</i>	771	40	687	432	1568	—	970	570
<i>Fusconaia flava</i>	—	—	72	—	—	165	—	20
<i>Megalonaias nervosa</i>	—	—	—	—	—	186	—	107
<i>Obliquaria reflexa</i>	—	265	—	—	—	94	—	45
<i>Quadrula metanevra</i>	400	295	277	473	157	2	438	247
<i>Quadrula pustulosa</i>	871	465	1009	934	302	171	945	275
Other species <sup>1</sup>	—	—	30	7	70	12	8	87
Total	3002	1360	2910	2667	2516	2023	2971	2246
Plot size (m <sup>2</sup> )	250	120	250	250	250	170	180	200

<sup>1</sup>Includes: 2 *Arcidens confragosus*; 85 *Elliptio crassidens*; 70 *Lampsilis fasciola*; 1 *Leptodea fragilis*; 5 *Ligumia recta*; 7 *Pleurobema cordatum*; 30 *Potamilus alatus*; 7 *Quadrula verrucosa*; 7 *Truncilla truncata*. Additionally, 59 *Ligumia recta* were introduced outside the borders of plot 4, and therefore are not included in total.

Table VI. Density of mussels translocated to each plot on the lower French Broad River and estimated mean density with 95% CIs following translocation. Lower recoveries are due both to mortality and to mussel emigration

Translocation			Year and estimated mean density (95% CI)				
Plot	Year	Density (mussels/m <sup>2</sup> )	1998	1999	2000	2001	2002
1	1997	12.00	6.60 (4.47–8.73)	6.52 (4.39–8.65)	6.16 (4.64–7.68)	4.12 (3.00–5.24)	—
2	1997	11.33	5.92 (4.67–7.16)	4.58 (3.32–5.85)	3.75 (2.35–5.15)	2.50 (1.50–3.50)	—
3	1998	11.64	—	7.60 (5.83–9.37)	10.24 (8.07–12.41)	12.96 (10.87–15.05)	9.20 (6.80–11.60)
4	1999	10.67	—	—	11.57 (9.15–14.00)	11.17 (9.25–13.09)	—
5	1999	10.06	—	—	—	9.70 (7.17–12.23)	3.20 (2.01–4.39)
6	2000	11.90	—	—	11.29* (8.03–14.56)	8.73 (6.38–11.07)	—
7	1999	16.51	—	—	11.33 (7.68–14.99)	9.11 (6.78–11.44)	—
8	2000	11.23	—	—	—	7.69 (5.73–9.65)	4.10 (2.87–5.33)

\*Mussels were translocated in May and sampled 5 months later.

At Seven Islands (plots 3–6, and 8), densities of live mussels estimated 1 year after translocation varied from 65% to 108% of the densities translocated into each plot (Table VI). Densities of dead translocated mussels were  $\leq 0.5$  individuals/m<sup>2</sup> in all plots at Seven Islands. Estimated densities of live resident mussels varied from 0.05 to 2.5/m<sup>2</sup> among the five plots at Seven Islands. Retention (mean density) of live mussels on all sites 2 years after translocation was positively correlated with density of live resident mussels ( $r = 0.84$ ;  $p < 0.05$ ). This relationship seemed to persist throughout the study. In three plots sampled for 4 years, retention of live translocated mussels was 22% and 34% in two plots where densities of resident mussels were  $\leq 0.01$ /m<sup>2</sup> but retention was 79% in plot 3 where the density of resident mussels was 2.5/m<sup>2</sup>.

From 1999 to 2002, we infested 202 banded sculpins (*Cottus carolinae*) with glochidia of pheasantshells, 581 redline darters (*Etheostoma rufilineatum*) with glochidia of Cumberland moccasainshells, and 18 redline darters with glochidia of fluted kidneyshells. In 2002, no juveniles of these three species were found during a search of the substrate in the area where infested fish were released.

## DISCUSSION

Prior to instituting a minimum flow release, operation of Douglas Dam as a peaking hydroelectric project resulted in dewatering of riffles and shallow shoreline areas during periods of no generation, and bank-full flows during peak generation. Daily peaking operations result in the amount and location of suitable fish habitat to be in a state of constant flux (Gore *et al.*, 1989). Operating Douglas Dam as a peaking project for 35 years resulted in an impoverished fish fauna. Harned (1979) sampled 12 sites below Douglas Dam by a variety of methods, including rotenone, and collected only 42% of the historic fish assemblage in 1977. Species composition was similar 11 years later when we collected 40% of the historical fauna.

The establishment of a minimum flow and oxygenation of the discharge from Douglas Dam did much to restore the fish fauna to the lower French Broad River. Since 1988, we have collected 82% of the fish species historically occurring in the lower French Broad River. This twofold increase in species richness over a 14-year-long period clearly demonstrates that if there is connectivity between source populations and improved tailwater conditions, natural fish recolonization is possible and most of the historical fauna will re-colonize the tailwater in a relatively short time.

It is possible that we did not collect all rare fish species present; however, Howard (2000) sampled 14 sites every other month in 1999 and failed to collect any species that we did not collect. The 18% of the historical fauna that has not re-colonized the lower French Broad River consists primarily of two groups of fishes. One group consists of those species (e.g., Alabama shad, *Alosa alabamae*) that have either been extirpated from the entire Tennessee River system or are isolated from the lower French Broad River. The second group includes cyprinids such as the warpaint shiner (*Luxilus coccogenis*) that inhabit the mid-water column. Although we did collect several

mid-water cyprinid species, they were uncommon in our samples. The minimum flow release during periods of no generation has been effective in providing diverse habitats and suitable conditions for many of the 36 fish species that have re-colonized the river. Nonetheless, the continued operation of Douglas Dam as a peaking hydroelectric facility continues to impact the fish fauna. During full generation, there are few velocity refugia, a likely limiting factor for mid-water column species. Furthermore, the bank-full flows eliminate most shallow water habitats that are important as nursery areas (Holland, 1986; Scheidegger and Bain, 1995). In the French Broad River, loss of these nursery areas or nest destruction during peak generation may limit recruitment of many species (Farmer, 2001).

The historically rich mussel fauna of the lower French Broad River was also drastically reduced by the construction and operation of Douglas Dam; however, poor land-use practices starting with clearing of the forested watershed were a contributing factor (Hughes and Parmalee, 1999). Only 12 of the original 53 species remain in the tailwater. The effects of construction and operation of dams on mussel populations have been well documented (Williams *et al.*, 1992; Layzer *et al.*, 1993; Heinricher and Layzer, 1999; Vaughn and Taylor, 1999). Hydroelectric peaking operations are particularly harmful to mussels because of the alternate aerial exposure of shoals at low discharge and the scouring action of high flows during periods of electric power generation (Layzer *et al.*, 1993). Discharge of anoxic water from Douglas Dam likely exacerbated the stress of aerial exposure on mussels.

Retention of translocated mussels varied greatly among plots, and downstream dispersal was evident. Downstream movement of mussels has been common in other translocation studies (e.g., Layzer and Gordon, 1993; Dunn, 1993; Morgan *et al.*, 1997). Selection of sites to re-establish mussel populations is problematic. There are no widely accepted criteria for selecting sites to re-establish mussel populations. Microhabitat variables such as water depth and velocity tend to be poor predictors of natural mussel distributions (Strayer, 1981; Holland-Bartels, 1990; Strayer and Ralley, 1993), whereas complex hydraulic variables such as shear stress are better predictors (Layzer and Madison, 1995; Hardison and Layzer, 2001). Moreover, Strayer (1999) demonstrated that mussel beds occur in areas of hydraulic refuge with substrates that are stable during flood events; immediately adjacent to these beds, few mussels occur.

In the French Broad River, the size and eroded condition of most resident mussels suggest that they were present when Douglas Dam was constructed in 1943. Consequently, their distribution, particularly at Seven Islands (rkm 24) where densities reached  $2.52/\text{m}^2$ , probably reflect the location of existing hydraulic refugia, and perhaps the locations of some of the original mussel beds. While we did not measure microhabitat variables, substrate composition appeared to be composed primarily of gravel and rubble in all translocation plots, and during minimum flow there were no observable differences in water depths or velocities. Nonetheless, densities of resident mussels varied greatly among plots. Moreover, the positive correlation between resident mussel densities and retention of translocated mussels suggests differences in habitat (presumably hydraulic conditions) among plots. The scope of our study did not include determining specific habitat criteria for identifying sites for re-establishing mussel beds in other rivers. Nevertheless, based on the results of our study, we believe that future attempts to re-establish mussels in other streams will be most successful if translocations occur at sites of existing or historical beds.

#### PROGNOSIS FOR RE-ESTABLISHING THE HISTORICAL FAUNA

Re-establishment of fish and mussel populations requires suitable water quality, and habitat conditions that are temporally stable. Although the established minimum flow and increased DO concentrations released from Douglas Dam maintain good habitat conditions in shoal and riffle areas during periods of nongeneration, the continued operation of Douglas Dam as a peaking hydroelectric project remains a formidable obstacle to restoring viable populations of some fish and many mussel species that historically occurred in the lower French Broad River. During our study, the number of fish species in the lower French Broad River doubled since inception of minimum flows and oxygenation of the discharge; however, there remains an under-representation of some habitat guilds. In particular, the occurrence and abundance of mid-water column cyprinids is limited. While slow-moving pools, backwaters, and quiescent stream margins are prevalent during minimum flow conditions, these areas largely disappear during peaking flows, leaving little suitable habitat for mid-water cyprinids. Restoration of abundant populations of these cyprinids is unlikely to occur unless the discharge regime of Douglas Dam is changed to a run-of-the-river operation.



Clearly, mussel species relying on cyprinids that occupy the mid-water column, as hosts for their larvae (glochidia), cannot be re-established unless their hosts are present; however, the effects of hydroelectric peaking operations on mussels are more insidious. The large volume of water discharged during peaking operations dilutes mussel sperm concentrations in the water column, and may reduce egg fertilization rates. The glochidia of all extirpated mussel species are obligate parasites on fish, and many are host specific. During peak discharge, host fishes may move into hydraulic refugia that contain few mussels. Thus, glochidia released into the water column may have a reduced probability of contacting and infesting these fishes. Conversely, host fishes that become infested during minimum flows may move into hydraulic refugia during peak discharge where juveniles excyst, but these areas may not be suitable mussel habitat. Furthermore, juveniles excysting over suitable habitat during peak discharge may not be able to settle because of high shear stress (Layzer and Madison, 1995). Since velocity refugia for small, benthic fishes may exist in habitat suitable for mussels during peak discharges (see Gore *et al.*, 1989), the re-establishment of mussel species that use benthic fishes as hosts may be most likely.

In the absence of empirical data on reproductive success of specific mussel species in peaking hydroelectric tailwaters, we based our judgment of the likelihood of re-establishing extirpated mussel species and maintaining resident species based on the occurrence, abundance, and habitat of their known (or in some cases suspected) host fishes, and availability of potential donor populations for translocation or propagation. For instance, we assigned a prognosis of 'good' for the probability of re-establishing mussel species such as the endangered oyster mussel (*Epioblasma capsaeformis*) and birdwing pearlymussel (*Lemiox rimosus*) that utilize as hosts, some of the most abundant benthic fishes (i.e., banded sculpin and banded darter, *Etheostoma zonale*) present in the lower French Broad River (Table II). Moreover, sizable populations of these two mussel species exist within the Tennessee River drainage. We assigned a prognosis of 'poor' to those mussel species where the availability of a donor population is limited or their glochidial hosts occupy the mid-water column. For instance, we consider the probability of re-establishing a population of the endangered ringpink (*Obovaria retusa*) to be poor because the last known population is in the Green River, Kentucky, where it seemingly is on the brink of extinction. In all, we judged that 30 species of mussels can be re-established, but it is unlikely that 16 species can be re-established under the existing discharge regime (Table II). Furthermore, the future composition of the mussel fauna will likely include some species that were not part of the original fauna; the nonnative pistolgrip has already colonized the lower French Broad River. Other species such as the washboard (*Megaloniaias nervosa*) have moved >600 km up the Tennessee River since impoundment (Scruggs, 1960), and may continue their upstream movement into the French Broad River. Additional species listed by Hughes and Parmalee (1999) as recent invaders of the Tennessee River may also colonize the French Broad River. Thus, whether or not species of historical occurrence are introduced, the future composition of the mussel assemblage will differ markedly from the historical one because of invading, nonindigenous species and the previous global extinction of others.

#### ACKNOWLEDGEMENTS

The United States Fish and Wildlife Service (USFWS), Asheville, North Carolina Field Office funded this research. We thank the numerous students and staff of the Tennessee Cooperative Fishery Research Unit, and personnel from the Tennessee Valley Authority, Tennessee Wildlife Resources Agency, USFWS, and United States Geological Survey for their assistance in the field. P.W. Parmalee, University of Tennessee, and J.R. Shute and P. Rakes, Conservation Fisheries, Inc., Knoxville, Tennessee graciously supplied unpublished data on the historical mussel fauna. Bob Butler, USFWS, and two anonymous reviewers provided helpful comments on the manuscript.

#### REFERENCES

- Ahlstedt SA. 1991. Cumberlandian Mollusk Conservation Program: mussel surveys in six Tennessee Valley streams. *Walkerana* 5: 123–160.
- Anderson BA, Layzer JB, Gordon ME. 1991. A recent catastrophic decline of the mussel (Bivalvia: Unionidae) fauna in the Little South Fork of the Cumberland River. *Brimleyana* 17: 1–8.
- Boepple JF, Coker RE. 1912. *Mussel resources of the Holston and Clinch rivers of eastern Tennessee*. Bureau of Fisheries Document 725.
- Cope ED. 1870. On some etheostomine perch from Tennessee and North Carolina. In *Proceedings of the American Philosophical Society* 11: 261–270.

- Dortch M, Martin JL. 1989. Water quality modeling of regulated streams. In *Alternatives in Regulated River Management*, Gore JA, Petts GE (eds). CRC Press, Inc.: Boca Raton, Florida; 63–90.
- Dunn HL. 1993. Survival of unionids four years after relocation. In *Conservation and Management of Freshwater Mussels*. Proceedings of a UMRCC Symposium, Cummings KS, Buchanan AC, Koch LM (eds). Upper Mississippi River Conservation Committee: Rock Island, Illinois; 93–99.
- Dunn CS, Layzer JB. 1997. Evaluation of various facilities for maintaining freshwater mussels in captivity. In *Conservation and Management of Freshwater Mussels II: Initiatives for the Future*. Proceedings of a UMRCC Symposium, Cummings KS, Buchanan AC, Mayer CA, Naimo TJ (eds). Upper Mississippi River Conservation Committee: Rock Island, Illinois; 205–213.
- Etnier DA, Starnes WC. 1993. *The Fishes of Tennessee*. The University of Tennessee Press: Knoxville, Tennessee.
- Farmer JK. 2001. *Abundance and Distribution of Larval Fish in the Douglas Dam Tailwater*. MS Thesis, Tennessee Technological University: Cookeville, Tennessee.
- Gehrke PC, Astles KL, Harris JH. 1999. Within-catchment effects of flow alteration on fish assemblages in the Hawkesbury–Nepean River system, Australia. *Regulated Rivers: Research & Management* **15**: 181–198.
- Gillis PL, Mackie GL. 1994. Impact of the zebra mussel, *Dreissena polymorpha*, on populations of Unionidae (Bivalvia) in Lake St. Clair. *Canadian Journal of Zoology* **72**: 1260–1271.
- Gore JA, Nestler JM, Layzer JB. 1989. Instream flow predictions and management options for biota affected by peaking hydropower releases. *Regulated Rivers: Research & Management* **3**: 35–48.
- Hardison BS, Layzer JB. 2001. Relations between complex hydraulics and the localized distribution of mussels in three regulated rivers. *Regulated Rivers: Research & Management* **17**: 77–84.
- Harned WD. 1979. *A Qualitative Survey of Fish and Macroinvertebrates of the French Broad River and Selected Tributaries June–August 1977*. Tennessee Valley Authority Technical Note B-35, Norris, Tennessee.
- Heinricher JR, Layzer JB. 1999. Reproduction by individuals of a nonreproducing population of *Megaloniais nervosa* (Mollusca: Unionidae) following translocation. *The American Midland Naturalist* **141**: 140–148.
- Holland LE. 1986. Distribution of early life history stages of fishes in selected pools of the upper Mississippi River. *Hydrobiologia* **136**: 121–130.
- Holland-Bartels LE. 1990. Physical factors and their influence on the mussel fauna of a main channel border habitat of the upper Mississippi River. *Journal of the North American Benthological Society* **9**: 327–335.
- Howard JM. 2000. *Temporal and Spatial Characteristics of the Fish Assemblage in a Large Regulated River*. MS Thesis, Tennessee Technological University: Cookeville, Tennessee.
- Hughes MH, Parmalee PW. 1999. Prehistoric and modern freshwater mussel (Mollusca: Bivalvia: Unionoidea) faunas of the Tennessee River: Alabama, Kentucky, and Tennessee. *Regulated Rivers: Research & Management* **15**: 25–42.
- Karr JR, Fausch KD, Angermeier PL, Yant PR, Schlosser IJ. 1986. *Assessing Biological Integrity in Running Waters. A Method and its Rationale*. Illinois Natural History Survey Special Publication 5: Champaign, Illinois.
- Layzer JB, Gordon ME. 1993. Reintroduction of mussels into the upper Duck River, Tennessee. In *Conservation and Management of Freshwater Mussels*. Proceedings of a UMRCC Symposium, Cummings KS, Buchanan AC, Koch LM (eds). Upper Mississippi River Conservation Committee: Rock Island, Illinois; 89–92.
- Layzer JB, Gordon ME, Anderson RM. 1993. Mussels: the forgotten fauna of regulated rivers. A case study of the Caney Fork River. *Regulated Rivers: Research & Management* **8**: 63–71.
- Layzer JB, Madison LM. 1995. Microhabitat use by freshwater mussels and recommendations for determining their instream flow needs. *Regulated Rivers: Research & Management* **10**: 329–345.
- Lemarié DP, Smith DR, Villella RF, Weller DA. 2000. Evaluation of tag types and adhesives for marking freshwater mussels (Mollusca: Unionidae). *Journal of Shellfish Research* **19**: 247–250.
- Morgan AM, Welker NJ, Layzer JB. 1997. Feasibility of reintroducing threatened and endangered mussels into Shoal Creek in Alabama and Tennessee. In *Conservation and Management of Freshwater Mussels II: Initiatives for the Future*. Proceedings of a UMRCC Symposium, Cummings KS, Buchanan AC, Mayer CA, Naimo TJ (eds). Upper Mississippi River Conservation Committee: Rock Island, Illinois; 196–205.
- Morrison JPE. 1942. Preliminary report on mollusk found in shell mounds of the Pickwick Landing Basin in the Tennessee River Valley. *Bureau of American Ethnology Bulletin* **129**: 339–392.
- Nestler JM, Milhous RT, Layzer JB. 1989. Instream flow modeling techniques for fisheries. In *Alternatives in Regulated River Management*, Gore JA, Petts GE (eds). CRC Press, Inc.: Boca Raton, Florida; 295–315.
- Nichols SJ, Black MG, Allen JD. 2000. Use of on-site refugia to protect unionid populations from zebra mussel-induced mortality. In *Freshwater Mollusk Symposia Proceedings*, Tankersley RA, Warmolts DI, Watters GT, Armitage BJ, Johnson PD, Butler RS (eds). Ohio Biological Survey: Columbus, Ohio; 67–75.
- Parmalee PW. 1988. A comparative study of late prehistoric and modern molluscan faunas of the Little Pigeon River system, Tennessee. *American Malacological Bulletin* **6**: 165–178.
- Parmalee PW, Bogan AE. 1998. *The Freshwater Mussels of Tennessee*. The University of Tennessee Press, Knoxville, Tennessee.
- Quinn RD. 2002. *Investigation Into the Efficacy of Static Systems for Quarantining Unionids*. MS Thesis, Tennessee Technological University: Cookeville, Tennessee.
- Scheidegger KJ, Bain MB. 1995. Larval fish distribution and microhabitat use in free-flowing and regulated rivers. *Copeia* **1995**: 125–135.
- Schloesser DW, Nalepa TF. 1994. Dramatic decline of unionid bivalves in offshore waters of western Lake Erie after infestation by the zebra mussel, *Dreissena polymorpha*. *Canadian Journal of Fisheries and Aquatic Sciences* **51**: 2234–2242.

- Scott EM. 1999. Tailwater Fish Index (TFI) development for Tennessee River tributary tailwaters. In *Assessing the Sustainability and Biological Integrity of Water Resources Using Fish Communities*, Simon T (ed.). RC Press: New York ; 507–522.
- Scott EM, Gardner KD, Baxter DS, Yeager BL. 1996. *Biological and Water Quality Responses in Tributary Tailwaters to Dissolved Oxygen and Minimum Flow Improvements*. Tennessee Valley Authority, Resource Group, Water Management: Norris, Tennessee.
- Scruggs GD Jr. 1960. *Status of fresh-water mussel stocks in the Tennessee River*. U.S. Fish and Wildlife Service Special Scientific Report-Fisheries No. 370.
- Sickel J, Herod J, Blalock H. 1997. Potential for the Kentucky Dam tailwater of the Tennessee River to serve as a mussel refuge from invading zebra mussels. In *Conservation and Management of Freshwater Mussels II: Initiatives for the Future*.
- Proceedings of a UMRCC Symposium, Cummings KS, Buchanan AC, Mayer CA, Naimo TJ (eds). Upper Mississippi River Conservation Committee: Rock Island, Illinois; 214–219.
- Strayer DL. 1981. Notes on the microhabitats of unionid mussels in some Michigan streams. *The American Midland Naturalist* **106**: 411–415.
- Strayer DL. 1999. Use of flow refuges by unionid mussels in rivers. *Journal of the North American Benthological Society* **18**: 468–476.
- Strayer DL, Ralley J. 1993. Microhabitat use by an assemblage of stream dwelling unionaceans (Bivalvia), including two rare species of *Alasmidonta*. *Journal of the North American Benthological Society* **12**: 247–258.
- Strayer DL, Downing JA, Haag WR, King TL, Layzer JB, Newton TJ, Nichols SJ. 2004. Changing perspectives on pearly mussels, North America's most imperiled animals. *BioScience* **54**: 429–439.
- Vaughn CC, Taylor CM. 1999. Impoundments and the decline of freshwater mussels: a case study of an extinction gradient. *Conservation Biology* **13**: 912–920.
- Waller DL, Holland LE, Mitchell LG, Kammer TW. 1985. Artificial infestation of largemouth bass and walleye with glochidia of *Lampsilis ventricosa* (Pelecypoda: Unionidae). *Freshwater Invertebrate Biology* **4**: 152–153.
- Williams JD, Fuller SL, Grace R. 1992. Effects of impoundments on freshwater mussels (Mollusca: Bivalvia: Unionidae) in the main channel of the Black Warrior and Tombigbee Rivers in western Alabama. *Bulletin Alabama Museum of Natural History* **13**: 1–10.