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MONITORING ECOLOGICAL RECOVERY IN A STREAM IMPACTED BY CONTAMINATED GROUNDWATER

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ABSTRACT

Past in-ground disposal practices in Bear Creek Valley resulted in contamination of Bear Creek and consequent ecological damage. A biological monitoring program initiated in 1984 has evaluated the effectiveness of the extensive remedial actions undertaken to address contamination sources. It has documented substantial ecological recovery in the Bear Creek ecosystem. Elements of the monitoring program included toxicity testing with fish and invertebrates, bioaccumulation monitoring, and instream monitoring of streambed invertebrate and fish communities. In the mid 1980's, toxicity tests on stream water indicated that the headwaters of the stream were acutely toxic to fish and aquatic invertebrates as a result of infiltration of a metal-enriched groundwater from ponds used to dispose of acid wastes. Over a twelve year period, measurable toxicity in the headwaters decreased, first becoming non-toxic to larval fish but still toxic to invertebrates, then becoming intermittently toxic to invertebrates. By 1997, episodic toxicity was infrequent at the site that was acutely toxic at the start of the study. Recovery in the fish community followed the pattern of the toxicity tests. Initially, resident fish populations were absent from reaches where toxicity was measured, but as toxicity to fish larvae disappeared, the sites in upper Bear Creek were colonized by fish. By 1990, resident populations were present year round at densities comparable to unimpacted reference streams. The Tennessee dace, an uncommon species receiving special protection by the State of Tennessee, became a numerically important part of the fish population throughout the upper half of the creek, making Bear Creek one of the most significant habitats for this species in the region. Although by 1990 fish populations were comparable to those of similar size reference streams, episodic toxicity in the headwaters coincided with a recruitment failure in 1996. Benthic invertebrate studies also indicated ecological recovery in Bear Creek; however adverse impacts remained obvious throughout the upstream half of the stream. Numbers of sensitive species were much lower than reference streams, and mayflies, a group particularly sensitive to metals, were virtually absent in the upper reaches. Bioaccumulation monitoring indicated the presence of PCBs and mercury in predatory fish in Bear Creek, and whole forage fish contained elevated levels of cadmium, lead, lithium, nickel, mercury, and uranium. Remedial actions targeting PCB sources reduced bioaccumulation for several years, but concentrations in fish increased in the mid 1990's.

Keywords: toxicity testing, bioaccumulation, ecological recovery, monitoring

INTRODUCTION

The Bear Creek Valley watershed drains the area surrounding several closed waste disposal areas at the U.S. Department of Energy Y-12 Plant in Oak Ridge, Tennessee. Past in-ground disposal practices in Bear Creek Valley resulted in contamination of Bear Creek and consequent ecological damage. Extensive remedial actions have been conducted at most of the waste sites, and further remedial efforts continue. A biological monitoring program was initiated in 1984, with the objectives of (1) assisting in the development of an effective remedial action plan related to past waste disposal operation in Bear Creek Valley and (2) evaluating the effectiveness of those actions by monitoring the ecological recovery of Bear Creek. The monitoring program consisted of an initial characterization phase to address the first objective (Southworth et al. 1992), followed by long term monitoring to address the second objective (Hinzman 1996). The monitoring program consists of three major tasks that focus on (1) toxicity testing, (2) bioaccumulation studies, and (3) instream monitoring of benthic invertebrate and fish communities.

DISCLAIMER

Waste disposal areas were located in the upper four kilometers of the Bear Creek drainage (Fig. 1).The S-3 Ponds, located at the source of Bear Creek, were four unlined ponds with a total volume of 38 million liters. These ponds received acid wastes from a variety of processes from 1951 to 1983. Waste disposal included nitrate solutions, nitric acid, pickling and plating wastes, miscellaneous wastes associated with routine cleanup operations, dilute acids, machine coolants, depleted uranium, technetium, caustic solutions and bionitrification sludges. The waste infiltrated the soil and calcareous bedrock at the site, creating a large plume of acidic contaminated groundwater high in dissolved salts. That plume extends down Bear Creek Valley several kilometers and contributes to the surface flow in Bear Creek over that reach. The S3 ponds were neutralized, denitrified, filled, and capped between 1983 and 1988.

Approximately 1.5 kilometers downstream from the S3 ponds, the boneyard/burnyard served as an active site from 1943 to 1970. A portion of this site continued to burn hazardous wastes until 1981. The site was capped in 1989. This site was used for disposal and burning of sanitary, metallic, chemical, and radioactive wastes. The nearby oil landfarm was used from 1973 to 1982 to dispose of various waste oils and chlorinated solvents. The site was closed as a capped landfill in 1990. A sanitary landfill at the same site received decomposable wastes and sludge from 1968 to 1980. The large burial grounds 1.5 kilometers further down the valley was used for disposal of oily liquid and solid wastes from 1955 to 1979. Waste materials disposed of in trenches at this site included heavy metals, oils (including PCBs) and coolants, solvents, salts, asbestos, and radioisotopes. Oil retention ponds were constructed at the site to collect oil seeping from hillsides into Bear Creek tributaries. Groundwater at the site is contaminated by chlorinated solvents and metals. The ponds and portions of the burial grounds were closed and capped in 1989. A collection and treatment system was constructed to capture and treat PCB-contaminated shallow groundwater leaching from the site. Other parts of the Bear Creek watershed were used for storage and disposal of construction debris, spoil, and scrap.

Bear Creek is a small stream (average flow 250 L/s) flowing through a forested watershed that is undeveloped except for the in-ground waste disposal sites. Much of the bedrock in Bear Creek valley is limestone and dolomite, and the creek receives inputs from numerous springs along its 13 kilometer length. Although flow is relatively stable because of the calcareous aquifers feeding it, major portions of the upper 5 km. have been relocated from the original stream channel. These reaches tend to be de-watered during periods of low flow when surface flow apparently follows the buried natural channel and network of underlying solution cavities. Water quality in Bear Creek is greatly affected by inputs from the waste disposal sites. Water chemistry is characterized by (1) high concentrations of dissolved salts in the headwaters as a result of infiltrating groundwater in the vicinity of the S3 pond site; (2)elevated concentrations of some trace ions in the headwaters that decline rapidly within a short distance; (3) elevated levels of many metals in sediments in the upper reaches; and (4) volatile organic compounds and PCBs in the vicinity of the burial grounds. Major constituents present at elevated concentrations include cations calcium, magnesium, sodium, and potassium, and anions nitrate, sulfate, and chloride. Elevated trace metals include aluminum, cadmium, lead, mercury, boron, barium, lithium, manganese, cobalt, iron, nickel, silver, uranium, and zinc. The stream accrues uncontaminated groundwater and increases in size rapidly with distance downstream from its headwaters, with conservative tracers of the S3 groundwater plume (nitrate, excess calcium or excess conductivity) undergoing roughly a ten-fold dilution between kilometer 12.4 and kilometer 7.9 (Southworth et al. 1992).

METHODOLOGY

Toxicity studies

Ambient toxicity of water from various sites in Bear Creek was evaluated using 7-day static-renewal toxicity tests based on the survival and growth of fathead minnow (*Pimephales promelas*) larvae and the survival and reproduction of the crustacean (*Ceriodaphnia dubia*). Test procedures are detailed in Weber et al. (1989); examples of the use of these test procedures for ambient assessments can be found in Burton et al. (1987), Stewart et al. (1990), Nimmo et al. (1990), Norberg-King et al.(1991),and Kszos et al. (1992). Ambient toxicity testing focused on sites in the upper reaches of Bear Creek at sites BCK 12.36, 11.83, 11.09, 9.91, 9.40, and 7.87 (Fig. 1). Concurrent tests were generally run with both species. Diluted mineral water served as control and was also used to dilute creek water when serial dilutions were required to quantify its toxicity.

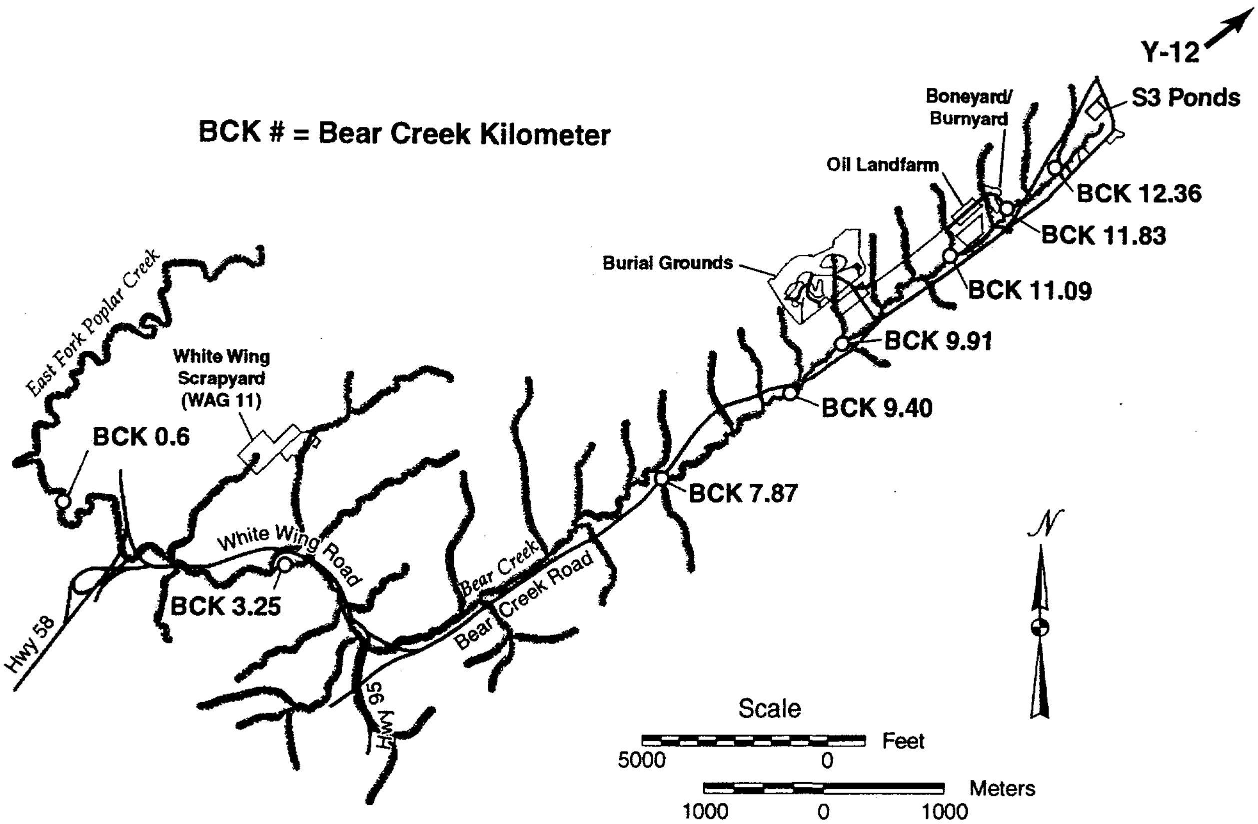

Figure 1. Location of waste disposal areas and biological monitoring sites in Bear Creek valley

Bioaccumulation studies

Three species of organisms; rockbass (*Ambloplites rupestris*), asiatic clams (*Corbicula fluminia)*, and central stoneroller (*Campostoma anomalum*) were used to monitor the accumulation of contaminants in aquatic biota in Bear Creek. Rockbass served as a tool to measure year-to-year changes in PCB and mercury contamination in Bear Creek, and were collected in the lower reaches of the stream (BCK 4.5 and BCK 0.6). Caged clams served a similar purpose, but provided a more direct index of aqueous concentrations than fish, which may accumulate PCBs through their food as well as by direct aqueous uptake. Stonerollers were used to assess accumulation of metals and PCBs in forage species to provide data for use in ecological risk analysis, and were sampled at BCK 12.4, 9.4, and 3.3. Rockbass were filleted, and analyses conducted on the edible tissue of eight individual fish per site. Stonerollers were also analyzed individually, but the entire body was digested prior to analysis. Samples were frozen until analyzed. PCBs were analyzed using gas chromatography and electron capture detection (EPA 1984). Mercury was determined by cold vapor atomic absorption spectrophotometry (EPA 1991), and other metals by inductively coupled plasma/mass spectrometry (EPA 1991). Procedural details can be found in Hinzman et al. (1996), Southworth (1990), and Peterson et al. (1994).

Instream ecological monitoring

Quantitive sampling of fish populations was conducted at seven sites in Bear Creek (Fig. 1). Two nearby streams, Grassy Creek and Mill Branch, were initially used as reference sites to estimate population parameters typical of unimpacted streams similar in size to Bear Creek. Two additional reference sites, Pinhook Branch and Gum Hollow Branch were added as new reference sites in 1993. A three pass removal procedure was used to estimate the size of fish populations in 50 - 200 m reaches of stream isolated by block nets at either end (Carle and Strub 1978). Backpack electrofishers were used to stun and collect fish, which were then identified, measured, and released upon completion of the three passes. Annual production was estimated using a size-frequency method (Garman and Waters 1983). Procedural details can be found in Hinzman (1996).

Stream-bottom invertebrates (benthic macroinvertebrates) were sampled at the same sites in Bear Creek as fish communities (Fig. 1). Three 0.09 m^2 samples were collected and analyzed from a riffle at each site using a Surber sampler (365 μm mesh). Samples were preserved in 80% ethanol, and the invertebrates removed, identified, and counted. Identification was carried to the lowest practical taxon, usually genus. Further procedural details are found in Hinzman (1996).

RESULTS

Toxicity testing

Fathead minnow survival was markedly impacted by water from the uppermost site in Bear Creek in the period 1984 - 1986 (Southworth 1992). In seven tests over that period, fathead minnow survival averaged 24%, ranging from 0 to 85%. A similar pattern was observed for growth of surviving larvae, with growth at BCK 12.4 being strikingly reduced. Clear evidence of toxicity to fish was not apparent at sites farther downstream, although artifacts peculiar to the application of the fathead minnow test to ambient waters makes attribution of toxicity tenuous when mortality is less than 50% (Kszos and Stewart 1992). From 1988 to 1996, fathead minnow survival in toxicity tests at BCK 12.4 did not present clear evidence of toxicity, averaging over 90% with a range of 55 - 100%. Growth of larvae in those tests where survival was less than 80% differed little from controls. Toxicity remained absent at sites farther downstream. Growth of larval fish in water from all sites in Bear Creek was seldom less than that of controls, and provided no clear evidence of toxicity at any sites.

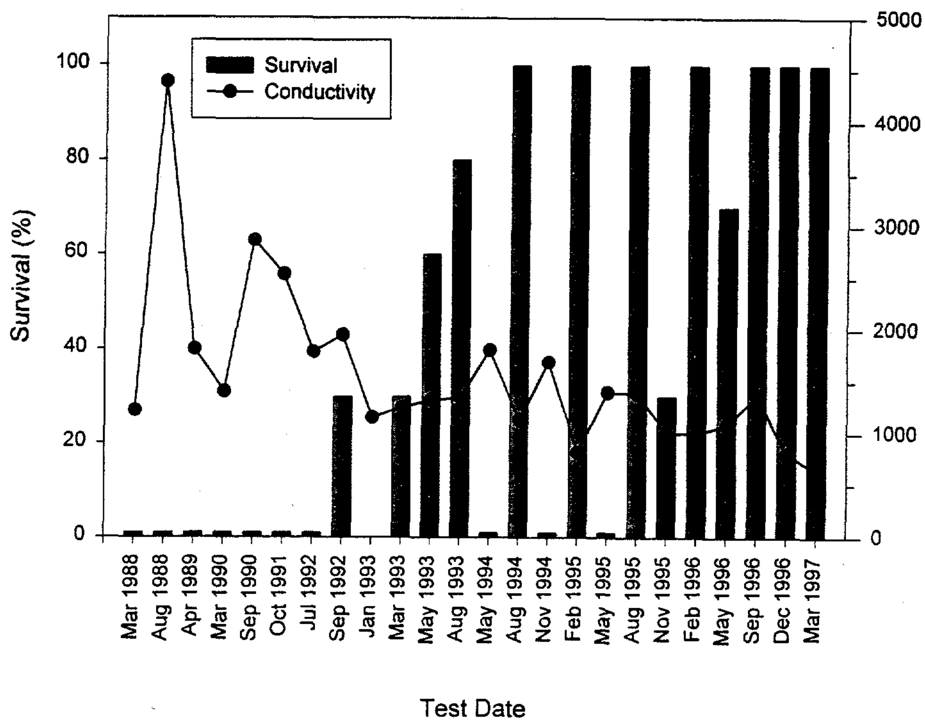

Figure 2. ***Ceriodaphnia*** **survival and conductivity in toxicity tests at BCK 12.4**

Results of toxicity tests using the crustacean *Ceriodaphnia dubia* differed considerably from those of the fathead minnow tests. From 1988 through mid 1992, water from BCK 12.4 was toxic to 100% of organisms in all *Ceriodaphnia* tests (Fig. 2), and survival was reduced at sites within 2 kilometers downstream. In late 1992 and thereafter, *Ceriodaphnia* tests provided evidence of improved water quality in upper Bear Creek. In September 1992, less than 100% mortality was observed in *Ceriodaphnia* at BCK 12.4 for the first time, and by late 1994, 100% survival was occasionally observed at that site. (Fig. 2). From late 1994 to 1996, tests showed an unusual pattern of either high toxicity (100% mortality) or no measurable toxicity . Survival rates in these tests continued to improve through 1996 and into 1997, as periodic tests showing high mortality disappeared. Similar improvement was evident at downstream sites where toxicity had been observed in the past. *Ceriodaphnia* should reproduce twice in the seven day course of the toxicity test, and number of young produced per surviving female is a second, somewhat more sensitive endpoint of the test. When this endpoint is used as an indicator of toxicity, a small reduction in production of young was observed in the tests showing high survival in 1995 - 1997.

Bioaccumulation

The accumulation of polychlorinated biphenyls(PCBs) in fish from Bear Creek was apparent at the outset of monitoring in 1987 (Fig. 3). PCB concentrations in rockbass in lower Bear Creek (BCK 0.6) decreased in the late 1980s, but thereafter increased again to levels typical of those observed earlier. Average PCB concentrations in rockbass collected further upstream (BCK 4.5) were typically four fold higher than at the lower site, indicating the presence of an upstream source. Caged clams placed at the BCK 4.5 site for four week exposures accumulated PCB concentrations typical of resident fish at the site, confirming the presence of waterborne contamination. Analysis of forage fish, which are found in upper reaches that don't support rockbass populations, indicated highest PCB concentrations in fish from the reach downstream from BCK 9.4 (Table 1.). PCB concentrations in fish from the headwater site (BCK 12.4) were much lower. The pronounced downstream decrease in PCB concentrations in fish was typical of the pattern below a point source of contamination (Southworth 1990).

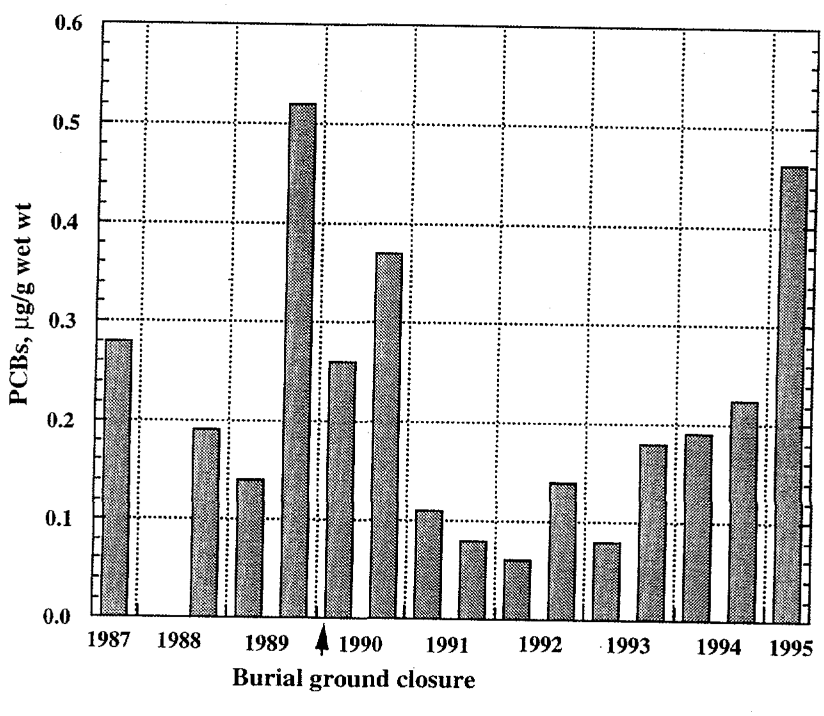

Figure 3. Average concentrations of polychlorinated biphenyls in rock bass fillets at BCK 0.6

Table 1. Mean (± SE, n=8) concentrations (µg/g wet wt) of metals and polychlorinated biphenyls (PCBs) in stonerollers (*Campostoma anomalum*) from Bear Creek, June 1994

Analyte	Site			
	BCK 12.4	BCK 9.4	BCK 3.3	Hinds Cr
Antimony	0.004 ± 0.002	0.003 ± 0.001	0.003 ± 0.001	0.003 ± 0.001
Arsenic	0.25 ± 0.047	0.43 ± 0.054	0.31 ± 0.033	0.22 ± 0.016
Beryllium	0.016 ± 0.007	0.020 ± 0.004	0.011 ± 0.003	0.007 ± 0.002
Cadmium	1.73 ± 0.19	0.48 ± 0.060	0.19 ± 0.026	0.023 ± 0.002
Chromium	0.70 ± 0.093	0.98 ± 0.082	0.79 ± 0.072	0.72 ± 0.082
Copper	0.83 ± 0.060	1.03 ± 0.096	1.00 ± 0.039	0.80 ± 0.040
Lead	0.44 ± 0.12	0.53 ± 0.091	0.23 ± 0.057	0.25 ± 0.045
Lithium	0.24 ± 0.081	0.76 ± 0.144	0.34 ± 0.079	0.18 ± 0.047
Mercury	0.120 ± 0.0099	0.079 ± 0.0058	0.060 ± 0.0059	0.013 ± 0.0015
Nickel	2.45 ± 0.57	0.85 ± 0.11	0.57 ± 0.075	0.61 ± 0.042
Selenium	0.44 ± 0.031	0.61 ± 0.080	0.56 ± 0.044	0.42 ± 0.009
Silver	0.015 ± 0.002	0.013 ± 0.002	0.025 ± 0.003	0.013 ± 0.001
Thallium	0.008 ± 0.001	0.012 ± 0.003	0.006 ± 0.001	0.006 ± 0.001
Uranium	0.73 ± 0.108	0.98 ± 0.092	0.42 ± 0.041	0.010 ± 0.003
Zinc	40.5 ± 1.3	48.3 ± 2.8	57.9 ± 4.2	42.1 ± 1.7
PCBs	0.28 ± 0.08	2.86 ± 0.57	0.98 ± 0.17	<0.06

Although most metals (mercury is an exception) do not appreciably accumulate in fish muscle, whole body analysis of fish is capable of detecting evidence of exposure to many metals. In Bear Creek, stonerollers contained elevated (more than 2 fold higher than reference site fish) concentrations of cadmium, lead, lithium, nickel, mercury, and uranium (Table 1.) Highest concentrations of cadmium, mercury, and nickel were found at the uppermost site, while maximum levels of lead, lithium and uranium occurred at BCK 9.4. Mercury, which accumulates as methylmercury in the muscle of predatory fish, was found to be roughly 2 -3 times reference site concentrations in rockbass from lower Bear Creek (BCK 0.6) in 1987. In the ensuing nine years, average mercury concentrations in this species increased from 0.3 mg/kg to about 0.7 mg/kg wet wt., with no apparent source or cause.

Instream ecological monitoring

The portion of Bear Creek upstream from BCK 4.5 contains only eight species of fish, and is numerically dominated by three of those. This pattern is typical of small streams in the region, and hence cannot be taken as evidence of adverse water quality. A weir at BCK 4.5 blocks colonization by other species, preventing any further increase in species richness. Nineteen species have been identified in Bear Creek downstream from the weir, a value typical of reference streams of similar size. Fish were seldom found in the uppermost reaches of Bear Creek in the mid to late 1980s (Fig. 4.). Viable populations were absent, and those collected were likely recent migrants from downstream areas or tributaries. In 1989, fish populations became established at the uppermost site (BCK 12.4), and densities increased to levels comparable to the highest observed in reference sites (Fig. 4.). Biomass and production estimates for fish populations followed a pattern similar to that of numerical abundance. In fall 1995, numerical abundance of fish at BCK 12.4 dropped precipitously, with most of the change associated with low numbers of fish hatched the preceding spring.

An unusual aspect of the fish population of Bear Creek is the presence of an uncommon species, the Tennessee dace (*Phoxinus tennesseensis*). This species is listed as a species "in need of management" by the Tennessee Wildlife Resources Agency, and its habitat is protected (Starnes and Etnier 1993). This species has flourished in Bear Creek in the 1990s, where its abundance exceeds that typical of regional reference streams. (Fig. 4.)

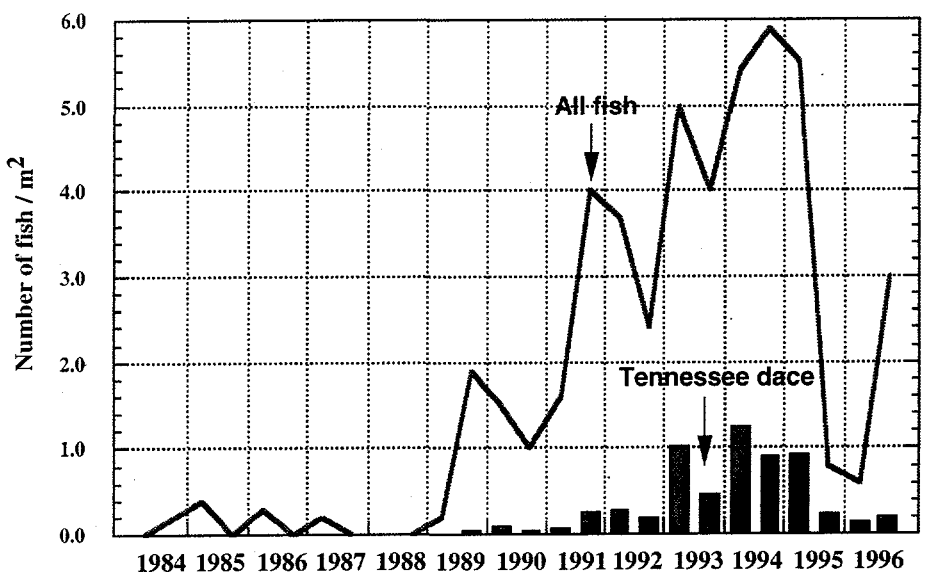

Figure 4. Abundance of all fish and Tennessee dace (*Phoxinus tennesseensis*) at BCK 12.4, 1984 - 1996

Abundance of streambed invertebrates increased over the 1985 - 1996 period at virtually all sites in Bear Creek, and often exceeded levels typical of reference sites. However, marked differences were evident in the kinds of organisms comprising the populations, and particularly in the species richness and abundance of pollution sensitive organisms. In the upper reaches of Bear Creek, benthic invertebrate populations are numerically dominated by midge (Chironomidae) and beetle (Coleoptera) larvae, with representatives of sensitive families (Lenat 1988) Ephemeroptera (mayflies), Plecoptera (stoneflies), and Tricoptera (caddisflies) being rare. These latter taxa are grouped together as EPT taxa for further analysis. Total numbers of these EPT taxa per sample at BCK 12.4 have increased since 1985, but remain about 16% of reference site levels (Fig. 5.). EPT taxonomic richness increases with distance downstream from the headwaters of Bear Creek, and at BCK 3.25 this parameter, as well as others, indicates no deviation from reference site conditions (Fig. 5.). Mayflies are exceptionally sensitive to enriched concentrations of many metals in water (Wiederholm 1984). Members of this order have been absent from BCK 12.4 from 1985 to the present, and remain extremely rare as far downstream as BCK 9.9.

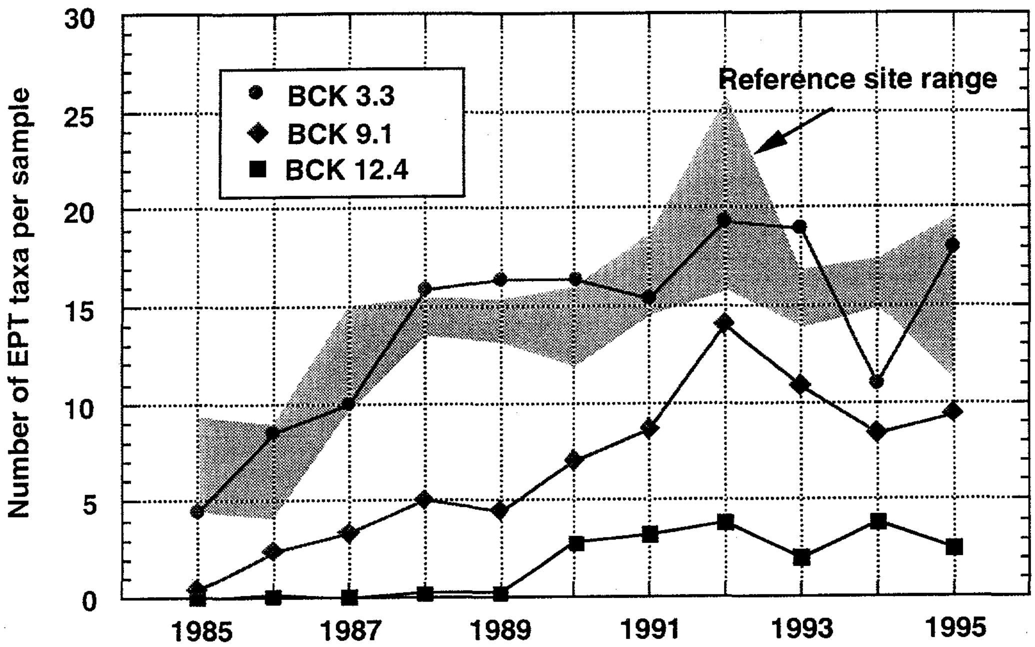

Figure 5. Mean number of EPT taxa (mayflies, stoneflies, and caddisflies) per sample at sites in Bear Creek, 1985 - 1995

DISCUSSION

Measurable toxicity in Bear Creek water appears to originate only in the headwaters, undoubtedly as a consequence of metal-contaminated groundwater inputs. Toxicity test results provide clear evidence of improvements in water quality in Bear Creek over time. Measurable toxicity to fish has disappeared, and toxicity to the more sensitive *Ceriodaphnia* has decreased to being an ephemeral phenomenon. These improvements have been accompanied by a gradual decline in electrical conductivity of stream water at the headwater site consistent with gradual dilution of the S3 plume (Fig. 2.). Follow-up studies implicated nickel as the likely primary cause of toxicity to *Ceriodaphnia* (Kszos et al. 1992), but other metals and high salt content were likely contributors in the 1980's.

During the 1993 - 1996 period, upper Bear Creek appears to have oscillated between toxic (as measured in *Ceriodaphnia* tests) and non-toxic conditions. In 1995, the large drop in fish numbers (primarily young-of-the- year) between spring and fall in upper Bear Creek indicates poor recruitment from the 1995 spawning season. Toxic conditions observed in May 1995 (Fig. 2.) may have persisted or worsened in that year enough to cause the observed year class failure in fish. Intermittent toxicity would be expected to occur in response to fluctuations in the level of the shallow ground water in upper Bear Creek valley, with the S3 plume constituting a greater proportion of inputs to surface flow in periods of extended dry weather.

Although PCB-contaminated waste had been placed in several of the disposal sites in Bear Creek valley, the greatest volume of such waste was disposed of as liquids poured into trenches in the burial grounds. The downstream profile of PCBs in stonerollers confirmed that this area was the primary source of PCB contamination in Bear Creek (Table 1.). Actions to eliminate inputs to the creek from oily seeps and surface runoff that were completed in 1989 appeared to reduce contamination in fish downstream from the burial grounds, but six years later PCB concentrations in fish had returned to levels comparable to those preceding remediation (Figure 3.).

Elevated concentrations of metals in forage fish from the headwaters of Bear Creek confirmed exposure of aquatic life to biologically available forms of potentially toxic metals, particularly nickel, a suspected cause of *Ceriodaphnia* mortality in toxicity tests. These data also indicated a likely source of mercury in the stream headwaters, probably the S3 groundwater plume. Follow-up analyses of mercury in surface water at BCK 12.4 using ultra-trace level techniques found mercury to be present in water at 36 ng/L, approximately ten times regional background concentrations. The slow increase over time in mercury concentrations in predatory fish in lower Bear Creek remains inexplicable. A possible explanation for the phenomenon may be linked to improved water quality in the upper portions of the creek that has greatly increased the biomass of fish and invertebrate populations in the upper reaches where dissolved mercury is highest. Accumulation of methylmercury in these organisms creates a new reservoir of mercury-contaminated biota that is slowly exported downstream to accumulate in animals high on the food chain.

Fish populations in upper Bear Creek have recovered strikingly since the mid 1980's, when resident populations were absent from the headwater sites (Fig. 4.). By 1996, fish abundance and species richness throughout the stream were comparable to reference site values when consideration is given to impediments to recolonization. Although substantial recovery has been noted, high variability in fish abundance and production has been observed recently. Because of their life cycle (single annual, reproductive period, several years to sexual maturity), fish populations are susceptible to episodic toxicity, as appears to have been the case in 1995. Although conditions may be habitable nearly all the time, episodic toxicity can eliminate virtually an entire year class of fish, causing reductions in populations that persist for a year or more.

It is likely that the Tennessee dace has benefited from the extirpation of competitors that occurred when sites were used for waste disposal, followed by improved water quality and continued exclusion of many other species by the weir at BCK 4.5. Bear Creek is now one of very few streams in the region where this species is a major component of the fish population, and is an important habitat for sustaining viable populations of this species.

The streambed invertebrate community was the most sensitive indicator of water quality in Bear Creek. The downstream profile of sensitive measures of the integrity of this community, such as EPT taxonomic richness, showed a clear pattern of high impact in the headwaters grading to full recovery at BCK 3.25 (Fig. 5.). The absence of mayflies at most sites in the upper half of Bear Creek indicates likely effects of metal contamination. Like the other biological measures of water quality, the invertebrate data indicate that measurable ecological impacts originate in the uppermost reaches of the creek, and do not provide evidence that sources other than the S3 groundwater plume adversely affect aquatic life in the system. At sites where toxicity tests and fish community studies were unable to detect environmental degradation, the invertebrate community demonstrated clear evidence of adverse impact. The increase in numbers of EPT taxa over time at sites in upper Bear Creek provides evidence that improvement in water quality is gradually occurring, but the rate of increase suggests that it will be at least 5 - 10 years before approaching full recovery.

CONCLUSIONS

The biological monitoring program detected acute toxicity to aquatic life in the headwaters of Bear Creek in the mid-1980's, and documented ecological effects on fish and invertebrate communities for a 5 - 10 km reach downstream. Cessation of waste disposal activities, combined with actions designed to lessen transport of contaminants to surface waters enabled the ecological recovery process to proceed. Toxicity (as measured in laboratory tests) to fish disappeared from the headwaters in the late 1980's, but measurable toxicity to invertebrate test organisms persisted. By the mid 1990's, invertebrate toxicity had become episodic in nature, with frequency of detection lessening each year. Fish populations, absent from the reaches of stream where toxicity was measurable, expanded into those reaches within 2 years after toxicity to fish became unmeasurable. By the mid 1990's, fish populations throughout Bear Creek generally contained numbers of species and overall abundance typical of reference streams of similar size. Several pollution sensitive species remained absent from the upper 2/3 of the stream, but the presence of a weir that impedes immigration of new species is a likely cause of their absence. Although most measures of fish community indicate near total recovery, a recruitment failure was observed in 1995 that coincided with detection of acute toxicity to *Ceriodaphnia* twice following the spring spawning season.

Although toxicity monitoring and fish population studies indicate substantial recovery in Bear Creek, stream-bottom invertebrate communities continue to show clear evidence of adverse impacts over the upper half of the stream. Overall densities of invertebrates are typical of unimpacted streams, but populations are dominated by pollution resistant species, with pollution sensitive mayflies, stoneflies, and caddisflies being low in abundance and represented by very few species. Mayflies, a group highly sensitive to metal contamination, are virtually absent in the upper reaches and poorly represented in the mid-reaches. Despite continuing evidence of adverse impacts, improvements have been noted in the invertebrate community. All sites in Bear Creek now contain more species of invertebrates, especially pollution sensitive species, than were found when monitoring was initiated in 1984. This improvement has been gradual but steady. At the lowermost site monitored, BCK 3.25, full recovery of the benthic invertebrate population is evident.

The accumulation of contaminants by aquatic biota does not appear to have been as effectively remediated as toxicity. PCB accumulation in fish decreased following site capping and seep interception in major PCB source areas, but several years later PCB concentrations in fish had returned to pre-remediation levels. Mercury bioaccumulation in fish in Bear Creek has increased as water quality has improved. Aqueous concentrations of mercury in the creek are low, but are higher than typical of reference sites. It is likely that mercury bioaccumulation is a problem that will be an unavoidable consequence of ecological recovery in Bear Creek.

Biological monitoring has been an effective tool for demonstrating the effectiveness of corrective measures in achieving the goal of restoring natural communities. It has shown that long term evaluation is necessary to document the success of remedial measures, and that the recovery process proceeds in gradual steps that can be best measured using a combination of chemical, toxicological, and ecological measures. Toxicity monitoring provided an effective tool for measuring the rate of improvement in the early phases of the restoration process. Toxicity monitoring was able to indicate the point at which water quality had improved enough to sustain diverse and sensitive fish populations, but neither it nor fish community measures could demonstrate that water quality had improved enough to support a streambed invertebrate community typical of unimpacted waters. Extrapolation based on the observed rates of recovery in Bear Creek suggest that full ecological recovery may be attained in another decade if no additional actions are taken, as natural processes act to sequester and dilute toxic metals in the portions of the groundwater plume that intercept the creek.

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