Transactions of the American Fisheries Society 127:979–994, 1998

Impacts of Gravel Mining on Gravel Bed Streams

ARTHUR V. BROWN*
Department of Biological Sciences, University of Arkansas, Fayetteville, Arkansas 72701, USA

MADELEINE M. LYTTLE
U.S. Fish and Wildlife Service, Federal Building
11 Lincoln Street, Essex Junction, Vermont 05452, USA

KRISTINE B. BROWN
Department of Biological Sciences, University of Arkansas, Fayetteville, Arkansas 72701, USA

Abstract.—The impacts of gravel mining on physical habitat, fine-sediment dynamics, biofilm, invertebrates, and fish were studied in three Ozark Plateaus gravel bed streams. Intense studies were performed upstream, on site, and downstream from one large mine on each stream. Invertebrates and fish were also sampled in disturbed and reference riffles at 10 small mines. Gravel mining significantly altered the geomorphology, fine-particle dynamics, turbidity, and biotic communities. Stream channel form was altered by increased bank-full widths, lengthened pools, and decreased riffles in affected reaches. Fine particulate organic matter transported from riffles to pools was decreased. Biofilm organic content was decreased on flats and increased on remaining riffles. Density and biomass of large invertebrates and density of small invertebrates were reduced at the small, more frequently mined sites. Total densities of fish in pools and game fish in pools and riffles were reduced by the large mines. Silt-sensitive species of fish were less numerous downstream from mines. Attempts to mitigate or restore streams impacted by gravel mining may be ineffective because the disturbance results from changes in physical structure of the streambed over distances of kilometers upstream and downstream of mining sites. Stream morphology was changed by lack of gravel bedload, not by how bedload was removed. Mining gravel from stream channels results in irreconcilable multiple-use conflicts.

Introduction

Many streams are of the alluvial gravel, riffle and pool channel form, especially in the midcontinental United States where their beds pass through geologically old gravel deposits (Brussock et al. 1985; Brown and Matthews 1995). Gravel is taken directly from these stream channels in increasingly large quantities primarily for construction of roads and highways. Large volumes of aggregate (sand and gravel) are obtained by the dredging of navigable rivers to maintain deep channels (Lagasse et al. 1980; Lagasse 1986). Considerable amounts are also mined from small streams, where there is less regulation by governmental agencies, such as the U.S. Army Corps of Engineers. Removal of sand and gravel from rivers and streams may have extensive negative effects on their biotic communities.

Considerable interest in the effects of the removal of aggregate on rivers and streams has developed recently (Kanehl and Lyons 1992; Hartfield 1993; Mossa and McLean 1997; Pringle 1997, and references therein), but there have been no comprehensive studies of the impacts of gravel removal on the various components of gravel bed stream ecosystems. A study by Weigand (1991) in the Puyallup River system in Washington reported that gravel scalping (the removal of alluvial material above the wetted perimeter) reduced the amount of habitat suitable for rearing juvenile steelhead *Oncorhynchus mykiss* and juvenile coho salmon *O. kisutch* that require side-channel pools during their first year of growth. Other studies of the effects of gravel harvest (Rivier and Sequier 1985; Martin and Hess 1986) on stream communities have indicated that environmental degradation is difficult to document through standard methods of environmental monitoring unless the impact is obvious (e.g., stranding of fish and invertebrates) and immediate (e.g., samples taken during gravel removal operations). It has been suggested that alterations in biological communities resulting from extraction of gravel have been caused primarily by alteration of flow patterns due to changes in the shape of the river channel and by excessive sediment suspension (Reiser and Bjornn 1979; Rivier and Sequier 1985).

The impact of dredging on large rivers has re-

* Corresponding author: artbrown@comp.uark.edu

ceived more attention (Lagasse et al. 1980; Lagasse 1986) than gravel mining on small streams. Dredges remove larger particles that, if left in place, form an effective armor plating on alluvial deposits (Livesey 1963; Hallmark and Smith 1965; Gessler 1970; Little and Mayer 1972). When armoring is removed, exposed sediments are much more easily transported, and sediment load and turbidity are increased (Lagasse et al. 1980). The decrease in the average size of bed material between 1968 and 1974 from Smith Point to Racetrack Reach in the lower Mississippi River was presumably a result of gravel mining and the limiting of the normal movement of the channel (Robbins 1977; Lagasse et al. 1980). Similar problems associated with gravel removal have been reported from other countries (Egyazarov 1970; Kira 1972; Janzen et al. 1979). The reduction of mean sediment particle size, removal of armoring, restructuring of channels, and increased sediment transport documented for large rivers may also occur in smaller streams, although these effects are less well studied. The more complex geometry of small, unconfined stream channels is probably more vulnerable to deformation by gravel removal than the highly regulated structure of large rivers.

Alluvial gravel streambeds, though complex, have rather predictable geometry (Brussock et al. 1985, and references therein). Riffles occur at intervals of approximately five to seven bank-full stream widths (Leopold et al. 1964). Repeated bed-forming flows (more than one-half bank full) gradually shape a stream channel through alluvial gravel deposits that are concordant with flow patterns during these high flows (see Keller 1971; Richards 1982). Subsequent to formation of a three-dimensional channel shape that is harmonious with the path of flowing water, movement of the bedload (sediments in the stream channel) is minimal. Alteration of the shape of the stream channel by removal of a portion of the bedload, such as a gravel deposit, has important consequences. During subsequent high flows, the stream spends considerable hydraulic energy to realign the channel to reestablish normal riffle–pool spacing and reshape the bed to conform to flow patterns. Other stream channel forms (debris-regulated, sandbed, and braided; see Brussock et al. 1985) have less predictable shapes. Therefore, removal of equivalent volumes of substrate from different stream channel forms has the most impact on alluvial gravel streams, as discussed in relation to flood effects by Resh et al. (1988).

The overall objective of this study was to assess the impacts of gravel mining on several major components of gravel bed stream ecosystems. This broad-spectrum study would suggest, and help focus, subsequent investigations that could affirm cause and effect relationships. More specific objectives were to measure mining impacts on (1) structure of the stream channels, especially the riffle and pool physical template; (2) organic and inorganic sedimentation dynamics during base flow conditions; (3) biofilm abundance and quality (organic content); (4) macroinvertebrate densities and biomass of two size-classes; (5) fish species assemblages, with special concerns for sport fishes and silt-sensitive taxa.

Methods

General.—We chose three streams and surveyed them and their tributaries to determine the number, location, and approximate size of gravel mines in 1991. We then examined the effects of gravel removal on one large (intensive) site in each of the three streams and, less intensely, additional small (extensive) sites. Fish were collected at six extensive sites in the Illinois River and from one extensive site on each of the other two streams. Macroinvertebrates were collected from four extensive sites in the Kings River and three extensive sites in each of the other streams.

Our principal focus was on fish and macroinvertebrate species assemblages, but at the intensive sites, we also measured stream channel geomorphology, biofilm, benthic particulate organic matter (BPOM), turbidity, and sediment dynamics at low flow. Intensive sites were larger (in area and volume of gravel removed) but were disturbed with less frequency than extensive sites.

The overall design at the three intensive sites was that of a natural experiment comparing contiguous upstream reference, mined, and downstream reaches. Riffles and pools were sampled and analyzed separately. At the extensive sites, we sampled only the riffles at upstream reference and mining areas. The reference areas were not undisturbed controls because other mining activities occurred farther upstream and because removal of bedload from the mined channel might have caused upstream headcutting (Schumm 1977; Gordon et al. 1992; Hartfield 1993; Pringle 1997). However, the upstream references were the most suitable areas for comparison because they were the least-disturbed reaches available that were comparable in other respects (e.g., stream order, flow volume, adjacent land use). Each of the three replicate stream sites consisted of three adjacent study areas, totaling several kilometers of stream reach. A better experimental design might have been to pair different streams, comparing those with and without gravel mining, but all the gravel bed streams in the region have been mined extensively. Laws passed by the state of Arkansas subsequent to this study now protect the Kings River and other streams designated as ''primary resource'' waters from large-scale commercial gravel mining.

Morphometry.—A morphometric study was performed in 1992 at the intensive site in each stream that included three pairs of pools and riffles upstream, three pairs of pools and riffles downstream, and the entire reach in between where gravel was mined (two to five riffles and pools). We measured the length, width, and depth of each riffle and pool and the bank-full width in each reference, disturbed, and downstream reach using 100-m tapes and meter sticks. Riffles were distinguished by rippling on the water surface. Bank-full and wetted channel widths were measured on transects perpendicular to channels at 5-m intervals along the streams. Water depths were measured at 1-m intervals along each transect.

Sediment dynamics.—Siltation rates were measured at intensive sites during inactive (no mining) periods by placing a set of 10 standard Petri dish covers (9 cm diameter, 8 mm depth) filled with marbles in locations above and below reference, disturbance, and downstream riffles for 6 hours in flows of approximately 15 cm/s. Sediments from the marble traps were collected on preweighed 0.7-μm glass fiber filters, weighed, ashed, and reweighed to determine ash-free dry weights (AFDW) and inorganic fractions. These procedures were used to assess fine-sediment movement among sites during base flow when gravel mining was inactive. Petri dish covers were used because they can be deployed without disturbance to natural substrates, and their low profile allows capture of particles close to the bottom at a scale meaningful to fish eggs, fry, and benthic organisms. The marbles provide uniformity among samplers regarding particle shape, effects on flow across the upper surface, and interstitial space for retaining sediments. Turbidity was measured both at inactive times and during gravel removal.

To assess aggradation and degradation at the intensive sites, small chains were placed vertically in gravel deposits along transects across the upstream, middle, and downstream ends of the stream riffles in reference, mining, and downstream reaches. After floods, the length of chain that is horizontal represents the extent of degradation, and the depth of gravel above the horizontal portion of chain represents aggradation. Lengths of chain of 50 cm (or less if bedrock was encountered) were placed with a 75-cm-long steel tube (50-caliber gun barrel) driven into the gravel. An expanding anchor (drywall screw) was attached to the end of the chain, and it was pushed past the bottom of the tube with a small rod. After removing the tube, the chain was cut off at the surface of the substrate.

Biofilm.—Biofilm was quantitatively obtained from reference, mined, and downstream areas at each intensive site by brushing 15 cm^2 from 10 separate small cobbles (64–100 mm, Wentworth 1922) taken from the surface of existing substrates. The rocks were collected from areas with similar flows (25–35 cm/s) and depths (15–25 cm) to ensure comparability among sites. We quantified organic and inorganic portions of the biofilm using gravimetric techniques as described above for sediment analysis.

Invertebrates.—Benthic invertebrates were collected with a 0.05-m^2 vacuum benthos sampler (Brown et al. 1987) near the center of each riffle (Brown and Brown 1984). Five samples were collected from each of the nine intensive study reaches and three samples were collected from each of the 20 (10 pairs) extensive study riffles. Invertebrates were sorted and identified to the lowest feasible taxa, the number in each taxon was recorded, and taxa were then grouped into four categories (smaller invertebrates, *Corydalidae*, crayfish, and mollusks) for drying and weighing. Too few of the three large invertebrate taxa were collected for independent analysis so they were combined and analyzed as large invertebrates.

Fish.—Fish were collected from at least one riffle and one pool from each treatment reach (reference, disturbed, downstream) at each site. Minimum areas recommended for obtaining representative samples of fish were exceeded in each sampled area (Matthews 1990; Lyons 1992). Before habitat and fish were sampled, block nets were placed at the upstream and downstream ends of sampling sections to ensure that fish could not escape. Three sweeps to capture fish were conducted at each site with a standard-pulse DC bank shocker with a Smith-Root model 1.5 KVA-83 VVP in shallow areas and a standard-pulse DC boat shocker with a Smith-Root type VI-A VVP in pools too deep to wade. Fish were retained in 500-L containers at streamside until all three sweeps were completed. Many ($>$800) of the smaller fish were preserved in 10% formalin, returned to the laboratory for identification, and later placed in the

University of Arkansas Museum. Larger fish were identified and released.

We sampled 4,376 m^2 of riffles, of which 36% was in reference reaches, 39% was in disturbed reaches, and 25% was in downstream reaches. We sampled a total pool area of 27,120 m^2, of which 16% was in reference reaches, 47% in disturbed reaches, and 37% in downstream reaches. The total number of fish, number of fish in each family, number of each species, and number of species among sites were analyzed, as well as percent game fish and number and type of silt-sensitive fish species.

Statistics.—For statistical analyses, the experimental design for the three intensive sites was a $3 \times 3 \times 2$ factorial model, consisting of three treatments (reference, disturbed, downstream) in each of the three streams, with samples taken from two distinct habitats (riffles and pools, or riffles and flats). Flats are areas of intermediate depth and flow relative to riffles and pools. Data were analyzed with the general-linear-models procedure of the SAS program for analysis of variance (ANOVA; SAS Institute 1988). Multiple comparisons among all pairs of means were made with Tukey's Studentized range tests or least-squares means tests. All analyses were accompanied by tests for normality of data and equality of variances. Natural log transformations were used for invertebrate and fish data. Fish collections from riffles and pools were analyzed separately because fish densities and species compositions are known to be very different between these habitats in these streams. Large and small invertebrate size-classes were analyzed independently by density and by biomass. At the extensive sites we used a 2×3 factorial model because fish and invertebrate data were collected only from riffles at reference and disturbed reaches. Paired (by stream) *t*-tests were used to compare reference sites with disturbed sites and reference sites with downstream sites with regard to physical sizes of riffles, pools, and bank-full widths.

Study sites.—The Illinois and Kings rivers and Crooked Creek are in northwestern Arkansas in the Ozark Plateaus region (36°N, 93°W). They represent Ozark gravel bed streams geomorphologically, although they differ in fish and invertebrate species assemblages. Principal rock types for this area consist of Ordovician limestone and dolomite, Pennsylvanian sandstone, and Pennsylvanian and Ordovician shales. The stream basins have abundant chert gravel bedloads and a modest slope (<1 m/km), resulting in the predictable riffle–pool sequences in undisturbed reaches typical of gravel bed streams (Brussock et al. 1985). All three streams have rather long pools that usually occur in bends, separated by relatively short riffles. Pool bottoms have areas of exposed bedrock, with abundant gravel deposits along the deposition side of the meanders. Bedrock strata are virtually horizontal, so riffles are rarely formed of bedrock outcroppings but more often from accumulated gravel bedload deposits on top of the underlying bedrock. The bedrock in channels is continuous, but highly fractured. Surface lithology of the basins is karst and porous, so surface runoff is uncommon, although rainfall generally exceeds 100 cm/year. Flooding is unpredictable, but June to November is usually a dry period when many headwater streams become intermittent. The Illinois River basin drains primarily grassland (56%) and deciduous forests (34%; USDA 1988). Land use patterns in the other two stream basins are similar to those in the Illinois River basin, but the percentage of forest is slightly higher.

Results

Physical Habitat and Sedimentation Dynamics

The Illinois River had 38 gravel mining sites, and the Kings River and Crooked Creek each had 11 sites. Of the three intensive (largest) sites, those on the Kings River and Crooked Creek were larger than the one on the Illinois River, although no records of the amount of aggregate removed were available. Several aspects of channel geomorphometry were altered as a result of gravel mining (Table 1). Bank-full widths were significantly increased (reference versus mined reaches, paired *t*-test, $P \leq 0.05$) at the mining sites and for at least a kilometer downstream from each site (reference versus downstream, paired *t*-test, $P < 0.05$). Downstream pools were significantly longer ($P < 0.01$) but not deeper ($P > 0.10$) than reference pools. The expected spacing of riffles (five to seven stream widths, Leopold et al. 1964), as determined by width of the streams in their upstream reference areas, did not occur in any of the disturbed or downstream areas (Table 1). Riffle spacing in the downstream reaches of the Illinois River and Crooked Creek had adjusted to the larger bank-full widths of their downstream reaches, and no longer fit predictions based on bank-full widths in their upstream reference reaches. The riffle interval was as expected in the reference area of the Illinois River, but intervals in the reference areas of the other two streams were longer than predicted

TABLE 1.—Mean lengths, widths, and depths (m) of riffles and pools at three intensive gravel mining areas on three Ozark streams and the expected interval (every 5–7 stream widths; Leopold et al. 1964) and actual average riffle interval for each site.

Stream and site	Riffle			Pool			Bank-full width (m)	Riffle interval (m)	
	Length	Width	Depth	Length	Width	Depth		Expected (5–7 times width)	Actual
Crooked Creek									
Reference	22	15	0.18	170	18	1.25	26	130–182	192
Disturbed	98	10	0.22	252	26	0.86	39	195–273	350
Downstream	19	7	0.18	245	16	0.77	38	190–266	264
Illinois River									
Reference	16	5	0.30	151	17	0.72	27	135–189	167
Disturbed	12	5	0.26	38	15	0.54	36	180–252	50
Downstream	20	7	0.16	194	22	0.73	34	170–238	214
Kings River									
Reference	59	15	0.20	276	28	1.15	39	195–273	335
Disturbed	37	15	0.18	138	25	0.49	55	275–385	175
Downstream	14	16	0.22	1,620	25	0.36	49	245–343	1,634

by Leopold et al. (1964). Lengths, widths, and depths of riffles showed no pattern among treatment reaches.

We observed that there were large areas of exposed bedrock in pools and riffles and fewer boulders in mined and downstream areas. Downstream riffles (i.e., shallow areas with fast flow) in the Kings River were composed primarily of bedrock outcroppings. All but a few of the 81 chains placed vertically 50 cm deep in gravel deposits at reference, disturbed, and downstream sites were completely washed out during 1 year.

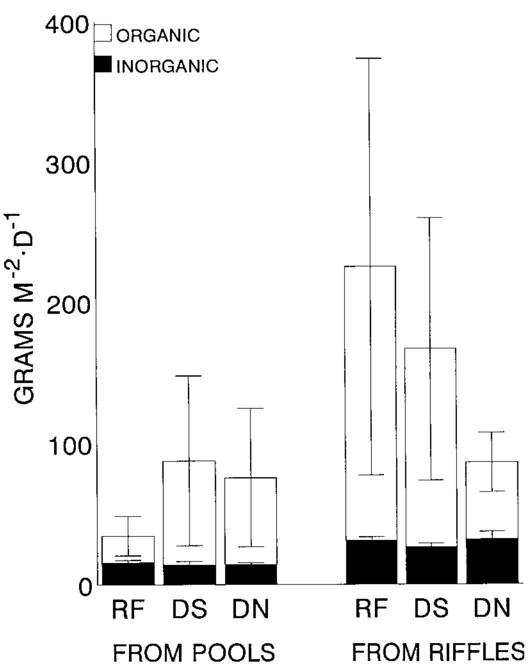

FIGURE 1.—Sedimentation rates of fines at the upstream ends of riffles (from pools) and pools (from riffles) during base flow conditions in three Ozark streams in reference (RF), disturbed (DS), and downstream (DN) reaches near large gravel mines. Error bars = ±2 SE of means.

Sedimentation rates measured near the downstream ends of pools and riffles in areas of comparable flow rate (15 cm/s) and depth (15 cm) during base flow revealed an interesting pattern among treatment reaches (Figure 1). In reference areas, riffles exported 10.5 times more organic matter than they received from pools ($P = 0.0098$), but in disturbed and downstream reaches, organic sediment import and export rates were not significantly different ($P = 0.125$). Inorganic sedimentation rates were not significantly different among treatments within habitats (pools or riffles, $P = 0.41$), but the inorganic sedimentation rate was significantly higher coming from riffles than from pools ($P = 0.0001$; Figure 1). Inorganic sedimentation rates were significantly higher ($P = 0.0001$), and organic matter sedimentation significantly

TABLE 2.—Mean turbidity (nephelometric turbidity units) at reference, disturbed, and downstream reaches while gravel was being loaded from point bars. Reaches within the same stream followed by different letters were significantly different ($P < 0.05$).

Reach	Crooked Creek, 17 Jul 1991	Illinois River, 23 Jul 1991	Kings River	
			30 Jul 1991	10 Sep 1991
Reference	1.9 y	9.6 y	3.0 y	14.8 y
Disturbed	3.6 z	26.0 z	9.9 z	33.0 z
Downstream	4.4 z	28.0 z	4.2 z	29.4 z

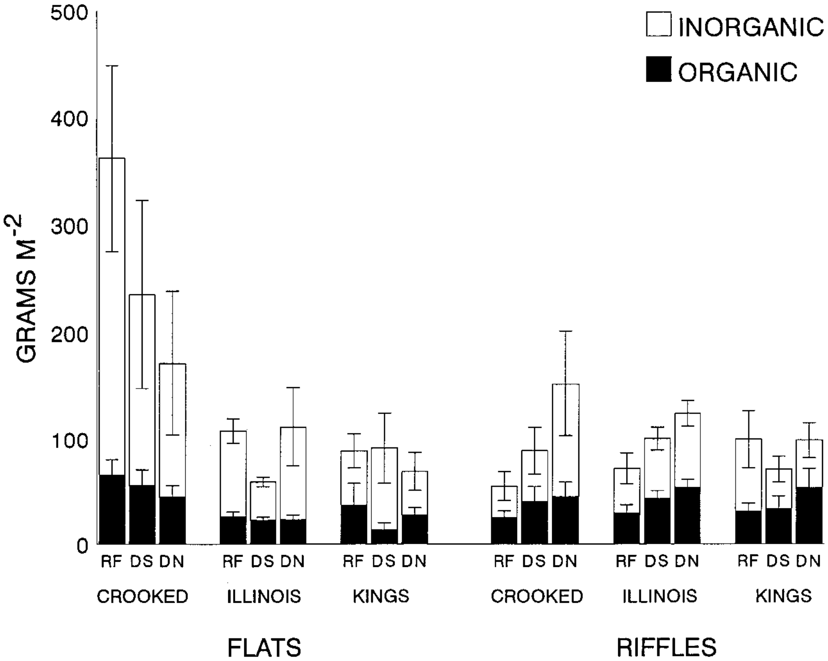

FIGURE 2.—Mass of biofilm on cobbles (64–100 mm) taken from riffles and flats in three Ozark streams in reference (RF), disturbed (DS), and downstream (DN) reaches near large gravel mines. Error bars = ±2 SE of means.

lower in the Illinois River ($P = 0.001$), where more instream gravel mining occurred.

Turbidity was significantly higher ($P < 0.05$) in disturbed and downstream than reference reaches while mining activities were in progress (Table 2). A 3 × 3 factorial analysis showed no significant differences in turbidity among reference, disturbed, and downstream reaches in the three streams during periods when gravel was not being collected or washed. The Illinois River was consistently more turbid ($P < 0.05$) than the other two streams.

Biofilm, Invertebrates, and Fish

The AFDW of biofilm decreased in flats and increased in riffles from reference to disturbed to downstream sites (Figure 2). There was no pattern to the organic : inorganic ratio among sites that indicated an effect of gravel mining on this parameter. Biofilm (AFDW) available to scrapers (e.g., the central stoneroller *Campostoma anomalum* and the snail *Elimia potosiensis*) ranged from about 13 to 65 g/m^2.

Total densities and biomass of all size-classes of invertebrates at intensive sites were not significantly different among treatments ($P > 0.35$) but were significantly different among streams ($P < 0.05$; Figure 3). Invertebrate density and biomass in the Illinois River were higher than the other two streams. Large invertebrate densities at intensive sites differed significantly among streams ($P = 0.0002$) but not among treatments ($P = 0.09$). Crooked Creek showed a contrasting pattern with that of the Illinois and Kings rivers (Figure 3.I.A, white bars).

Invertebrates at extensive sites showed more consistent patterns (Figure 3.II.A, B). Densities of small invertebrates at these 10 pairs of sites differed significantly between treatments ($P = 0.029$) and among streams ($P = 0.0001$). Their biomass differed significantly among streams ($P = 0.0005$) but not between treatments ($P = 0.31$). Small invertebrates were more abundant in reference than disturbed areas and in the Illinois River. However, biomass of small invertebrates was highest in the Kings River. Densities of large invertebrates were significantly higher at reference than disturbed reaches in the Illinois River ($P = 0.033$), which were also higher than in the other streams ($P = 0.0001$). Biomass of the large invertebrates was also significantly higher in reference than disturbed reaches ($P = 0.014$) and highest in the Illinois River ($P = 0.0001$).

Detrital benthic particulate organic matter (BPOM) collected with invertebrate samples at in-

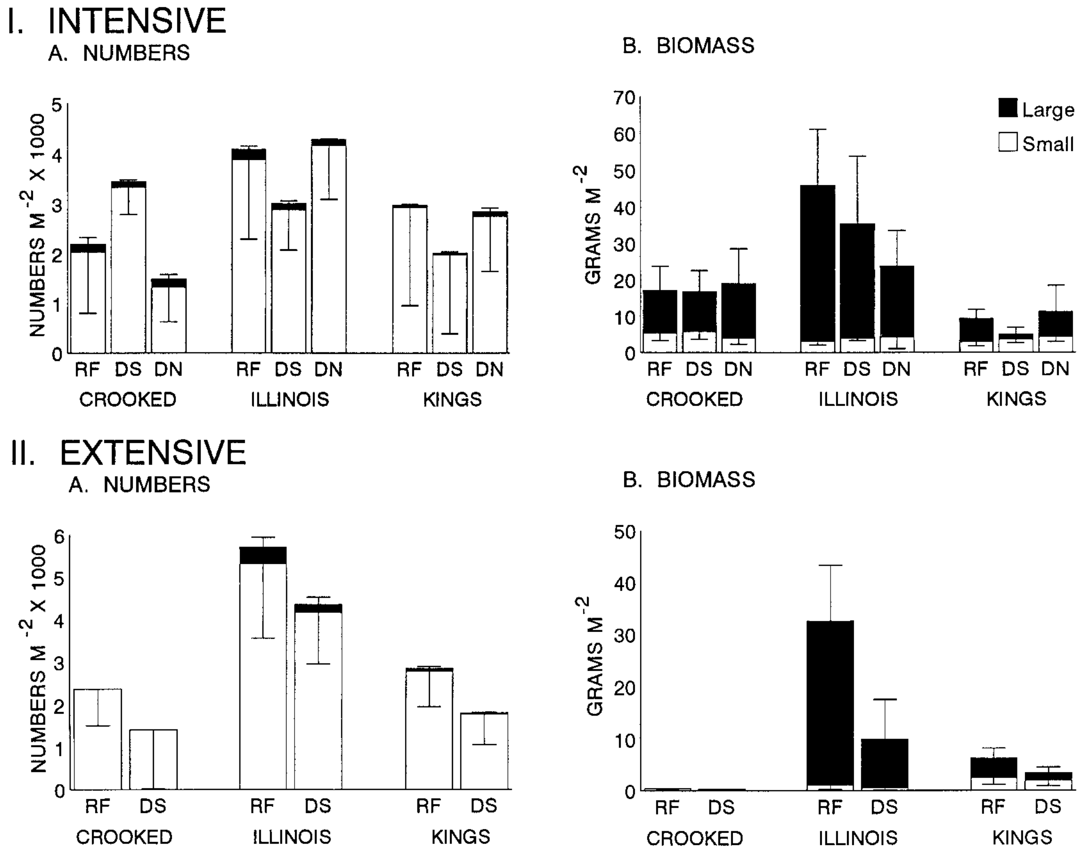

FIGURE 3.—Abundance and biomass of small (white portion of bars) and large (*Corydalidae*, crayfish, and mollusks) invertebrates from riffles in three Ozark streams in reference (RF), disturbed (DS), and downstream (DN) reaches at large gravel mines. Error bars = +2 SE of means for large invertebrates and −2 SE for small invertebrates.

tensive sites averaged 9.3 g/m^2 and was not significantly different among treatments ($P > 0.12$) or streams ($P > 0.52$). Functional group analysis (Cummins 1973) of macroinvertebrates disclosed a pattern of increased percentages of collector-gatherers on disturbed and downstream riffles at extensive and intensive sites (Figure 4). Analysis of densities (i.e., not percentages) of each functional group revealed that collector-gatherers did not significantly increase ($P > 0.10$) but collector-filterers and scrapers significantly decreased (for both, $P < 0.05$) at extensive sites. At intensive sites only collector-filterers significantly decreased ($P < 0.05$); none of the other groups changed significantly.

Total densities of fish captured in pools were significantly higher in the reference areas for intensive gravel mining sites ($P = 0.017$), although a few species showed a different pattern (Table 3). For example, longear sunfish in pools of Crooked Creek and central stonerollers in the Kings River were more abundant in downstream and disturbed pools, respectively (Table 3). Mean densities of game fish (all Centrarchidae) were higher in reference pools than in disturbed and downstream pools (1,249, 393, and 236/ha, respectively). Total densities of fish captured in riffles (Table 4) were not significantly different among reference, disturbed, and downstream sites ($P = 0.22$), but densities of centrarchids were significantly different ($P = 0.037$).

The central stoneroller was the most abundant fish species collected in all three streams (Tables 3–5). This species of minnow tended to be more abundant on riffles at disturbed and downstream reaches in the Kings River but showed an opposite pattern in the other two streams (Table 4). Results of statistical analyses of fish in riffles and pools

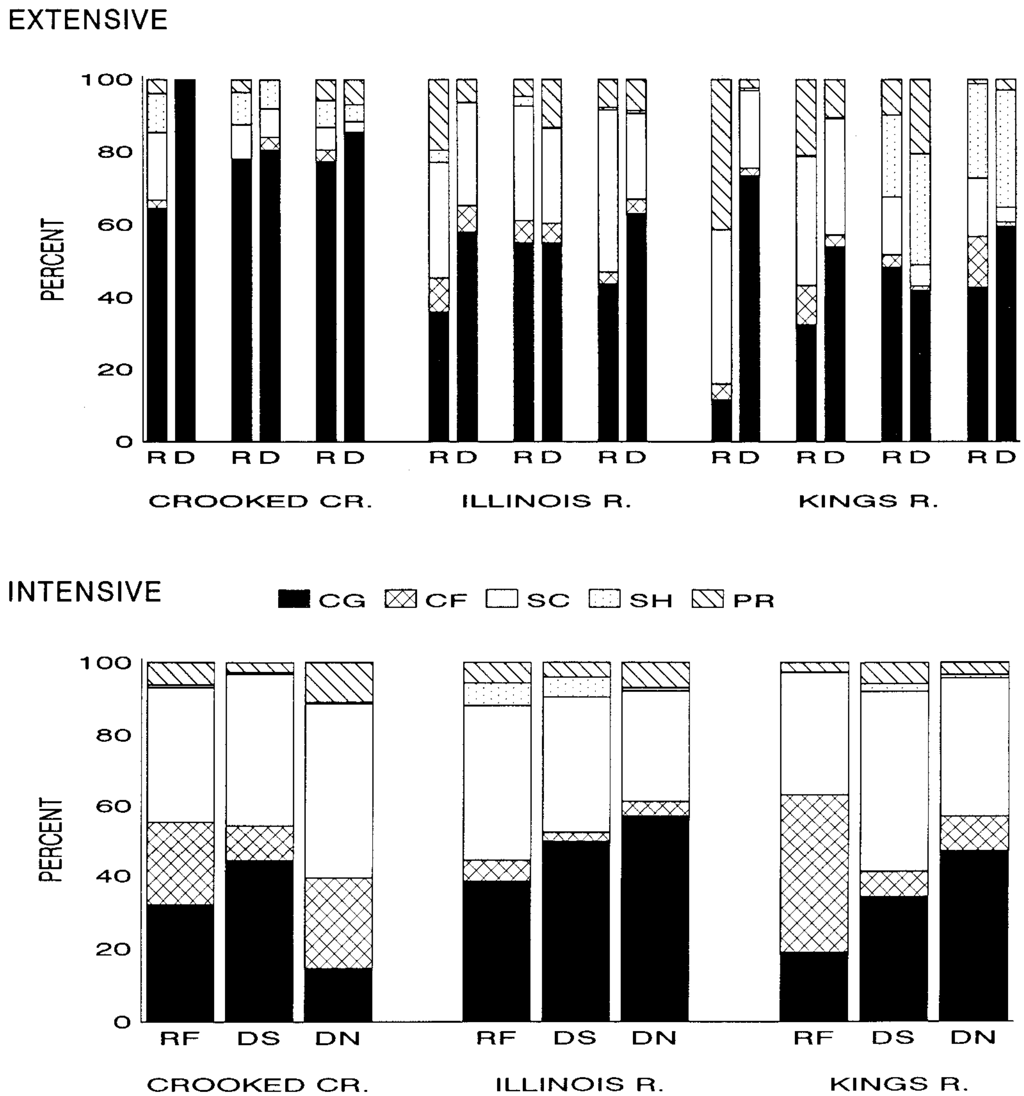

FIGURE 4.—Numerical percentages of functional groups of invertebrates from riffles of three Ozark streams at larger, less frequently disturbed mines (intensive reaches: RF = reference, DS = disturbed, DN = downstream) and at small, frequently disturbed gravel mines (extensive reaches: R = reference, D = disturbed). Functional groups are collector-gatherers (CG), collector-filterers (CF), scrapers (SC), shredders (SH), and predators (PR), after Cummins (1973).

were not changed by removal of the central stoneroller from data sets. Downstream pools contained the least numbers of all families of fish (including cyprinids without the central stoneroller), but the pattern was not as consistent in riffles (Figure 5).

Seven species of fish we collected have been described as sensitive to silt (Robison and Buchanan 1988). These silt-sensitive species were more abundant in reference than in downstream reaches, although a few were equally abundant in reference and disturbed reaches (Figure 6).

Fish densities in the riffles sampled at the extensive sites showed no consistent patterns among the three study streams or among the multiple sites in the Illinois River for total fish or for any particular taxon (Table 5). Only two more fish species were collected in reference than mined areas in the eight extensive sites (34 versus 32). A few very

TABLE 3.—Densities (number/ha) of fish in pools at intensive gravel (large, infrequent) mining sites on three Ozark streams in reference (RF), disturbed (DS), and downstream (DN) reaches.

	Crooked Creek			Illinois River			Kings River		
Species	RF	DS	DN	RF	DS	DN	RF	DS	DN
Spotted gar *Lepisosteus oculatus*							33		
Gizzard shad *Dorosoma cepedianum*	4	7					56	72	304
Central stoneroller *Campostoma anomalum*	63		28	40	75	25	2,678	4,489	448
Whitetail shiner *Cyprinella galactura*							11	11	26
Steelcolor shiner *C. whipplei*		11					22	33	
Streamline chub *Erimystax dissimilis*	4						600	306	37
Cardinal shiner *Luxilus cardinalis*				500	89	5			
Striped shiner *L. chrysocephalus*				160	32	2			
Duskystripe shiner *L. pilsbryi*	54	14					56	178	4
Redspot chub *Nocomis asper*					25	7			
Wedgespot shiner *Notropis greenei*							11		4
Ozark minnow *N. nubilus*		10		80	7	7	67	17	19
Rosyface shiner *N. rubellus*				40				28	33
Telescope shiner *N. telescopus*							122		
Bluntnose minnow *Pimephales notatus*		7							
Northern hog sucker *Hypentelium nigricans*	8	17	17	50	25	2	133	211	78
Black redhorse *Moxostoma duquesnei*	38	54	48	420	243	84	367	383	122
Golden redhorse *M. erythrurum*							22		
Yellow bullhead *Ameiurus natalis*	4		3				22		4
Ozark madtom *Noturus albater*							33	6	
Slender madtom *N. exilis*					71		122		
Checkered madtom *N. flavater*							11		
Northern studfish *Fundulus catenatus*					7		11		7
Ambloplites spp.	46		21			2	333	56	19
Green sunfish *Lepomis cyanellus*		6				2	67	28	30
Bluegill *L. macrochirus*		3		680	64	55	56	6	19
Longear sunfish *L. megalotis*	67	13	145	260	104	43	1,600	617	248
Redear sunfish *L. microlophus*				74		2			
Smallmouth bass *Micropterus dolomieu*	96	17	28	110	7	7	200	172	33
Spotted bass *M. punctulatus*							67	50	41
Largemouth bass *M. salmoides*	21	26		50		2		11	11
Black crappie *Pomoxis nigromaculatus*				20					
Greenside darter *Etheostoma blennioides*	4		3		18		267	61	
Rainbow darter *E. caeruleum*							267	39	
Arkansas saddled darter *E. euzonum*							189	94	
Yoke darter *E. juliae*							4	6	
Orangethroat darter *E. spectabile*					100		78		
Banded darter *E. zonale*							122	39	
Logperch *Percina caprodes*	4		3	190	50	2	100	128	30
Banded sculpin *Cottus carolinae*				29					
Total numbers	413	185	296	2,674	950	247	7,723	7,041	1,517
Total species	13	12	9	15	15	15	31	24	20

abundant species (e.g., central stoneroller, cardinal shiner, duskystripe shiner, and fantail darter) had a large impact on total fish densities at most extensive sites.

Discussion

Physical Habitat Characteristics

Channel geomorphology was extensively altered as a result of gravel mining in all three streams (see Table 1). Bank-full widths were significantly increased at gravel mining and downstream reaches compared with adjacent upstream reaches. Bank-full widths in upstream reaches were probably also increased by headcutting, but this is not as easily determined. Gravel bedload in upstream reaches, as well as at mines and downstream, was moved extensively during floods, as indicated by the complete removal of most of the chains placed in gravel deposits. Surface areas of downstream pools were significantly increased, but pool depths were not. Distances between riffles were significantly increased (i.e., pools were longer), but riffle lengths were not significantly changed. Therefore, the percentage of riffle area in affected reaches was decreased from 9% to 1%, and pool area was increased.

Gravel bed channels have a highly predictable shape, with a balance among morphometric vari-

TABLE 4.—Densities (number/ha) of fish in riffles at intensive (large, infrequent) gravel mining sites on three Ozark streams in reference (RF), disturbed (DS), and downstream (DN) reaches.

	Crooked Creek			Illinois River			Kings River		
Species	RF	DS	DN	RF	DS	DN	RF	DS	DN
Central stoneroller	22,256	6,557	10,380	13,033	4,060	675	8,300	17,820	47,750
Whitetail shiner							767	60	300
Steelcolor shiner	11	57						140	50
Streamline chub	411						333	100	200
Cardinal shiner				4,233	2,060	1,750			
Duskystripe shiner	3,222	2,643	2,660				5,533	2,880	4,000
Redspot chub				100	40	150			
Hornyhead chub *Nocomis biguttatus*	56	71	100				333	100	
Bigeye chub *Notropis amblops*	56								
Bigeye shiner *N. boops*								360	200
Wedgespot shiner	11		40					50	
Ozark minnow	2,333	743	1,220	133	20	375	1,233	560	
Rosyface shiner		671	40		60	25	667		
Bluntnose minnow			20						
Creek chub *Semotilus atromaculatus*					233	20			
Northern hog sucker	156	314		33	20	25	233	60	
Black redhorse	44	14					100		
Ozark madtom	333	114	160				133	860	4,400
Slender madtom	411	100	340	7,833	780	125	233	140	2,550
Northern studfish	489	186			40	25		540	200
Blackspotted topminnow *Fundulus olivaceus*	11	43			20				
Western mosquitofish *Gambusia affinis*	11					25			
Ambloplites spp.	11	271	20					20	
Green sunfish		129		33	60			20	
Bluegill				700	580				
Longear sunfish	156	986	320	500	700	250	367	320	50
Redear sunfish						275			
Smallmouth bass		157			20	50		260	
Spotted bass								60	
Rainbow darter	3,567	629	1,260				1,133	1,180	7,150
Greenside darter	1,044	157	580		60		300	360	450
Arkansas saddled darter		100	20				633	40	150
Fantail darter *Etheostoma flabellare*				67	20				
Yoke darter	89	43	220		20	25	233	100	1,250
Orangethroat darter	411	143	440	2,200	860	375	33	120	150
Banded darter	478	43	240			25	100	360	2,350
Logperch					180		467	200	
Banded sculpin	200	100	80	8,533	1,040	200	167	120	150
Total number (thousands)	36	14	18	38	11	4	21	27	71
Total species	23	23	18	12	20	18	20	25	18

ables and flow characteristics. The predictable feature of gravel bed channel morphology that is most conspicuous is the spacing of riffles along the longitudinal profile (Leopold et al. 1964). Riffle–pool spacing must be related to other attributes of channel shape, such as pool length, width, and depth; point bar distribution; channel sinuosity; etc., which, therefore, also must be predictable. The relationships among cross-sectional area of stream channels; runoff volume and periodicity; slope; and nature of the substrate are recognized to be fairly predictable (Richards 1982). Other stream channel forms lack this degree of predictability of structure.

As a consequence of their predictable structure, gravel bed streams are less resilient. When gravel bedload is removed, not only is a depression created that must be filled by transport of gravel from upstream, but the removal of gravel bedload alters the riffle–pool spacing and other physical attributes that are normal for the reach. Gravel bed streams will continue to rearrange bedload depos-

TABLE 5.—Densities (number/ha) of fish collected at eight extensive sites in riffles which had been disturbed (DS) by gravel mining and comparison data from nearby reference (RF) riffles. Six sites were sampled in the Illinois River but only one each in Crooked Creek and the Kings River.

	Crooked Creek		Illinois River		Kings River	
	RF	DS	RF	DS	RF	DS
Central stoneroller	67,838	28,800	6,783	4,946	17,534	41,596
Steelcolor shiner					77	
Streamline chub	334	244			245	1,867
Cardinal shiner			18,418	6,341		
Duskystripe shiner	7,186	889			4,977	20,301
Redspot chub			419	227		
Hornyhead chub						30
Bigeye chub	32			7		482
Wedgespot shiner	16	489			276	3,765
Ozark minnow	286		7	60	31	2,801
Southern redbelly dace *Phoxinus erythrogaster*			10	32		
Creek chub			47	56		
Northern hog sucker	827	178	64	135	413	2,470
Black redhorse	32		48		31	361
Yellow bullhead				7	46	
Ozark madtom	32	44			383	2,801
Slender madtom	223	400	8,112	965	92	331
Checkered madtom	16				15	
Northern studfish	223	156	233	100	92	1,084
Blackspotted topminnow			329	71		
Rock bass *Ambloplites rupestris*					30	
Green sunfish			301	44		
Bluegill			296	26		
Longear sunfish			361	64	291	120
Smallmouth bass	525	311	10	21	123	241
Largemouth bass			20			30
Greenside darter	1,320	578	33	135	1,179	3,434
Rainbow darter	2,226	2,089			720	4,398
Arkansas saddled darter	1,431	1,067			398	422
Fantail darter			10,626	64		
Yoke darter	79	800			459	1,928
Orangethroat darter	207	267	9,600	2,598		
Banded darter	270	267	3		720	2,470
Logperch	48		50		337	1,175
Banded sculpin			4,541	773		
Total	83,151	36,579	60,311	16,672	28,469	92,107

its until the channel morphology is harmonious with flow patterns at near bank-full stage and riffles occur at five to seven bank-full widths.

Gravel mining can continue to remove large amounts from a single location on a stream because periodic spates deliver fresh deposits from upstream. When the entrained gravel reaches the enlarged channel at the mined reach, the water slows and the gravel is deposited. Excessive movement of gravel downslope to fill the hole in the streambed results in channel erosion upstream (i.e., headcutting, see Pringle 1997, and references therein). Stream-banks are eroded laterally more than vertically because bedrock underlies most gravel streambeds. Lateral erosion results in the undercutting of riparian trees, which then fall into the stream channels but not necessarily into the water. Sequential widening of the stream channels results in the loss of stream competence (ability to transport bedload) because flow is slower in the larger channels. Loss of competency delays reestablishment of concordance between channel shape and streamflow patterns.

Deep pools in incompetent streams tend to fill with gravel and fines. Thus, streams disturbed by gravel removal tend to be more uniformly shallow and wide and have less habitat heterogeneity. Shallow streams in wide channels provide abundant periphyton and refuge from predators for small grazing fish, like central stonerollers. Our results indicate that gravel mining reduced predaceous fish (e.g., centrarchids, ictalurids) and that central

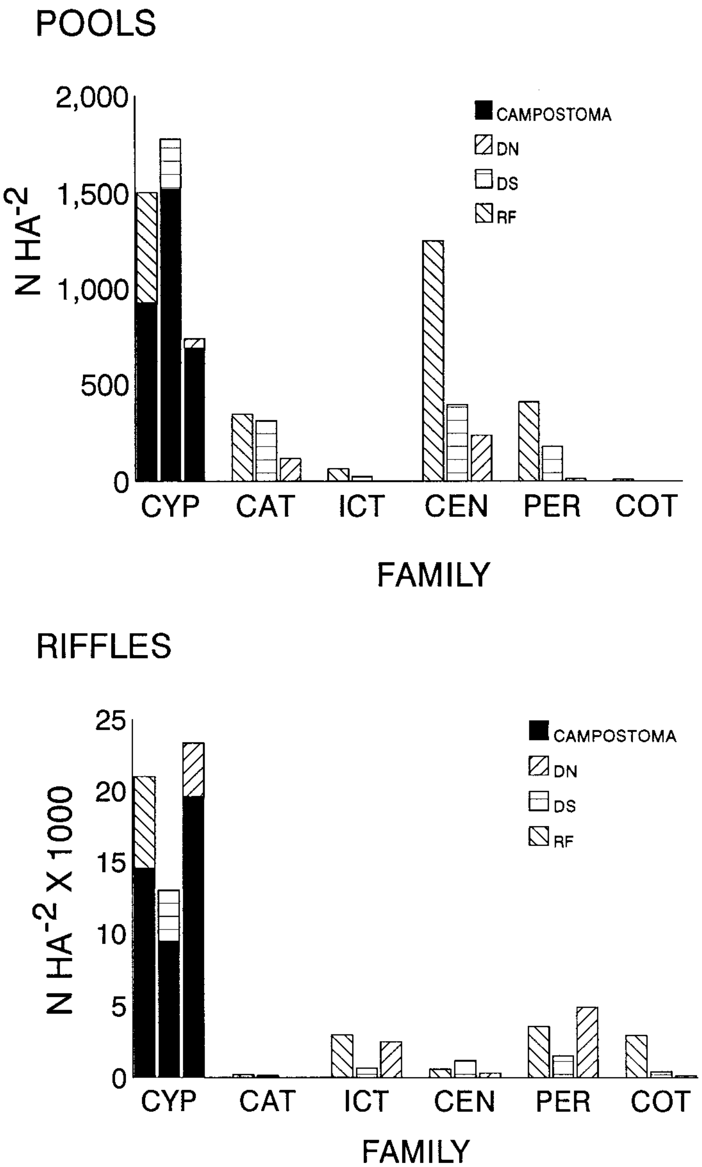

FIGURE 5.—Abundance of families of fish collected from upstream reference (RF), disturbed (DS), and downstream reaches (DN) in pools and riffles of three Ozark streams with the density of central stoneroller *Campostoma anomalum* indicated. CYP = Cyprinidae, CAT = Catostomidae, ICT = Ictaluridae, CEN = Centrarchidae, PER = Percidae, COT = Cottidae.

stonerollers were very abundant. The abundance of grazing fish and invertebrates (scrapers) indicate a shift to autochthonous streams.

Stream channels were 10–16 m wider in disturbed and downstream reaches than in reference reaches (Table 1), and reference channels were probably widened by headcutting (Pringle 1997). During base flow, a band of predominantly inorganic substrate separated the streams from their valleys (see Hynes 1975). Widened channels also have larger cross-sectional areas, so flooding (exceeding bank-full capacity) may be less frequent. Thus, streams disturbed by gravel mining appear to have changed from a continuum (Vannote et al. 1980) with a strong riffle–pool template (Brown and Brussock 1991; Brussock and Brown 1991; Brown and Matthews 1995) to a pulsed continuum (sensu Junk et al. 1989, because they have limited

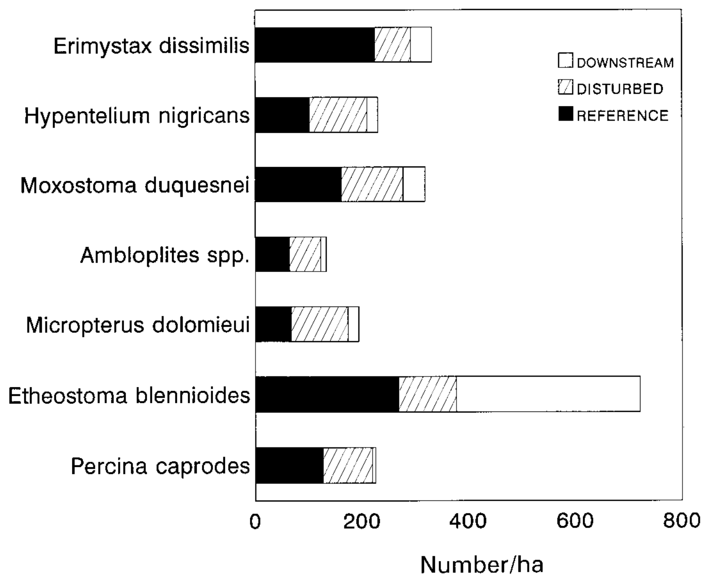

FIGURE 6.—Densities (number/ha) of silt-sensitive fish species from upstream reference, disturbed, and downstream reaches in three Ozark streams. Common names are given in Table 3.

access to their riparian zone and floodplains), with weak riffle–pool structure. The pulsed condition is exacerbated by intermittent flow of headwater reaches in this region from June to November.

Undisturbed gravel bed streams have highly variable physical habitat, both spatially and temporally, and individual species require some subset of these habitat characteristics. When the relative proportions of different types of physical habitat (e.g., riffles and pools) are changed, the biotic community composition can be expected to change. Additionally, alterations in physical habitat cause more insidious changes in resources (e.g., food production or retention, distance between patches, patch size, refuge security, refuge distribution, etc.). Such changes in physical habitat can affect species interactions and community composition (Naiman et al. 1988; Frid and Townsend 1989; Townsend 1989).

Biotic Responses

All components of the biotic communities that we measured (biofilm, invertebrates, and fish) were affected by gravel mining. Biofilm standing crops were significantly lower in flats and higher in riffles (but riffle area was decreased) in disturbed and downstream reaches. Significant reductions of invertebrate densities and biomass of both size-classes occurred at the 10 extensive sites. Collector-filterer and scraper invertebrate functional groups were reduced the most at large and small mining sites. The Illinois River, which had the most mines, had the least collector-filterers and the lowest seston quality (increased inorganic and decreased organic content). Most taxa of fish were significantly reduced in pools at sites disturbed by gravel mining, especially in areas downstream from the larger mines. Pools were changed more than riffles by sedimentation and morphological adjustment. Riffles were not changed morphologically but reduced in number per reach, and fish other than centrarchids in riffles were not affected as they were in pools (Tables 4, 5; Figure 5).

Alteration of normal riffle–pool morphology, flow patterns, and fine-sediment transport apparently resulted in the observed responses by the streams' communities. Distribution of biota in gravel bed streams is strongly related to physical habitat, which is dominated by riffle–pool structure (Brown and Brown 1984; Ebert et al. 1987; Brown et al. 1989; Brown and Brussock 1991; Brussock and Brown 1991; Brown and Matthews 1995). Some animals that live primarily on riffles (e.g., filter-feeding invertebrates) depend on food resources produced in pools (Illies 1958; Brown et al. 1989; Brown and Brussock 1991). Other organisms, such as drift-feeding fish, often reside in pools and exploit invertebrates produced in riffles. Grazing minnows (i.e., central stonerollers) normally reside in shallow flats and riffles, where they scrape biofilm and avoid the larger piscivorous fish in pools (Power et al. 1985). Changes in ratios among riffles, pools, and flats should be expected to alter the community structure and ecological functioning of gravel bed streams. We found that biofilms, macroinvertebrates, and fish were all affected. Determination of cause and effect relationships among them would be difficult because the large variety of species that make up the biofilm, invertebrate, and fish assemblages have very different requirements and interact in many different ways.

The direct effects of modification of the physical habitat, such as morphometry of pools and riffles, sedimentation, and turbidity, are of consequence to fish populations, but the indirect effects, such as food reduction, could also have reduced some fish populations. Invertebrates are more abundant in riffles than pools in gravel bed streams (Brown and Brussock 1991). Gravel mining probably decreased the frequency of riffles in both upstream reaches (due to headcutting) and downstream reaches. Our data show a reduction from 9% riffle area in upstream reaches to 1% riffle area in downstream reaches (from Table 1). This resulted in reductions of invertebrate prey for fish in those reaches.

Environmental degradation extended far beyond the boundaries of the immediate gravel mining areas. Headcutting has major consequences for many kilometers upstream from the mines (Smith and Patrick 1991; Pringle 1997). Downstream areas had too little gravel bedload to maintain normal stream channel structure because gravel was intercepted at the mines. Silt travels long distances downstream as a plume of turbidity while gravel is being removed. During floods, turbidity is likely to be higher than normal for even longer distances downstream due to the higher flow rate and increased entrainment of sediments as a result of channel deformation.

Channelization of streams is a form of disturbance that perhaps most closely resembles disturbances seen at gravel mining operations. The impact of stream channelization on biotic communities has received more attention by researchers than gravel removal, and its effects are better understood (Hubbard et al. 1988, and references therein). Channelization is generally devastating to fish communities in gravel bed streams, and the larger sport fishes are most severely impacted (Mauney and Harp 1979; Ebert and Filipek 1988). Other disturbances to the physical structure of stream channels (as opposed to chemical insults), such as road building activities, sedimentation from erosion, intense silvicultural practices, operation of gold dredges, and snag removal can be expected to have similar impacts if they affect a large enough area and are of sufficient frequency or severity (Resh et al. 1988). Disturbance to streambanks results in increased sedimentation that fills interstitial spaces in stream substrates. This causes suffocation of eggs, larvae, and benthic species (algae, fish, and invertebrates; Cordone and Kelley 1961; Berkman and Rabeni 1987). Sedimentation also results in decreased depths of the pools that are required habitat for larger species of fish. Gravel mining in streambeds could be expected to result in problems similar to those listed above, but complete removal of large quantities of substrate has additional consequences because the stream channel is deformed for long distances upstream as well as downstream from the site of removal (Pringle 1997).

There appears to be no way to successfully avoid or mitigate the effects of gravel removal on stream ecosystems as long as gravel is removed from within the bank-full confines of the stream channels. Physical structure is the very foundation upon which stream communities are assembled, and this appears to be especially true for gravel bed streams because of their predictable shape. Fundamental changes in water quality and the total biotic community are to be expected when the physical structure of streams is altered. Recovery time appears to be measured in decades (Kanehl and Lyons 1992). Total restoration of severely affected streams would probably be impossible. Even if comparable quantities of aggregate were returned to the stream channels, it would have to be distributed naturally and completely throughout the basin before the next flood, which would be impossible. The large riparian trees that have been undercut as a result of channel widening induced by headcutting and erosion cannot be replaced, at least in their natural positions, because the soil in which they were rooted is no longer in place.

Gravel mining from stream channels seems to create an irreconcilable multiple-use conflict among the various users of gravel bed stream resources. Removing gravel from gravel bed streams impairs the use of them for several other purposes, not the least of which is sportfishing, and the impairment is not avoidable or reparable.

Acknowledgments

This study was supported by a grant (F-52-2, Study II) from the Arkansas Game and Fish Commission Fisheries Division, Allen Carter, Chief, to

A.V.B., as a cooperator in the Arkansas Cooperative Fish and Wildlife Research Unit in the Department of Biological Sciences at the University of Arkansas. We thank Bill Matthews, Thomas Kwak, Peter Brussock, Steve Filipek, and Larry Willis for comments on an earlier draft of the manuscript. We appreciate the assistance of Jim Johnson, Lowell Aberson, and the numerous students who assisted with various parts of this study. Special thanks are due Kevin Pierson, Lori Livingston, and Jim Dunn for assistance with statistical analyses. We also thank the landowners and gravel miners who graciously allowed us access to the study sites. This paper was substantially strengthened by three anonymous reviewers.

References

Berkman, H. E., and C. F. Rabeni. 1987. Effect of siltation on stream fish communities. Environmental Biology of Fishes 18:285–294.

Brown, A. V., and K. B. Brown. 1984. Distribution of benthos within riffles of streams. Freshwater Invertebrate Biology 3:2–11.

Brown, A. V., and P. P. Brussock. 1991. Comparisons of benthic invertebrates between riffles and pools. Hydrobiologia 220:99–108.

Brown, A. V., R. L. Limbeck, and M. D. Schram. 1989. Trophic importance of zooplankton in streams with alluvial riffle and pool geomorphology. Archiv für Hydrobiologie 114:349–367.

Brown, A. V., and W. J. Matthews. 1995. Streams of the central United States. Pages 89–116 *in* C. E. Cushing, K. W. Cummins and G. W. Minshall, editors. River and stream ecosystems. Elsevier, Amsterdam, The Netherlands.

Brown, A. V., M. D. Schram, and P. P. Brussock. 1987. A vacuum benthos sampler suitable for diverse habitats. Hydrobiologia 153:241–247.

Brussock, P. P., and A. V. Brown. 1991. Riffle–pool geomorphology disrupts longitudinal patterns of stream benthos. Hydrobiologia 220:109–117.

Brussock, P. P., A. V. Brown, and J. C. Dixon. 1985. Channel form and stream ecosystem models. Water Resources Bulletin 21:859–867.

Cordone, A. F., and D. W. Kelley. 1961. The influence of inorganic sediment on the aquatic life of streams. California Fish and Game 4:189–228.

Cummins, K. W. 1973. Trophic relations of aquatic insects. Annual Review of Entomology 18:183–206.

Ebert, D. J., A. V. Brown, and C. B. Fielder. 1987. Distribution of fish within headwater riffles of the Illinois River system, Washington County, Arkansas. Proceedings of the Arkansas Academy of Science 41:38–42.

Ebert, D. J., and S. P. Filipek. 1988. Response of fish communities to habitat alteration in a small Ozark stream. Proceedings of the Arkansas Academy of Science 42:28–32.

Egyazarov, I. V. 1970. Effects of large range sediment mixtures and self-pavement of beds on the movement and discharge of streams. National Science Foundation, Report SFCSI-Agr (TT-70–57226), Washington, D.C.

Frid, C. L. J., and C. R. Townsend. 1989. An appraisal of the patch dynamics concept in stream and marine benthic communities whose members are highly mobile. Oikos 56:137–141.

Gessler, J. 1970. Self-stabilizing tendencies of alluvial channels. Journal of Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers 96:235–249.

Gordon, N. D., T. A. McMahon, and B. L. Finlayson. 1992. Stream hydrology: an introduction for ecologists. Wiley, New York.

Hallmark, D. E., and G. L. Smith. 1965. Stability of channels by armor plating. Journal of Waterways, Harbors and Coastal Engineering Division, American Society of Civil Engineers 91:117–135.

Hartfield, P. 1993. Headcuts and their effect on freshwater mussels. Pages 131–141 *in* K.S. Cummings, A.C. Buchanan and L.M. Koch, editors. Conservation and management of freshwater mussels. Proceedings of a conference on conservation and management of freshwater mussels. Upper Mississippi River Conservation Committee, Rock Island, Illinois.

Hubbard, W. D., D. C. Jackson, and D. J. Ebert. 1988. Stream impact evaluation guidelines: channelization. American Fisheries Society, Response to Warmwater Streams Committee, Southern Division, Bethesda, Maryland.

Hynes, H. B. N. 1975. The stream and its valley. Internationale Vereinigung für Theoretische und Angerwandte LimnologieVerhandlungen 19:1–15.

Illies, J. 1958. Die barbenregion mitteleuropischer fliessgewasser. Internationale Vereinigung für Theoretische und Angerwandte Limnologie Verhandlungen 13:834–844.

Janzen, P. P., L. van Bendegom, J. van den Berg, M. de Vries, and A. Zanen. 1979. Principles of river engineering—the non-tidal alluvial river. Pitman, London.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river–floodplain systems. Canadian Special Publication of Fisheries and Aquatic Sciences 106:110–127.

Kanehl, P., and J. Lyons. 1992. Impacts of in-stream sand and gravel mining on stream habitat and fish communities, including a survey on the Big Rib River, Marathon County, Wisconsin. Wisconsin Department of Natural Resources, Research Report 155, Monona.

Keller, E. A. 1971. Areal sorting of bed-load material: the hypothesis of velocity reversal. Geological Society of America Bulletin 82:753–754.

Kira, H. 1972. Factors influencing the river behavior—river-bed variation due to dam construction and gravel gathering. Transactions of the 8th International Committee on Irrigation and Drainage, volume 5, R. 26, Q 29.1, Varna, Bulgaria.

Lagasse, P. F. 1986. River response to dredging. Journal of Waterway, Port, Coastal and Ocean Engineering Division, American Society of Civil Engineers 112: 1–14.

Lagasse, P. F., B. R. Winkey, and D. B. Simmons. 1980. Impacts of gravel mining on river system stability. Journal of Waterway, Port, Coastal and Ocean Engineering Division, American Society of Civil Engineers 106:398–404.

Leopold, L. B., M. G. Wolman, and J. P. Miller. 1964. Fluvial processes in geomorphology. Freeman, San Francisco.

Little, W. C., and P. G. Mayer. 1972. The role of sediment gradation on channel armoring. Georgia Institute of Technology, Environmental Research Center, Atlanta.

Livesey, R. H. 1965. Channel armoring below Fort Randall Dam. Pages 461–469 *in* Proceedings of the federal inter-agency sedimentation conference, 1963. U.S. Department of Agriculture, Publication 970, Washington, D.C.

Lyons, J. 1992. The length of stream to sample with a towed electrofishing unit when fish species richness is estimated. North American Journal of Fisheries Management 12:198–203.

Martin, C. R., and T. B. Hess. 1986. The impacts of sand and gravel dredging on trout and trout habitat in the Chattahoochee River, Georgia. Georgia Department of Natural Resources, Game and Fish Division, Project F-26–13, Atlanta.

Matthews, W. J. 1990. Fish community structure and stability in warmwater midwestern streams. U.S. Fish and Wildlife Service Biological Report 90(5): 16–17.

Mauney, M., and G. L. Harp. 1979. The effects of channelization on fish populations of the Cache River and Bayou DeView. Proceedings of the Arkansas Academy of Science 33:51–54.

Mossa, J., and M. McLean. 1997. Channel planform and land cover changes on a mined river floodplain. Applied Geography 17:43–54.

Naiman, R. J., H. Decamps, J. Pastor, and C. A. Johnston. 1988. The potential importance of boundaries to fluvial ecosystems . Journal of the North American Benthological Society 7:289–306.

Power, M. E., W. J. Matthews, and A. J. Stewart. 1985. Grazing minnows, piscivorous bass and stream algae: dynamics of a strong interaction. Ecology 66: 1448–1456.

Pringle, C. M. 1997. Exploring how disturbance is transmitted upstream: going against the flow. Journal of the North American Benthological Society 16:425–438.

Reiser, D. W., and T. C. Bjornn. 1979. Habitat requirements of anadromous salmonids. Volume 1 *in* W. R. Meehan, editor. Influence of forest and range land management on anadromous fish habitat in western North America. U.S. Forest Service General Technical Report PNW-96.

Resh, V. H., and nine coauthors. 1988. The role of disturbance theory in stream ecology. Journal of the North American Benthological Society 7:433–455.

Richards, K. S. 1982. Rivers: form and process in alluvial channels. Methuen, New York.

Rivier, B., and J. Sequier. 1985. Physical and biological effects of gravel extraction in river beds. Pages 131–146 *in* J. S. Alabaster, editor. Habitat modification and freshwater fisheries. Butterworth, London.

Robbins, L. G. 1977. Suspended sediment and bed material studies on the lower Mississippi River. U.S. Army Engineers District, Potamology Investigations Report 300-I, Vicksburg, Mississippi.

Robison, H. W., and T. M. Buchanan. 1988. Fishes of Arkansas. University of Arkansas Press, Fayetteville.

SAS Institute. 1988. SAS/STAT user's guide, release 6.03 edition. SAS Institute, Cary, North Carolina.

Schumm, S. A. 1977. The fluvial system. Wiley, New York.

Smith, L. M., and D. M. Patrick. 1991. Erosion, sedimentation, and fluvial systems. Pages 169–181 *in* G. A. Kiersch, editor. The heritage of engineering geology: the first hundred years, volume 3. Geological Society of America, Boulder, Colorado.

Townsend, C. R. 1989. The patch dynamics concept of stream community ecology . Journal of the North American Benthological Society 8:36–50.

USDA (U. S. Department of Agriculture), Soil Conservation Service. 1988. Reconnaissance survey of water quality in the Illinois River, Arkansas. USDA, Washington, D.C.

Vannote, R. L., G. W. Minshall, K. W. Cummins, J. R. Sedell, and C. E. Cushing. 1980. The river continuum concept. Canadian Journal of Fisheries and Aquatic Sciences 37:130–137.

Weigand, D. C. 1991. Effects of gravel scalping on juvenile salmonid habitat. Master's thesis. University of Washington, Seattle.

Wentworth, C. K. 1922. A grade scale and class terms for clastic sediments . Journal of Geology 30:377–392.

Received August 4, 1997
Accepted March 6, 1998