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Road Crossings as Barriers to Small-Stream Fish Movement

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Abstract.—We used mark–recapture techniques to examine the effects of four types of road crossings on fish movement during spring base flows and summer low flows in small streams of the Ouachita Mountains, west-central Arkansas. We assessed movement for 21 fish species in seven families through culvert, slab, open-box, and ford crossings and through natural reaches. We detected no seasonal or directional bias in fish movement through any crossing type or the natural reaches. Overall fish movement was an order of magnitude lower through culverts than through other crossings or natural reaches, except no movement was detected through the slab crossing. In contrast, open-box and ford crossings showed little difference from natural reaches in overall movement of fishes. Numbers of species that traversed crossings and movement within three of four dominant fish families (Centrarchidae, Cyprinidae, and Fundulidae) also were reduced at culverts relative to ford and open-box crossings and natural reaches. In spring, retention of fishes was consistently highest in stream segments upstream of crossings and lowest in downstream segments for all crossing types, a response attributed to scouring associated with spring spates. Water velocity at crossings was inversely related to fish movement; culvert crossings consistently had the highest velocities and open-box crossings had the lowest. A key requirement for improving road crossing designs for small-stream fish passage will be determination of critical levels of water velocity through crossings.

The ability to disperse is often critical to fishes for access to spawning habitat (Fausch and Young 1995), for maintenance of populations in areas unsuitable for reproduction (Schlosser 1995; Schlosser and Angermeier 1995), and for access to prey or avoidance of predators (Power 1987; Harvey et al. 1988; Harvey 1991). Barriers to dispersal may delay or preclude recovery of fish assemblages following disturbance (Detenbeck et al. 1992) and increase extinction risk by fragmentation (Bestgen and Platania 1991; Winston et al. 1991).

Road crossings are potential barriers to the movement of small-stream fishes. Road crossing designs vary from simple, low-water fords to massive concrete or earth-filled structures. Some crossing types may act as semipermeable or seasonal barriers to fish movement, similar to shallow riffles (Matthews et al. 1994); others may preclude all movement by fishes, similar to effects of dams (Winston et al. 1991; Watters 1996).

Unlike salmonids (Fausch and Young 1995), little is known about movement of small-stream, warmwater fishes (Hill and Grossman 1987a; Bart 1989; Peterson and Bailey 1993; Freeman 1995), and even less is known about effects of road crossings on these fishes. Despite traditional views to the contrary (e.g., Gerking 1959), recent work has shown that small-stream fishes can be highly mobile (Decker and Erman 1992; Matheney and Rabeni 1995) and show rapid recolonization into defaunated stream reaches (Peterson and Bayley 1993; Sheldon and Meffe 1994). The effects of road crossings on fish movement in small warmwater streams, however, are unknown.

The potential of a road crossing to act as a barrier to fishes probably is related to the alteration of flow through the crossing. We hypothesized that crossing types that minimally alter natural flow may be less likely to influence fish movement. We examined the effects on fish movement of four road crossing types with different potentials to alter flows. Fish movement through crossings was determined at spring base and summer low flows in small streams in forested watersheds of the Ouachita Mountains, Ouachita National Forest, west-central Arkansas. We specifically asked four questions: (1) Does crossing type affect overall, directional, or seasonal fish movement? (2) Is crossing type associated with the diversity of fishes or fish families able to traverse the crossing? (3) Are patterns of fish retention affected by cross-

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ings? (4) Is there a relationship between fish movement and water depth and velocity through crossings?

Methods

Road crossings.—We selected nine crossings on eight streams in the Ouachita National Forest (Ouachita River drainage), Montgomery County, Arkansas, for study of fish movement at summer low flows (July–August 1993) and spring (March–May 1994) base flows. Crossing types included two fords, two open-box bridges, four cylindrical culvert crossings, and one solid concrete slab with no culverts (included only in summer samples). Gradients of study stream reaches, determined from 1:25,000-scale topographic maps, averaged 0.8% (SE = 0.14%); substrates were predominantly cobble, bedrock, and gravel. We characterized crossings by determining average water velocity (m/s, by timing a neutrally buoyant object traveling through the crossing a minimum of three times or by digital current meter), length (m, upstream to downstream distance of the crossing), and average depth (cm). Depths of culvert and open-box crossings were averages of the upstream and downstream opening depths; for other crossings, depths along the thalweg were averaged.

Ford crossings (Little and Big Cedar creeks, both stream order 2) were gently sloping, submerged roadbeds composed of compacted gravel substrate. Velocities through the fords were 0.10 m/s in summer and ranged from 0.12 to 0.28 m/s in spring. Lengths were 7 and 8 m, and depths were 6 cm (both) in summer and ranged from 12 to 20 cm in spring.

Open-box crossings (Twin and Martin creeks, orders 2 and 3, respectively) had one to three bays (3–4 m wide, 24–30 m long) topped with a concrete roadbed and underlain with a concrete or gravel bottom. Velocities were negligible in both spring and summer (<0.05 m/s), and depths ranged from 30 to 75 cm in summer and from 40 to 80 cm in spring.

Culvert crossings (Murphy Creek and Walnut Fork, both order 2; Little Cedar Creek, order 3; and South Fork, order 4) consisted of two to four 1-m-diameter concrete or corrugated plastic culvert pipes positioned on a concrete pad overlain by concrete or earth-and-gravel-filled roadbed with a concrete apron extending downstream 3–4 m. Culvert crossing water velocities were 0.4–1.4 m/s in summer and 0.8–1.4 m/s in spring; lengths were 6–10 m; and depths were 5–16 cm in summer and 14–47 cm in spring. One culvert (Murphy Creek) had a vertical drop of 5–8 cm in summer on the downstream edge of the concrete apron, and another (Walnut Fork) had a drop of 8 cm in summer and 5 cm in spring off the edge of the apron. Other culvert crossing aprons were submerged throughout the study.

The concrete slab crossing (East Fork Twin Creek, order 1) was a low dam across the stream with a 25-cm vertical drop off the downstream edge to the surface of the receiving pool. Velocity over the slab was negligible; length was 4 m; and depth was 5 cm during the summer.

Study design.—At each crossing, we divided the stream into three segments of about equal length (mean = 36 m, SE = 1.2 m, N = 51) in both seasons. We located the first segment (upstream segment) immediately upstream of the crossing and the second segment immediately downstream (downstream segment 1). We located the third segment (downstream segment 2) downstream of downstream segment 1 but separated from it by a natural stream reach equal in length to the crossing. At each crossing, the natural reach was a shallow riffle or run with a range in depths of 10–40 cm in summer and 20–70 cm in spring. We did not determine velocities through natural reaches.

Fish sampling.—At each site, we placed block nets at the ends of each stream segment and conducted two-pass electrofishing through the segment. We batchmarked all fishes with a subcutaneous injection of acrylic paint (Lotrich and Meredith 1974; Hill and Grossman 1987b; Freeman 1995) of a color unique to that stream segment and season.

After initial marking, we resampled each site twice during each season by blocknetting segments and conducting two-pass electrofishing. Mean interval between samples was 17 d (SE = 1 d) in the spring and 12 d (SE = 0.8 d) in the summer. We resampled one open-box crossing (Martin Creek) only once during the summer because shallow water precluded efficient sampling. During the first resample, unmarked fishes were marked, and fishes that had moved were re-marked with a color unique to the segment in which recapture occurred.

Data analyses.—At each site, we assessed fish movement through the crossing (between the upstream segment and downstream segment 1) and across the natural reach (between downstream segments 1 and 2). We expressed fish movement as proportional daily movement, $M \cdot R^{-1} \cdot D^{-1}$, where M was the number of fish that had moved, R was the total number of recaptures in both segments, and D was the number of days since the first mark-

TABLE 1.—Results of two-factor analysis of variance with orthogonal contrasts comparing proportional daily movement of fishes through three road crossing types and natural reaches.

Source of variation	df	F	P
Crossing type	3	7.54	0.0009
Season	1	3.39	0.0775
Interaction	3	1.78	0.1766
Orthogonal contrasts			
Natural, open-box, ford versus culvert	1	21.01	0.0001
Natural versus open-box, ford	1	4.28	0.0490
Open-box versus ford	1	1.49	0.2342
Within	25		
Total	32		

ing. We expressed directional movement similarly with M being the number of fish that moved upstream or downstream. We used an arcsine square root transformation of proportional daily movement to achieve equality of variances and normality for analyses of variance but present retransformed means and error terms (Sokal and Rohlf 1981). Significance values were $P < 0.05$ for all tests.

We tested for effects of crossing type and season on fish movement by using two-factor analysis of variance (ANOVA) with orthogonal contrasts of mean proportional daily movement (Sokal and Rohlf 1981) among crossing types and natural reaches (Table 1). No differences were found among natural reaches in mean proportional daily movement (ANOVA; $F = 1.54$, df = 3, 5; $P < 0.3127$ for summer; $F = 0.78$, df = 2, 5; $P < 0.5084$ for spring), thus natural reaches were pooled. For contrasts, we hypothesized that crossings with the greatest ostensible alteration of flow would show the greatest effects on fish movement (Table 1). The slab crossing was excluded from this analysis because of its inclusion only in summer samples. We analyzed directional movement separately for each season by using analysis of variance for all crossings pooled and for each crossing class separately.

We tested for association of crossing type with diversity of fishes or fish families that moved through a crossing by using G-tests (Sokal and Rohlf 1981) with exact P-values (Mehta and Patel 1992). For the diversity test, rows were crossing types and columns were the number of recaptured species that had moved or had not moved through a crossing. We excluded the slab crossing from this analysis because of low species richness. For tests of association between family and crossing type, we used the four families with the highest percentage of recaptures: Centrarchidae, Cyprinidae, Fundulidae, and Percidae (Table 2). We performed separate tests for each family; rows were crossing types and columns were the number of recaptured individuals that had moved or had not moved through a crossing. Because of sparse cell frequencies, we pooled slab and culvert crossings for this analysis.

We tested for differences in fish retention among the upstream segment and downstream segments 1 and 2 by using recapture data for each stream segment at each site. We estimated fish retention in each stream segment for each season as R/T, where R was the total number of fishes recaptured and T was the total marked in that segment. Under the null hypothesis that segment position relative to a crossing has no effect on fish retention, migration would be allocated randomly among segments within a site and would show no among-site patterns. To test this hypothesis, we used Friedman's method for randomized blocks in which within-site fish retention was ranked by segment and blocked by site (Sokal and Rohlf 1981).

We tested for relationships between physical

TABLE 2.—Results of G-tests (df = 3, all tests) on the proportion of recaptured fishes that moved through natural reaches or four crossing types in each of four families. Total number of recaptured fishes are given in parentheses below each proportion.

			Crossing type			
Family	G	P	Natural reach	Ford	Open-box	Culvert and slab
Centrarchidae	16.44	0.0011	0.112	0.104	0.220	0.038
(sunfishes)			(321)	(144)	(50)	(166)
Cyprinidae	33.02	0.0001	0.191	0.146	0.297	0.028
(minnows)			(210)	(123)	(101)	(107)
Fundulidae	10.87	0.0216	0.140	0.333	0.032	0.077
(topminnows)			(43)	(24)	(31)	(26)
Percidae	0.56	0.9061	0.048	0.038	0.063	0.030
(darters)			(105)	(26)	(16)	(69)

TABLE 3.—Summary of movement of fish species recaptured at four road crossing types and natural reaches. A "Y" indicates a species moved through a crossing type; "N" indicates a species not found to have moved through a crossing; an asterisk (*) indicates a species marked but never recaptured; and a dash (–) indicates a species not encountered for that crossing type.

Fish species	Crossing type				
	Slab	Culvert	Open-box	Ford	Natural reach
Fundulus catenatus northern studfish	–	Y	Y	Y	Y
Lepomis megalotis longear sunfish	–	Y	Y	Y	Y
Semotilus atromaculatus creek chub	N	Y	Y	Y	Y
Etheostoma radiosum orangebelly darter	N	Y	Y	Y	Y
Ameiurus natalis yellow bullhead	–	Y	*	N	Y
Notropis boops bigeye shiner	–	Y	N	Y	Y
Etheostoma blennioides greenside darter	–	Y	*	–	*
Lepomis cyanellus green sunfish	N	N	Y	Y	Y
Luxilus chrysocephalus striped shiner	–	N	Y	Y	Y
Pimephales notatus bluntnose minnow	–	N	Y	Y	Y
Campostoma anomalum central stoneroller	–	N	N	Y	Y
Micropterus salmoides largemouth bass	–	N	–	Y	Y
Hypentelium nigricans northern hog sucker	–	N	N	*	Y
Lepomis macrochirus bluegill	–	N	–	–	Y
Erimyzon oblongus creek chubsucker	–	*	–	N	Y
Micropterus punctulatus spotted bass	–	*	*	–	Y
Fundulus olivaceus blackspotted topminnow	–	N	N	N	*
Nocomis asper redspot chub	–	*	N	–	N
Aphredoderus sayanus pirate perch	–	N	–	–	–
Micropterus dolomieu smallmouth bass	–	*	*	–	N
Lythrurus umbratilis redfin shiner	–	*	*	*	N
Percent of recaptured species that moved	0	44	58	77	83

characteristics (velocity and depth) of a crossing and fish movement by using Kendall's coefficient of rank correlation (Kendall's tau-beta). We correlated V, d, and V/d (where V was average velocity and d was average depth) with proportional daily movement for crossings (N = 9 in summer; N = 8 in spring) for both seasons together and separately.

Results

We marked 6,113 individuals (2,721 in summer and 3,392 in spring) representing 26 species and 8 families of fishes during the study. Average number of individuals marked per site was 302 (SE = 69.4) for summer and 424 (SE = 87.9) for spring. For all sites, we recaptured 18% of fishes in spring and 21% in summer. We recaptured 21 species representing 7 families (Table 3). Four fish families—Centrarchidae (sunfishes), Cyprinidae (minnows), Fundulidae (topminnows), and Percidae (darters)—constituted more than 97% of all recaptures (Table 2).

Discharge and rainfall data from South Fork Ouachita River, Mt. Ida, Arkansas (NCDC 1993a, 1993b, 1994a, 1994b, 1994c; USGS 1994, 1995) and our personal observations indicated that study streams had lower than average summer flows and near average spring flows. Average daily discharges of the river were 2.7 m/s for summer and 26.9 m/s for spring samples. The corresponding 52-year average discharges of the river were 4.9 m/s (July and August) and 34.6 m/s (March, April, and May; USGS 1994, 1995). In summer sampling, rainfall was negligible (NCDC 1993a, 1993b); no bank-full conditions occurred in study streams. In spring sampling, four rainfall events greater than 1.2 cm/d (NCDC 1994a, 1994b, 1994c) produced bank-full to overflowing conditions at least three times in the study streams.

Movement of fishes was significantly affected by crossing type (Table 1; Figure 1). No differences were found in seasonal movement, and interaction was not significant. Contrasts indicated mean movement was significantly higher for open-box (0.0096) and ford crossings (0.0056) and natural reaches (0.0038) than for culvert crossings. Movement through natural reaches was lower than through open-box and ford crossings. No differences were detected between open-box and ford crossings. No movement was detected through the slab crossing.

Fish movement through crossings was bidirectional. No differences were detected between upstream and downstream movement across crossing

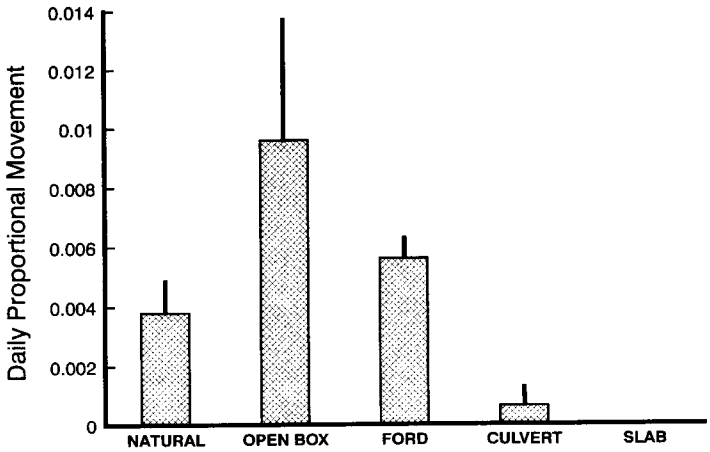

FIGURE 1.—Mean (+SE) daily proportional movement of fishes through four road crossing types and natural reaches.

types and natural reaches ($F = 0.36$, df = 1,32; $P < 0.5514$ in summer; $F = 0.40$, df = 1, 30; $P < 0.5315$ in spring). Likewise, neither individual crossing types nor natural reaches showed significant directionality in spring or summer.

The number of fish species that moved was associated significantly with crossing type ($G = 13.28$, df = 3; $P < 0.0146$; Table 3). Diversity of fishes traversing crossings increased along a gradient of slab, culvert, open-box, and ford crossings and natural reaches.

Movement of three of four fish families showed significant associations with crossing type (Table 2). Sunfish and minnow movement was lowest through culvert and slab crossings, intermediate through natural reaches and ford crossings, and highest in open-box crossings. Topminnows showed lowest movement through open-box, culvert, and slab crossings; intermediate movement in natural reaches; and highest movement through fords. Darter movement was independent of crossing type and generally was low relative to other families for all crossings.

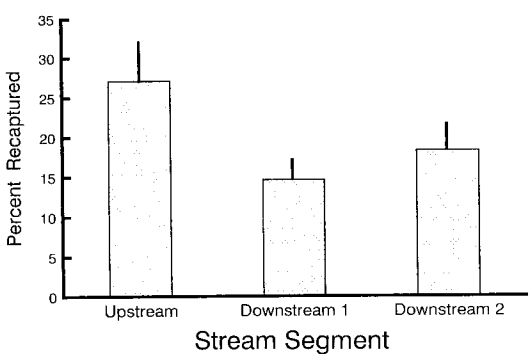

FIGURE 2.—Mean percentage (+SE) of tagged fish recaptured during spring in the same stream segment (upstream or downstream of road crossings) in which they were tagged.

Crossings showed consistent upstream–downstream differences in retention of marked fishes in spring (Figure 2) but not in summer (data not shown). In spring, segments upstream of crossings ranked significantly higher in retention of marked fishes (upstream segment, mean = 27.1%) than segments downstream of the crossing (downstream segment 1, mean = 14.6%; downstream segment 2, mean = 18.3%; $\chi^2 = 13.00$, df = 2, $P < 0.005$; Figure 2). Downstream segment 1 generally ranked lowest in retention; only two of eight of these segments were ranked higher than downstream segment 2. In summer, there was no effect of segment position on retention of fishes ($\chi^2 = 0.60$, df = 2, $P < 0.90$).

Movement of fishes through crossings was related inversely to velocity and the ratio of velocity to depth. Velocity was correlated negatively with proportional daily movement of fishes across seasons and in the summer (Table 4), but the relationship was nonlinear (Figure 3). The ratio of velocity to depth showed consistent negative correlations with fish movement for seasons pooled and for each season, but the strength of the association was similar to that shown for velocity alone. Depth was not correlated with fish movement. Mean velocities generally increased across road crossings from spring to summer but were consistently highest in culvert crossings (>0.90 m/s), intermediate in ford crossings (< 0.19 m/s), and lowest in open-box crossings (<0.03 m/s).

TABLE 4.—Correlations (Kendall's tau-beta) of proportional daily fish movement with velocity, depth, and the ratio of velocity to depth of four road crossing types. The P-value is given in parentheses.

Variable	Seasons pooled	Spring	Summer
Velocity (V)	−0.566	−0.500	−0.585
	(0.0022)	(0.0833)	(0.0382)
Depth (d)	0.294	0.214	0.377
	(0.1053)	(0.4579)	(0.1666)
$V:d$	−0.538	−0.571	−0.606
	(0.0034)	(0.0478)	(0.0300)

Discussion

Culvert and slab crossings reduced overall fish movement, diversity of movement, and movement of fish families relative to natural reaches. In contrast, movement through open-box and ford crossings generally was comparable with or higher than movement through natural reaches. Neither natural reaches nor any crossing type showed seasonal or directional bias for fish passage. For the slab crossing, we detected no movement of fishes in either direction, suggesting this crossing type may act as a total barrier for much of the year. Culvert crossings were bidirectional barriers to fish movement in both seasons despite a range of flow conditions (e.g., bank-full flows).

Retention of fishes at all crossings was higher in upstream segments than in downstream segments during spring but not summer. Although short-term, high turnover (i.e., low retention) of fishes in stream reaches is not unusual (Fausch and Young 1995), the reason for different retention rates between segments upstream and downstream of crossings is not readily apparent. The difference could be attributed to the interaction of crossings and elevated stream discharge in spring. Fishes immediately below a crossing might have been displaced downstream by scouring (Matthews 1986; Harvey 1987; Stock and Schlosser 1991), and fishes above a crossing, using it as a hydraulic refuge, might have tended to aggregate.

The degree to which a crossing acted as a barrier was related to alteration of flow through the crossing. Culvert crossings had the highest mean velocities and lowest fish passage, and open-box crossings had the lowest mean velocities and highest fish passage. All culverts had water velocities that exceeded 40 cm/s (Figure 3). At constant fish size and water depth, increasing water velocities limit swimming abilities of fishes. This relationship led to the suggestion that maximum water velocities of 30–40 cm/s for 100-m-length culverts would allow passage of most mature migratory fish species; shorter culverts could sustain passage at higher velocities (Jones et al. 1974). Fish passage across short distances (<10 m in culverts) in our study streams was reduced substantially at water velocities above 40 cm/s, suggesting flows through crossings for nonmigratory, small-stream fishes need to be much lower than the maximum suggested for migratory fishes.

Our familial-level analysis suggested passage

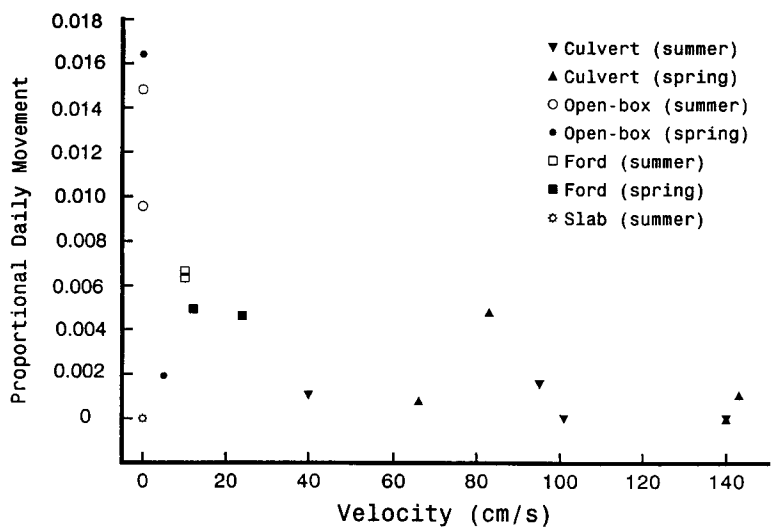

FIGURE 3.—Scatterplot of velocity and proportional daily movement of fishes through road crossings at summer and spring flows.

also was mediated by taxon-specific responses to crossings. Both sunfishes (mostly longear sunfish and green sunfish) and minnows (mostly the genera *Campostoma, Notropis,* and *Semotilus*), the dominant fishes in our streams, are capable of rapid dispersal (Detenbeck et al. 1992) and routine crossing of habitat boundaries (Berra and Gunning 1970, 1972; Ellis 1974; Bart 1989; Freeman 1995). However, the two families have different body morphologies and sizes, two primary determinants of swimming ability (Beamish 1978; Berry and Pimentel 1985; Harvey 1987). Culvert crossings produced fast flows that apparently were bidirectional barriers to passage for sunfishes and minnows despite a presumed range of swimming abilities in the two families and their observed ability to bidirectionally negotiate other crossings and natural reaches. In contrast, topminnows showed low movement through both open-box and culvert crossings, the two extremes in observed water velocities. Recaptured topminnows in our streams were predominantly northern studfish, diurnal feeders that may experience extensive seasonal movements (Fisher 1981). Topminnow inability to cross culverts may be attributed to water velocity, but responses to other aspects of crossing configurations also apparently influenced passage success. Movement of darters, primarily composed of the riffle-dwelling orangebelly darter, was relatively low for all crossings. Similarly, Scalet (1973) observed little movement in orangebelly darters in a natural stream setting. Studies of darter movement generally indicate long-term residence in relatively small areas, although interhabitat movements by a small proportion of individuals are not uncommon (e.g., Mundahl and Ingersoll 1983; Freeman 1995).

Our results indicate that culvert and slab crossings reduced or precluded movement of fish of most species. Ford and open-box crossings showed little difference from natural reaches in movement of fishes. We present evidence that increased water velocity through culverts is part of the mechanism by which these crossings restrict fish passage. Given the necessity of dispersal for fishes to meet their life history requirements (Schlosser and Angermeier 1995), road crossings should be designed to minimize effects on fish movement. Determination of critical levels of water velocity through crossings may be key to designs that facilitate rather than prevent movement of small-stream, warmwater fishes.

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References

Bart, H. L., Jr. 1989. Fish habitat association in an Ozark stream. Environmental Biology of Fishes 24: 173–186.

Beamish, F. W. H. 1978. Swimming capacity. Pages 101–187 *in* W. S. Hoar and D. J. Randall, editors. Fish physiology, volume VII. Locomotion. Academic Press, New York.

Berra, T. M., and G. E. Gunning. 1970. Repopulation of experimentally decimated sections of streams by longear sunfish, *Lepomis megalotis megalotis* (Rafinesque). Transactions of the American Fisheries Society 99:776–781.

Berra, T. M., and G. E. Gunning. 1972. Seasonal movement and home range of the longear sunfish, *Lepomis megalotis* (Rafinesque). American Midland Naturalist 99:368–375.

Berry, C. R., Jr., and R. Pimentel. 1985. Swimming performances of three Colorado River fishes. Transactions of the American Fisheries Society 114:397–402.

Bestgen, K. R., and S. P. Platania. 1991. Status and conservation of the Rio Grande silvery minnow, *Hybognathus amarus*. Southwestern Naturalist 36: 225–232.

Decker, L. M., and D. C. Erman. 1992. Short-term seasonal changes in composition and abundance of fish in Sagehen Creek, California. Transactions of the American Fisheries Society 121:297–306.

Detenbeck, N. E., P. W. DeVore, G. J. Niemi, and A. Lima. 1992. Recovery of temperate-stream fish communities from disturbance: a review of case studies and synthesis of theory. Environmental Management 16:33–53.

Ellis, J. E. 1974. The jumping ability and behavior of green sunfish (*Lepomis cyanellus*) at the outflow of a 1.6 ha pond. Transactions of the American Fisheries Society 103:620–623.

Fausch, K. D., and M. K. Young. 1995. Evolutionary significant units and movement of resident stream fishes: a cautionary tale. Pages 360–370 *in* J. L. Nielsen, editor. Evolution and the aquatic system:

defining unique units in population conservation. American Fisheries Society, Symposium 17, Bethesda, Maryland.

Fisher, J. W. 1981. Ecology of *Fundulus catenatus* in three interconnected stream orders. American Midland Naturalist 106:372–378.

Freeman, M. C. 1995. Movements by two small fishes in a large stream. Copeia 1995:361–367.

Gerking, S. D. 1959. The restricted movement of fish populations. Biological Reviews 34:221–242.

Harvey, B. C. 1987. Susceptibility of young-of-the-year fishes to downstream displacement by flooding. Transactions of the American Fisheries Society 116: 851–855.

Harvey, B. C. 1991. Interactions among stream fishes: predator-induced habitat shifts and larval survival. Oecologia 87:29–39.

Harvey, B. C., R. C. Cashner, and W. J. Matthews. 1988. Differential effects of largemouth and smallmouth bass on habitat use by stoneroller minnows in stream pools. Journal of Fish Biology 33:481–487.

Hill, J., and G. D. Grossman. 1987a. Home range estimates for three North American stream fishes. Copeia 1987:376–380.

Hill, J., and G. D. Grossman. 1987b. Effects of subcutaneous marking on stream fishes. Copeia 1987: 492–495.

Jones, D. R., J. W. Kiceniuk, and O. S. Bamford. 1974. Evaluation of the swimming performance of several fish species from the Mackenzie River. Journal of the Fisheries Research Board of Canada 31:1641–1647.

Lotrich, V. A., and W. H. Meredith. 1974. A technique and the effectiveness of various acrylic colors for subcutaneous marking of fish. Transactions of the American Fisheries Society 103:140–143.

Matheney, M. P., and C. F. Rabeni. 1995. Patterns of movement and habitat use by northern hog suckers in an Ozark stream. Transactions of the American Fisheries Society 124:886–897.

Matthews, W. J. 1986. Fish faunal structure in an Ozark stream: stability, persistence and a catastrophic flood. Copeia 1986:388–397.

Matthews, W. J., B. C. Harvey, and M. E. Power. 1994. Spatial and temporal patterns in fish assemblages of individual pools in a midwestern stream (U.S.A.). Environmental Biology of Fishes 39:381–397.

Mehta, C., and N. Patel. 1992. StatXact-Turbo. Cytel Software Corp., Cambridge, Massachusetts.

Mundahl, N. D., and C. G. Ingersoll. 1983. Early autumn movements and densities of johnny (*Etheostoma nigrum*) and fantail (*E. flabellare*) darters in a southwestern Ohio stream. Ohio Journal of Science 83:103–108.

NCDC (National Climatic Data Center). 1993a. Climatological data, Arkansas, July 1993, volume 98, number 7. National Oceanic and Atmospheric Administration, NCDC, Asheville, North Carolina.

NCDC (National Climatic Data Center). 1993b. Climatological data, Arkansas, August 1993, volume 98, number 8. National Oceanic and Atmospheric Administration, NCDC, Asheville, North Carolina.

NCDC (National Climatic Data Center). 1994a. Climatological data, Arkansas, March 1994, volume 99, number 3. National Oceanic and Atmospheric Administration, NCDC, Asheville, North Carolina.

NCDC (National Climatic Data Center). 1994b. Climatological data, Arkansas, April 1994, volume 99, number 4. National Oceanic and Atmospheric Administration, NCDC, Asheville, North Carolina.

NCDC (National Climatic Data Center). 1994c. Climatological data, Arkansas, May 1994, volume 99, number 5. National Oceanic and Atmospheric Administration, NCDC, Asheville, North Carolina.

Peterson, J. T., and P. B. Bayley. 1993. Colonization rates of fishes in experimentally defaunated warmwater streams. Transactions of the American Fisheries Society 122:199–207.

Power, M. E. 1987. Predator avoidance by grazing fishes in temperate and tropical streams: importance of stream depth and prey size. Pages 333–351 *in* W. C. Kerfoot and A. Sih, editors. Predation: direct and indirect impacts on aquatic communities. University Press of New England, Hanover, New Hampshire.

Scalet, C. G. 1973. Stream movements and population density of the orangebelly darter, *Etheostoma radiosum cyanorum* (Osteichthyes: Percidae). Southwestern Naturalist 17:381–387.

Schlosser, I. J. 1995. Dispersal, boundary processes, and trophic level interactions in streams adjacent to beaver ponds. Ecology 76:908–925.

Schlosser, I. J., and P. L. Angermeier. 1995. Spatial variation in demographic processes of lotic fishes: conceptual models, empirical evidence, and implications for conservation. Pages 392–401 *in* J. L. Nielsen, editor. Evolution and the aquatic system: defining unique units in population conservation. American Fisheries Society, Symposium 17, Bethesda, Maryland.

Sheldon, A. L., and G. K. Meffe. 1994. Short-term recolonization by fishes of experimentally defaunated pools of a Coastal Plain stream. Copeia 1994:828–837.

Sokal, R. R., and F. J. Rohlf. 1981. Biometry. Freeman, New York.

Stock, J. D., and I. J. Schlosser. 1991. Short-term effects of a catastrophic beaver dam collapse on a stream fish community. Environmental Biology of Fishes 31:1123–1129.

USGS (U.S. Geological Survey). 1994. Water resources data for Arkansas, water year 1993. USGS Water-Data Report, AR-93-1, Little Rock, Arkansas.

USGS (U.S. Geological Survey). 1995. Water resources data for Arkansas, water year 1994. USGS Water-Data Report, AR-94-1, Little Rock, Arkansas.

Watters, G. T. 1996. Small dams as barriers to freshwater mussels (Bivalvia, Unionoida) and their hosts. Biological Conservation 75:79–85.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming a prairie stream. Transactions of the American Fisheries Society 120:98–105.

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