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Effects of Contaminants in Dredge Material from the Lower Savannah River

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Abstract. Contaminants entering aquatic systems from agricultural, industrial, and municipal activities are generally sequestered in bottom sediments. The environmental significance of contaminants associated with sediments dredged from Savannah Harbor, Georgia, USA, are unknown. To evaluate potential effects of contaminants in river sediments and sediments dredged and stored in upland disposal areas on fish and wildlife species, solid-phase sediment and sediment pore water from Front River, Back River, an unnamed Tidal Creek on Back River, and Middle River of the distributary system of the lower Savannah River were tested for toxicity using the freshwater amphipod *Hyalella azteca.* In addition, bioaccumulation of metals from sediments collected from two dredge-disposal areas was determined using the freshwater oligochaete *Lumbriculus variegatus.* Livers from green-winged teals (*Anas crecca*) and lesser yellowlegs (*Tringa flavipes*) foraging in the dredge-spoil areas and raccoons (*Procyon lotor*) from the dredge-disposal/river area and an upland site were collected for metal analyses. Survival of *H. azteca* was not reduced in solid-phase sediment exposures, but was reduced in pore water from several locations receiving drainage from dredge-disposal areas. Basic water chemistry (ammonia, alkalinity, salinity) was responsible for the reduced survival at several sites, but PAHs, metals, and other unidentified factors were responsible at other sites. Metal residues in sediments from the Tidal Creek and Middle River reflected drainage or seepage from adjacent dredge-disposal areas, which could potentially reduce habitat quality in these areas. Trace metals increased in *L. variegatus* exposed in the laboratory to dredge-disposal sediments; As, Cu, Hg, Se, and Zn bioaccumulated to concentrations higher than those in the sediments. Certain metals (Cd, Hg, Mo, Se) were higher in livers of birds and raccoons than those in dredge-spoil sediments suggesting bioavailability. Cadmium, Cr, Hg, Pb, and Se in livers from raccoons collected near the river and dredge-disposal areas were significantly higher than those of raccoons from the upland control site. Evidence of bioaccumulation from laboratory and field evaluations and concentrations in sediments from dredge-disposal areas and river channels demonstrated that some metals in the dredge-disposal areas are mobile and biologically available. Drainage from dredge-disposal areas may be impacting habitat quality in the river, and fish and wildlife that feed and nest in the disposal areas on the lower Savannah River may be at risk from metal contamination.

Agricultural, industrial, and municipal activities have historically contributed contaminants to the lower Savannah River, although conditions have improved since the 1950s and 60s (Fallows 1971). Potential impacts to fish and wildlife resources from contaminants still exist (Goldberg *et al.* 1979), either directly through acute responses or indirectly through chronic impacts and food-chain relationships. During the last 15–20 years, striped bass (Van Den Avyle and Maynard 1994) and bird populations (Bieldstein *et al.* 1990) have declined significantly. Factors responsible for these declines are not known, but reduced habitat quality (physical and chemical) is suspected (Ogden 1994; Winger and Lasier 1995). Alteration of flow patterns (Van Den Avyle and Maynard 1994) and chemical contaminants and salinity regime have been implicated in reducing habitat quality in the lower Savannah River (Winger and Lasier 1994, 1995).

Savannah Harbor, located approximately 26 km from the Atlantic Ocean, is a major shipping center for the Southeast that contributes significantly to the economy of coastal Georgia. However, activities and industries associated with the harbor have the potential to adversely impact local fish and wildlife resources. Maintenance dredging to a depth needed for deep-draft ships results in significant habitat alteration and increases erosion and turbidity, which can adversely impact aquatic populations. Contaminants entering aquatic environments bind to particulate matter that settles and becomes incorporated into the bottom sediments where they remain until disturbed (Forstner 1987; Power and Chapman 1992). Although sediment-bound contaminants are generally considered biologically unavailable, disturbance of sediments through dredging has the potential to increase bioavailability (Seelye *et al.* 1982) and pose a hazard to wildlife utilizing upland dredge-disposal areas.

The objectives of this study were to evaluate the effects of runoff from dredge-disposal areas on habitat quality in Back and Middle rivers (Figure 1) using sediment toxicity testing and to determine the bioavailability of metals from dredge-disposal sediments using laboratory bioaccumulation studies and field collections of selected species.

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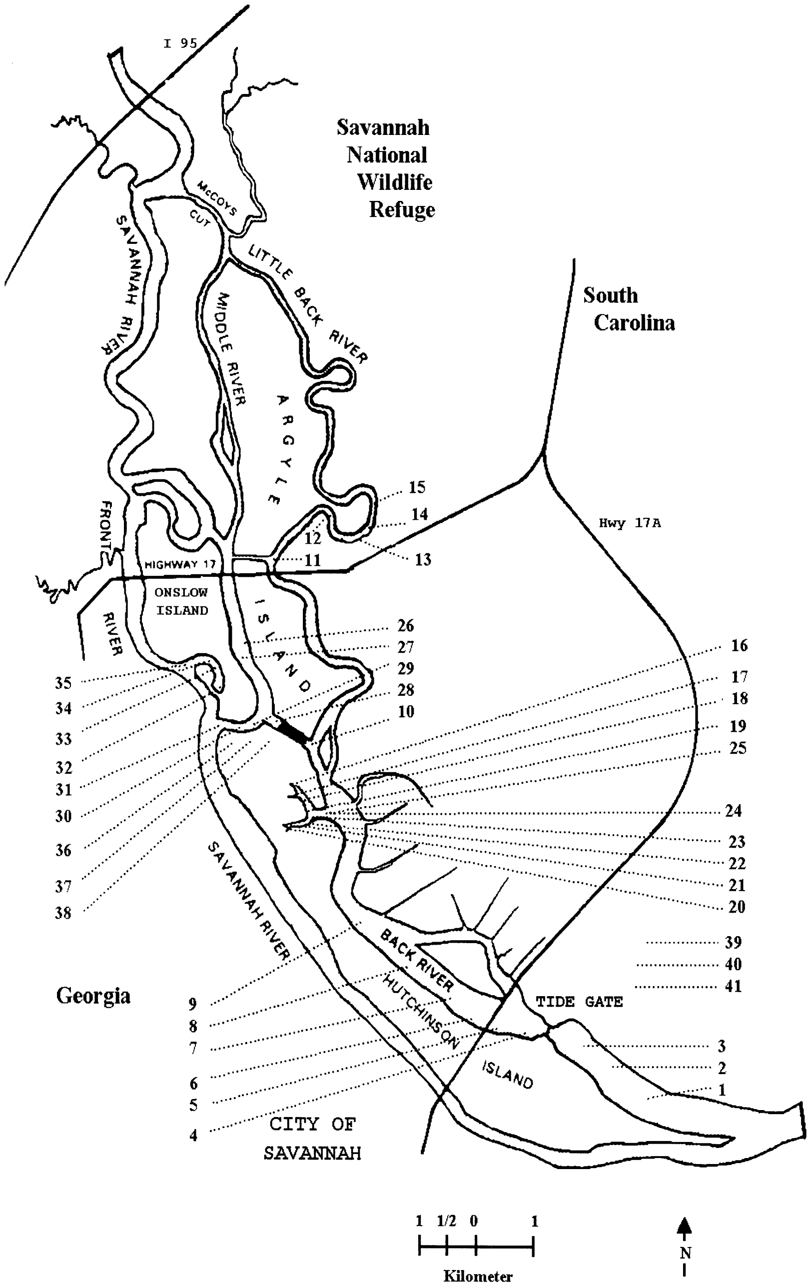

Fig. 1. Map of the lower Savannah River showing sediment sampling locations, 1996 and 1997

Materials and Methods

The distributary portion of the lower Savannah River, Georgia and South Carolina, USA, consists of Front River, Middle River, and Back River (Figure 1). Savannah and Savannah Harbor are located on the western bank of Front River and the Savannah National Wildlife Refuge (NWR) is located on the eastern side of the river and encompasses a portion of Back River. Sediments dredged from Front River are deposited in upland disposal areas on Hutchinson Island, Onslow Island, and Barnwell Island.

Sediment samples for toxicity testing were collected in 1996–1997 from Back River (Stations 1–15), an unnamed Tidal Creek to Back River (Stations 16–25) located on the northern end of Hutchinson Island, Middle River near the confluence with Front River (Stations 26–31), the cut-off oxbow in the southern portion of Onslow Island (Stations 32–35), and from two (Stations 36–41) dredge-disposal areas (Figure 1). Tidal Creek, Back River, and Middle River receive drainage from the dredge-disposal area on Hutchinson Island. Six sediments were collected from the dredge-disposal areas for bioaccumulation studies: Stations 36–38 from the northern end of the Hutchinson Island disposal area and Stations 39–41 from Dredge Spoil 12A on Barnwell Island near the Tide Gate.

Five Petite Ponar grab samples were collected from each site, composited, and homogenized by stirring. A 3.8-L sample was transferred to a plastic container for transport on ice to the laboratory. Samples were stored in a refrigerator at 4°C pending analyses. After rehomogenization in the laboratory, separate aliquots were used for metal analyses, percent organic content, particle-size analyses, acid-volatile sulfides (AVS) with simultaneously extracted metals (SEM), and solid-phase sediment toxicity testing. The remainder of each sample was used for pore-water extraction.

Following nitric acid and microwave digestion, elemental analyses (As, Cd, Cr, Cu, Fe, Mn, Mo, Ni, Pb, Se, Zn) were determined by inductively coupled plasma-mass spectrometry (Perkin Elmer Elan

6000). Mercury analyses were conducted with $SnCl_2$ reduction, dual gold amalgamation, and cold vapor atomic fluorescence detection after digestion with 7:3 HNO_3/H_2SO_4 and dilution with 10% (v/v) 0.2 N BrCl. Organic contaminants (organochlorine pesticides, polychorinated biphenyls, polycyclic aromatic hydrocarbons) were not analyzed during this study because they were found in only small concentrations in sediment samples collected previously from Savannah Harbor (Winger and Lasier 1995). Sediment properties were characterized in samples collected only in 1997. Percent organic content was determined by loss on ignition at 430°C for 4 h (Davies 1974). Particle sizes were determined according to Miller and Miller (1987). Organic material was measured by loss on ignition and subtracted from the initial sediment weight. Acid volatile sulfides (AVS) were determined using methods outlined by Brouwer and Murphy (1994). Simultaneously extracted metals (SEM) within the AVS digestate were analyzed using inductively coupled plasma-mass spectrometry.

Quality assurance data, including blanks, duplicates, spiked blanks, and standard aqueous samples, indicated that analyses were within acceptable limits. Detection limits were 10 ng/g dry weight for As, Cr, Se, and Zn; 10 µg/g dry weight for Cd, Cu, Mn, Mo, Ni, and Pb; and 2.5 ng/g for Hg in sediments and 0.3 ng/g in tissues. Limit of quantitation was established as three times the lower limit of detection. Relative standard deviation between duplicates averaged 13% for the ICP-MS analyses of metals and 11% for Hg analyses. Blanks were <1 ng/g for As, Cd, Cr, Hg, Mn, Mo, Ni, Pb, and Se; <2 ng/g for Cu; and <30 ng/g for Zn. Recovery from spiked blank samples averaged 98% for Hg and between 100% and 120% for the other elements. Recovery from aqueous standards averaged 105%.

Acute toxicity of sediments was determined on solid-phase sediment (Ingersoll *et al.* 1994) with two 70% renewals of overlying water daily (Zumwalt *et al.* 1994). Test chambers were 300-ml high-form glass beakers with a notch in the lip covered with stainless steel mesh (250 µm). Sediment volume was 100 ml and overlying water was 175 ml. Ten *Hyalella azteca* (Amphipoda, Crustacea) were placed in each of five replicate test chambers for each sediment. The 10-day exposures were maintained at 23 ± 1°C under wide-spectrum fluorescent lights with a 16-h light:8-h dark regime. Animals were fed 1.5 ml of YCT (yeast, Cerophyl, trout chow) daily (1.8 g solids/L). Deionized water reconstituted to a hardness of 100 mg/L, alkalinity of 70 mg/L, 350 µS/cm conductivity, and pH of 8 was used for the overlying and renewal water. Survival was the test endpoint. Dissolved oxygen, temperature, pH, alkalinity, hardness, conductivity, and ammonia of the overlying water were monitored during the test.

H. azteca were exposed to sediment pore water for 96 h under static conditions. Pore water was isolated by inserting 10 pore-water extractors into each sediment and applying a vacuum (Winger and Lasier 1995). Extractors consisted of fused-glass air stones attached with airline tubing to 60-cc syringes (Winger and Lasier 1991). About 300 ml of pore water were isolated from each sample, aerated, and 20 ml transferred to each of five replicate 30-ml glass beakers. Ten *H. azteca* and a 1.5-cm square of Nitex netting (275 µm) were placed in each beaker. Animals were not fed during the test, and survival was the test endpoint. Basic chemistry (the same as that for overlying water in the sediment test) of pore water was measured after aeration.

Some polycyclic aromatic hydrocarbons (PAHs) elicit phototoxicity when exposed to ultraviolet light (Ankley *et al.* 1994), therefore, after initial exposures to solid-phase sediment and pore water, surviving *H. azteca* were exposed to ultraviolet light (UVA 340 bulbs, Q-Panel Company, Columbus, OH) at wavelengths ranging from 295 to 370 nm for 24 h. Light intensities produced by bulbs similar to those used in this study have been reported as 8.32×10^2 µW/cm^2 for UV-A and 1.27×10^2 µW/cm^2 for UV-B (Kosian *et al.* 1998). Animals from sediment exposures were transferred into 30-ml beakers containing 20 ml of reconstituted water, and animals from the pore-water tests were exposed in the pore water within respective test beakers. The animals were placed directly under the ultraviolet lights at a distance of 12 cm from the bottom of the beakers.

Bioaccumulation of metals was determined using four replicates from each of six dredge spoil samples (Ingersoll *et al.* 1994). Each replicate consisted of a 4-L glass beaker, 1 L of sediment, 3 L of overlying water, and 300 freshwater oligochaetes, *Lumbriculus variegatus.* Overlying water (70%) was renewed twice daily. Exposures lasted for 28 days, and animals were not fed during the test. At the end of the test, metal residues were measured in the sediments and in the surviving oligochaetes that were allowed to purge their guts in fresh water for 24 h.

Metal residues in wildlife were evaluated using 10 green-winged teal (*Anas crecca*) and 11 lesser yellowlegs (*Tringa flavipes*) collected from the dredge-disposal area near Stations 39–41. Four raccoons (*Procyon lotor*) were collected from areas close to the dredge-disposal areas and river system, and three were collected from a control site on the northeastern portion of Savannah NWR (about 10 km from the river) at the interface between upland and marsh habitat. Metal residues were measured in livers from the birds and raccoons.

Data that were not normally distributed were transformed using log $(x + 1)$ prior to statistical analyses. Correlation analysis and analysis of variance (general linear models) with Dunnett's and Tukey's multiple comparison tests ($p \leq 0.05$) were conducted using Statistical Analysis Systems (SAS Institute 1990).

Results and Discussion

Solid-phase sediments from the lower Savannah River and dredge-disposal areas were toxic to *H. azteca* at only Stations 18, 39, and 40 (Table 1). Daily renewal maintained overlying water quality within acceptable ranges throughout the tests. Reduced survival in dredged sediments from Stations 39 and 40 may be related to high concentrations of Mn (Table 2). Survival in sediments from Station 18 in 1997 was not significantly less than in the control, but was significantly lower in 1996. Concentrations of most metals were higher at this site in 1996 (Table 2) and the SEM/AVS ratio was 3.6 (Table 3), a ratio that generally indicates metal toxicity (DiToro *et al.* 1992). Survival in solid-phase sediment was negatively correlated ($p \leq 0.001$) with As ($r = 0.66$), Mn ($r = 0.87$), and Mo ($r = 0.78$) in the sediment and alkalinity ($r = 0.45$), salinity ($r = 0.51$), and ammonia ($r = 0.58$) in the overlying water.

Survival of *H. azteca* was significantly reduced in pore waters from over half of the 41 stations (Table 1). Ammonia exceeded 20 mg/L at 11 stations, alkalinity exceeded 1,000 mg/L at seven stations, and salinity exceeded 4‰ at 15 stations. Poor water quality parameters were correlated with the reduced survival; ammonia ($r = 0.63$), alkalinity ($r = 0.47$), and salinity ($r = 0.36$) were negatively ($p \leq 0.05$) correlated with survival (Table 3). The trace elements As ($r = 0.38$), Mn ($r = 0.47$), and Mo ($r = 0.43$) in the sediments were also negatively correlated ($p \leq 0.05$) with survival in pore water (Table 2).

Exposure to ultraviolet light after the initial tests decreased survival of *H. azteca*, suggesting that PAHs may be contributing to the toxicity at some sites (Ankley *et al.* 1994). Decreases in survival after exposure to ultraviolet light were most notable at Stations 13, 14, 18, 20, 21, 22, 30, 33, 34, and 35 (Table 1). With the exception of Stations 13 and 14, these stations were in close proximity to dredge-disposal sites. Previous measurements of PAHs in sediments were generally low, except at a few sites in Front River (Winger and Lasier 1995), but runoff from sediments dredged from these areas could potentially contribute PAHs to Back and Middle Rivers. Increased exposure time to pore water, lack of food, and handling stress could also have

Table 1. Percent survival of *Hyalella azteca* exposed to solid-phase sediment (10 days) and pore water (96 h) and then survivors from initial tests were exposed to ultraviolet light (24 h) from samples collected from the lower Savannah River during 1996 and 1997

Station		Year	Solid Phase	Solid Phase/ UV Light	Pore Water	Pore Water/ UV Light
Settling	1	1996	88	80	40*	34*
Basin	2	1996	82	82	60*	52*
	3	1996	90	88	88	84
Back	4	1996	88	80	94	84
River	5	1996	98	96	86	74
	6	1996	96	88	58*	26*
	7	1996	88	72	66*	38*
	8	1996	98	86	80	58*
	9	1996	100	94	62*	52*
	10	1996	98	90	86	78
	11	1997	92	86	84	80
	12	1997	92	78	26*	12*
	13	1996	94	92	28*	12*
	13	1997	92	60*	74*	63*
	14	1997	92	52*	82	72*
	15	1997	96	80	62*	46*
Tidal	16	1997	98	94	86	80
Creek	17	1997	92	82	88	76
	18	1996	70*	52*	26*	0*
	18	1997	92	70*	8*	0*
	19	1997	96	92	66*	60*
	20	1997	98	94	90	76
	21	1997	96	90	92	72*
	22	1996	96	90	82	56*
	22	1997	92	70*	56*	34*
	23	1997	92	90	88	76
	24	1997	98	94	90	80
	25	1997	94	90	62*	56*
Middle	26	1997	96	82	48*	35*
River	27	1997	94	90	82	76
	28	1996	90	84	76	72*
	28	1997	92	88	42*	34*
	29	1996	88	80	82	80
	29	1997	94	86	66*	54*
	30	1997	92	82	80	62*
	31	1996	80	76	62*	40*
	31	1997	94	82	24*	14*
Front	32	1997	94	86	92	76
River	33	1997	98	82	44*	36*
	34	1996	96	94	44*	36*
	34	1997	93	66*	66*	48*
	35	1997	98	75	80	64*
Dredge	36	1996	90	76*	62*	62*
Spoil	37	1996	92	90	0*	0*
	38	1996	90	82	82	78
	39	1996	40*	34*	6*	4*
	40	1996	54*	42*	2*	0*
	41	1996	86	84	42*	28*
Control		1996	98	96	100	98
		1997	99	96	96	92
Reference		1996	100	96	96	92
		1997	99	96	96	92

* = Significantly different than control, $p \leq 0.05$

contributed to the decreased survival of animals exposed to ultraviolet light.

The sediments were organic, ranging from 1 to 17% (Table 3). Percent moisture (not shown) was >70% and particle size was dominated by silt and clays. Acid volatile sulfides were generally high enough to preclude availability of metals in the pore water under anaerobic conditions, except at 12 sites where the SEM/AVS ratio was >1. Eight of these 12 sediments had significantly reduced survival of *H. azteca* in the pore water (Table 1). Metal concentrations in pore waters with SEM/AVS ratio <1 are generally below those that cause adverse biological effects (DiToro *et al.* 1992).

Metals in some sediments from the lower Savannah River exceeded concentrations associated with adverse biological effects. The effects range-low (ER-L) represents the lower 10th percentile of the screened data base where effects were observed (Long and Morgan 1990; Long *et al.* 1995). The ER-L for As (8.2 mg/kg dry weight) was exceeded at 29 of the 41 stations (Table 2). Stations in lower Back River (Stations 1–8), Tidal Creek (Stations 1–25), and dredge-disposal areas (Stations 36–41) accounted for these exceedances. Metal concentrations were comparatively lower in the upper Back River and in Front River. The ER-L for Cd (1.2 mg/kg) was exceeded at nine stations, but showed no distributional pattern other than sediments immediately above and below the Tide Gate exceeded this value. The Cr ER-L of 81 mg/kg was exceeded at 15 stations, with most of these in the Tidal Creek area and Middle River. These areas are in close proximity to the Hutchinson Island dredge-disposal area that also had Cr concentrations that exceeded the ER-L. ER-Ls for Cu (34 mg/kg) and Pb (46 mg/kg) were not exceeded at any site. The ER-L level of 0.15 mg/kg for Hg was exceeded at five sites, but the distribution of these sites showed no pattern. The ER-L for Ni (20.9 mg/kg) was exceeded at 19 stations. These sites were in Tidal Creek, Middle River, and the dredge-disposal area on Hutchinson Island. The ER-L of 150 mg/kg for Zn was exceeded at six stations, mainly in the lower Back River. ER-Ls were not available for Mn and Mo, but concentrations of these trace elements appear to be elevated at several sites; concentrations of Mn > 1,000 mg/kg and Mo > 1 mg/kg were measured in sediments from 15 sites (Back River, Middle River, and dredge-disposal areas).

Residues in sediments suggest that drainage from the dredge-disposal areas may influence the distribution of metals in adjacent Tidal Creek, Middle River, and Back River stations (Table 2). All stations in Middle and Back rivers were close to dredge-disposal areas, with the exceptions of Stations 11–15 on Back River. Drainage through culverts from the disposal areas into Back River occurred in the vicinity of Stations 36–38 in the dredge-disposal area on the northern end of Hutchinson Island. Drainage pipes also discharge into Middle River at the southern end of Onslow Island. Back River Stations 4–9 and Tidal Creek Stations 16–25 are potentially subjected to seepage or overflow from adjacent dredge-disposal areas. Similarities of metal concentrations in sediments from Tidal Creek, Back River, and Middle River with those in the Hutchinson Island dredge-disposal area reflect the influence of drainage from the disposal area. This is most evident for As, Cr, Mn, Mo, Pb, and Zn. Chromium, for example, was elevated in sediments from Stations 36–38 (dredge-disposal area) on Hutchinson Island and also in sediments from stations in the Tidal Creek area. Zinc and Mn were uniformly high in sediments from the stations upstream of the Tide Gate in Back River (Stations 4–9) that potentially receive drainage, seepage, or overflow from adjacent dredge-disposal areas. These data suggest drainage from the dredge-disposal areas could potentially reduce habitat quality in the marsh and river environments, but the environmen-

Table 2. Concentrations (mg/kg dry weight) of trace elements in sediments and dredge spoils from the lower Savannah River, 1996 and 1997 (concentrations with an asterisk exceed ER-L levels [Long *et al.* 1995])

Station		As	Cd	Cr	Cu	Hg	Mn	Mo	Ni	Pb	Se	Zn
Settling Basin	1	10.9*	1.4*	33.2	12.9	0.09	826	0.6	9.9	16.6	0.9	164.9*
	2	12.1*	1.3*	39.4	15.9	0.03	929	0.5	11.7	19.2	0.9	126.5
	3	3.3	5.5*	13.4	4.8	0.03	158	0.4	3.7	5.7	0.4	48.7
Back River	4	4.5	1.5*	18.1	9.0	0.03	230	0.7	6.3	9.4	0.5	59.3
	5	12.7*	0.7	58.2	24.5	0.02	1,253	1.5	17.8	26.6	1.6	158.1*
	6	12.9*	1.2*	56.7	26.5	0.03	1,244	1.4	18.1	27.9	1.3	145.3
	7	13.4*	1.1	65.6	28.3	0.03	1,431	1.4	20.5	31.9	1.4	153.1*
	8	9.9*	0.9	55.6	22.9	0.02	930	1.3	16.5	27.6	1.5	330.3*
	9	7.1	0.8	41.3	17.7	0.03	705	1.0	12.7	20.3	1.1	155.9*
	10	6.3	0.6	50.5	22.5	0.04	506	1.1	15.9	24.0	1.1	115.7
	11	6.8	0.3	63.5	22.3	0.13	742	0.5	20.6	20.4	1.3	78.9
	12	5.6	0.3	52.8	20.2	0.07	1,152	0.4	18.4	17.8	1.2	75.3
(1996)	13	7.5	0.7	38.9	20.1	0.14	963	0.6	11.6	18.4	0.9	107.5
(1997)	13	2.6	0.1	18.4	17.4	0.02	289	0.4	7.0	22.8	0.5	37.0
	14	6.4	0.3	78.1	24.0	0.21*	553	0.4	23.7*	29.6	1.4	76.4
	15	4.4	0.3	49.3	18.8	0.12	550	0.3	17.2	17.6	1.1	63.5
Tidal Creek	16	14.5*	0.3	69.0	16.3	0.10	683	0.7	18.7	18.5	1.2	63.5
	17	9.5*	0.4	68.7	16.7	0.12	330	0.6	16.4	22.6	1.1	54.2
(1996)	18	8.9*	1.6*	70.6	27.4	0.04	745	1.5	20.3	31.3	1.4	137.5
(1997)	18	10.1*	0.4	89.8*	25.1	0.16*	520	0.8	23.2*	31.8	1.7	85.5
	19	11.6*	0.7	90.5*	26.2	0.15*	685	0.9	24.5*	24.6	1.8	95.7
	20	10.3*	0.6	93.8*	27.6	0.12	770	0.8	26.2*	26.6	2.0	102.4
	21	13.1*	0.9	95.5*	29.5	0.04	743	1.0	25.0*	32.8	1.8	94.8
(1996)	22	9.7*	0.8	64.5	27.8	0.03	799	1.5	20.9*	29.5	1.3	138.3
(1997)	22	17.6*	0.4	130.1*	31.6	0.08	566	1.3	29.5*	44.2	2.0	104.2
	23	12.7*	0.7	100.8*	27.2	0.12	823	0.9	27.5*	31.3	1.9	106.7
	24	12.5*	0.9	99.8*	26.4	0.12	754	1.0	27.1*	23.7	1.8	102.3
	25	10.9*	0.8	100.1*	27.1	0.11	651	0.7	26.8*	31.8	2.3	101.5
Middle River	26	7.1	0.2	72.5	31.2	0.11	762	0.3	26.9*	30.2	1.5	85.4
	27	13.3*	0.7	92.3*	31.2	0.09	2,133	0.8	30.4*	38.5	2.1	124.3
(1996)	28	9.8*	0.5	71.0	22.8	0.09	1,249	0.6	23.1*	20.7	1.5	89.2
(1997)	28	5.0	1.6*	24.6	10.5	0.03	532	0.9	8.2	11.5	0.6	60.1
(1996)	29	11.4*	0.5	84.9*	27.0	0.09	1,274	0.5	24.9*	31.0	1.7	108.2
(1997)	29	9.0*	0.9	77.7	24.7	0.31*	1,104	0.7	13.9	28.9	1.2	112.4
	30	4.2	2.5*	39.2	10.6	0.02	360	0.6	11.4	8.0	0.7	49.7
(1996)	31	10.8*	0.7	82.6*	25.2	0.07	1,139	0.8	25.4*	22.5	1.8	126.0
(1997)	31	3.7	0.6	20.8	9.6	0.04	432	0.3	6.6	12.2	1.8	58.9
Front River	32	7.8	0.6	58.4	21.7	0.07	550	0.8	20.3	17.9	1.3	81.7
	33	4.2	0.2	44.6	16.3	0.00	400	0.3	15.1	14.2	0.9	60.6
(1996)	34	5.9	0.8	43.8	23.3	0.12	559	0.6	15.2	22.7	1.0	207.9*
(1997)	34	7.7	0.4	64.5	23.5	0.11	720	0.3	20.2	22.8	1.2	78.4
	35	3.2	0.4	35.2	11.9	0.04	410	0.2	11.2	10.7	0.9	52.6
Dredge Spoil	36	15.0*	0.5	90.2*	27.6	0.09	1,533	0.3	29.8*	31.1	2.0	125.7
	37	20.3*	1.3*	114.3*	26.9	0.14	1,705	1.6	30.0*	26.9	2.7	118.2
	38	17.4*	1.1	101.4*	23.9	0.08	1,399	1.3	27.1*	27.7	2.6	103.5
	39	30.0*	0.8	46.3	16.4	0.06	17,498	4.8	16.7	19.1	2.5	61.2
	40	32.8*	0.9	40.9	14.9	0.15*	12,533	6.1	15.6	16.5	2.0	95.3
	41	20.8*	0.3	97.8*	22.7	0.03	1,601	0.7	26.7*	25.2	2.4	106.2

tal significance may depend on the intensity of dredging activities and the amount and quality of water draining or leaching from the disposal areas.

Metal residues in oligochaetes from laboratory cultures were low at test initiation, but increased significantly during the 28-day exposures to sediments from the dredge-disposal areas. Arsenic, Cu, Hg, Se, and Zn bioaccumulated to concentrations higher than levels measured in the sediments (Table 4). Arsenic had a bioaccumulation factor (BAF), calculated by dividing the concentration in the oligochaetes by the concentration in the sediments, that ranged from 1 to 2. The BAF for Cu ranged from 2 to 6, Hg ranged from 1 to 5, Se from 1.5 to 9, and Zn from 4 to 19. Cadmium, Cr, Mo, Ni, and Pb concentrations increased over initial body burdens during the exposure period; however, they did not accumulate to concentrations higher than those in the sediments. For example, Pb concentrations in oligochaetes increased two to four times over levels in animals from the systems used to culture the animals, but concentrations did not exceed levels in the sediments.

Biological uptake of metals by wildlife living in or utilizing dredge-disposal areas varied with species and metal (Table 5). Cadmium, Hg, Mo, and Se concentrations in livers from birds and raccoons were higher than those in sediments from the dredge-disposal areas and oligochaetes exposed to dredged sediments during bioaccumulation studies (Table 4). Differences in residue concentrations between bird species may be

Table 3. Characteristics of sediment and pore water collected from the lower Savannah River, 1996 and 1997

		Sediments					Pore Water			
Station		Organic (%)	Sand (%)	Fines (%)	AVS (μmol/g)	SEM/AVS (ratio)	pH (unit)	Alkalinity (mg/L)	Salinity (‰)	Ammonia (mg/L)
Settling Basin	1	10	NA	NA	NA	NA	8.7	1,044	15.0	25.0
	2	11	NA	NA	NA	NA	8.7	1,052	13.0	23.4
	3	3	NA	NA	NA	NA	8.7	358	6.0	7.9
Back River	4	2	NA	NA	0.6	3.5	8.5	294	6.0	3.1
	5	7	NA	NA	1.4	0.9	8.4	608	8.0	10.9
	6	9	NA	NA	1.3	2.1	8.6	1,120	5.0	13.2
	7	9	NA	NA	1.3	403.8	8.7	1,126	4.0	14.3
	8	7	NA	NA	1.5	1.4	8.7	369	3.0	9.0
	9	6	NA	NA	0.9	0.9	8.6	904	2.0	20.2
	10	7	NA	NA	1.2	0.8	7.8	136	1.0	0.0
	11	13	24	76	15.1	0.8	8.5	100	0.0	1.5
	12	13	25	75	2.5	4.8	8.5	526	0.0	17.4
(1996)	13	12	NA	NA	NA	NA	8.6	320	0.0	20.8
(1997)	13	3	87	13	1.8	4.0	8.2	50	0.0	0.0
	14	11	20	80	33.3	0.2	8.1	94	0.0	2.2
	15	14	22	78	1.6	6.1	8.3	182	0.0	5.9
Tidal Creek	16	12	13	87	26.7	0.2	8.6	234	0.5	7.6
	17	11	45	55	25.1	0.3	8.6	196	0.5	2.5
(1996)	18	8	NA	NA	1.4	3.6	5.8	6	2.0	5.2
(1997)	18	17	19	81	52.1	0.2	5.7	8	0.5	5.4
	19	14	15	85	45.1	0.3	8.5	242	0.5	11.3
	20	14	14	86	131.9	0.1	8.7	286	1.5	6.4
	21	14	24	76	46.7	0.2	8.6	164	0.0	4.4
(1996)	22	7	NA	NA	1.5	1.7	8.5	200	1.0	9.2
(1997)	22	3	19	81	149.1	0.1	6.5	20	1.5	0.0
	23	11	11	89	45.3	0.2	7.9	60	1.5	7.9
	24	9	16	84	32.0	0.3	8.3	110	2.0	5.5
	25	12	17	83	54.1	0.2	7.5	36	4.0	4.3
Middle River	26	9	26	74	19.7	0.3	8.3	132	0.3	3.1
	27	10	9	91	3.8	3.1	8.8	620	1.0	7.8
(1996)	28	4	NA	NA	NA	NA	8.5	240	3.0	20.8
(1997)	28	8	12	88	8.7	1.1	8.6	688	1.7	14.0
(1996)	29	10	NA	NA	NA	NA	8.7	290	2.0	7.6
(1997)	29	6	15	85	32.9	0.3	8.7	446	2.3	9.1
	30	1	76	24	5.1	0.7	8.6	298	2.0	5.6
(1996)	31	5	NA	NA	NA	NA	8.4	362	6.0	7.4
(1997)	31	6	18	82	23.4	0.4	8.8	564	3.7	22.1
Front River	32	7	38	62	58.1	0.1	8.5	186	0.0	4.6
	33	4	50	50	31.1	0.2	8.2	86	0.4	1.2
(1996)	34	10	NA	NA	NA	NA	8.6	218	1.0	5.1
(1997)	34	8	35	65	24.7	0.3	8.3	104	0.2	4.2
	35	4	60	40	14.7	0.3	8.3	120	0.5	3.7
Dredge Spoil	36	5	5	95	1.5	2.5	8.3	980	12.0	24.7
	37	8	6	94	1.6	2.2	8.2	1,256	13.0	32.0
	38	5	4	96	3.9	0.5	8.4	226	9.0	4.7
	39	12	33	67	NA	NA	8.9	1,200	11.0	32.1
	40	3	23	77	NA	NA	8.7	1,344	12.0	56.5
	41	12	11	89	NA	NA	8.7	892	10.0	27.1

NA = not available

dependent on feeding preferences (Furness 1996). Residues in raccoons were significantly different between those collected near the dredge-disposal/river area compared to those collected at the edge of the tidal marsh and upland, especially for Cd, Hg, and Se. Differences in Hg residue levels in raccoons from the two locations may reflect different feeding habits, different concentrations in food items, or different methylation rates and availability between the two areas.

The environmental significance of metal bioaccumulation and body residue concentrations is not straightforward and varies with each metal, species, and trophic level. Some metals have no known metabolic function and are usually toxic (Cd, Pb, Hg). Some are essential elements (Cu, Fe, Mn, Zn) and needed in small quantities, but are toxic at higher concentrations (Rainbow 1996). Essential metals are generally regulated by the body to such a degree that body-residue levels are difficult to interpret. Some toxic metals (Hg) biomagnify through the food chain and some (Pb) do not. Generally, predators are at greater risk from metals than animals further down the food chain. The important environmental conse-

Table 4. Concentrations (mg/kg dry weight; mean with standard deviation, n = 4) of trace elements in oligochaetes (*Lumbriculus variegatus*) exposed during 28-day bioaccumulation tests to dredge spoil sediments collected from the lower Savannah River in 1997

Station	As	Cd	Cr	Cu	Hg	Mn	Mo	Ni	Pb	Se	Zn
Oligochaetes											
Lab Culture	0.7	0.1	0.0	9.2	0.08	3	0.1	0.7	1.4	1.4	266
Control*	4.1 (1.0)	0.3 (0.1)	0.1 (0.3)	27.1 (16.1)	0.17 (0.08)	51 (15)	0.3 (0.1)	0.5 (0.5)	4.9 (1.7)	2.6 (0.9)	430 (135)
36	26.7 (3.2)	0.5 (0.1)	1.3 (1.3)	68.3 (25.8)	0.16 (0.04)	48 (21)	0.7 (0.1)	1.6 (0.6)	6.3 (2.7)	5.1 (0.6)	956 (304)
37	25.5 (0.8)	0.4 (0.1)	3.3 (3.8)	57.0 (18.2)	0.15 (0.06)	57 (30)	0.7 (0.3)	1.4 (1.0)	6.6 (4.0)	4.1 (0.5)	788 (157)
38	24.0 (2.0)	0.5 (0.0)	1.3 (0.9)	79.2 (42.1)	0.15 (0.01)	51 (22)	0.7 (0.1)	1.1 (0.4)	6.4 (1.3)	4.4 (0.4)	825 (57)
39 + 40	5.6	0.2	0.0	17.6	0.01	113	0.2	0.0	3.4	3.7	446
41	15.3 (1.2)	0.2 (0.1)	0.3 (0.4)	21.1 (1.2)	0.13 (0.06)	41 (16)	0.5 (0.3)	0.5 (0.3)	3.6 (0.9)	3.6 (0.4)	680 (56)
Sediments											
Control	6.6	0.4	48.8	14.7	0.10	803	0.4	13.8	32.8	1.4	76
36	15.0	0.5	90.2	27.6	0.09	17,498	0.3	29.8	31.1	2.0	126
37	20.3	1.3	114.3	26.9	0.14	12,553	1.6	30.0	26.9	2.7	118
38	17.4	1.1	101.4	23.9	0.08	1,601	1.3	27.1	27.7	2.6	104
39	30.0	0.8	46.3	16.4	0.06	1,533	4.8	16.7	19.1	2.5	61
40	32.8	0.9	40.9	14.9	0.15	1,705	6.1	15.6	16.5	2.0	95
41	20.8	0.3	97.8	22.8	0.03	1,399	0.7	26.7	25.2	2.4	106

* Control = Ogeechee River sediment

Table 5. Mean (with SD) trace metal concentrations (mg/kg dry weight) in liver tissue from birds and racoons collected from the lower Savannah River in 1997

Element	Raccoon—Hutchinson Island (n = 4)	Raccoon—Control Site (n = 3)	Green-Winged Teal (n = 10)	Lesser Yellowlegs (n = 11)
As	0.45 (0.17)	0.20 (0.17)	0.77 (0.25)	0.96 (1.02)
Cd	2.90 (0.74)	0.30 (0.0)	0.93 (0.77)	1.24 (0.66)
Cr	1.23 (0.96)	0.88 (0.79)	1.07 (0.21)	1.53 (0.94)
Cu	68.9 (35.9)	56.4 (15.1)	49.2 (19.9)	19.9 (3.4)
Hg	28.20 (19.19)	7.20 (2.84)	0.24 (0.08)	1.02 (1.14)
Mn	12.8 (3.3)	11.8 (3.3)	28.5 (11.2)	20.1 (10.0)
Mo	4.6 (0.9)	5.3 (1.6)	3.6 (0.7)	3.0 (0.9)
Ni	0.32 (0.36)	0.90 (0.65)	0.07 (0.06)	0.34 (0.43)
Pb	0.47 (0.24)	0.20 (0.13)	0.07 (0.06)	1.13 (1.54)
Se	12.18 (5.95)	4.17 (0.35)	6.74 (1.07)	11.38 (6.96)
Zn	159 (25)	150 (34)	166 (23)	107 (22)
Moisture (%)	71.6	70.8	70.7	70.7

quence from metal body burdens in food chain organisms is not direct toxicity to them, but as the dietary source to other trophic levels.

Most metals that demonstrated availability and bioaccumulation in laboratory or field evaluations were not at levels considered high enough to pose an environmental risk. For example, As bioaccumulated in oligochaetes to concentrations higher than those in the dredge-disposal sediments in the laboratory. This trace element, however, does not biomagnify through food chains and would not be expected to pose a risk at the concentrations measured during this study, which are typical of estuarine environments (Eisler 1994). Similarly, Cd residues in livers from birds and raccoons were higher than those in sediments and levels accumulated in the laboratory by oligochaetes, but did not exceed the 8 μg/g dry weight threshold level associated with biological impacts (Furness 1996).

Although Pb increased in oligochaetes over control (culture) conditions, levels were below those expected to cause adverse biological effects. Biomagnification of Pb does not occur in nature (Beyer and Storm 1995). The low concentrations in livers of birds and raccoons demonstrated that uptake of Pb from food was low (Table 4). Concentrations of Pb $<$ 100 μg/g dry weight in food organisms usually do not cause adverse biological effects (Scheuhammer 1987, 1991). Body residues of Pb $>$ 5 μg/g are considered biomarkers for toxic exposure in wildlife (Ma 1996), and levels in birds and raccoons from the lower Savannah River system were below this threshold.

Selenium concentrations in oligochaetes were twice those in the sediments from the dredge spoils (Table 4). These concentrations exceed the 3 μg/g dry weight threshold level in food-chain animals that have been associated with reproductive failure (most sensitive indicator of biological impact) in fish and wildlife (Lemly 1996; Heinz 1996). Birds and other wildlife that feed on invertebrates from the Savannah dredge-disposal areas may be at risk from Se exposure, assuming other invertebrates bioaccumulate Se at concentrations comparable to those in oligochaetes from the bioaccumulation tests.

Zinc bioaccumulated in oligochaetes to concentrations six times higher than those in the dredged sediments (Table 4). Although there is a large amount of variability in concentrations reported to elicit adverse biological responses, the most sensitive species appear to be adversely impacted by Zn when concentrations in food-chain organisms are in the range of those measured in oligochaetes at the end of the bioaccumulation tests (Rainbow 1996). Zinc concentrations in livers from birds and raccoons were very similar (Table 5), but substantially lower than those in oligochaetes exposed to dredge-spoil sediment. This probably reflects the ability of these species to regulate the body burdens of Zn (Rainbow 1996); the physiological requirements needed for this type of regulation are not known. Invertebrates that inhabit dredge-disposal areas and accumulate Zn to levels comparable to those measured during the bioaccumulation studies may pose a risk to indigenous wildlife.

Mercury biomagnifies readily through food chains (Wiener and Spry 1996), and low concentrations in the sediments and in animals at lower trophic levels can reach biologically significant concentrations within short steps in the food chain.

Mercury concentrations doubled in oligochaetes exposed to dredged sediments compared to cultured oligochaetes and were about twice as high as sediments concentrations (Table 4). Residue levels in bird livers had BAFs (compared to sediment concentrations of ∼0.1 μg/g dry weight) ranging from 2 to 10, and raccoon livers showed BAFs for mercury ranging from 72 to 280 (Table 5). Piscivorous birds inhabiting the lower Savannah River system would probably have higher concentrations of mercury in their livers than the green-winged teal and yellowleg, which feed on plant material and invertebrates (Wiener and Spry 1996). Mercury residues in fish from the lower Savannah River were ∼1.5 μg/g dry weight in 1984 (Winger *et al.* 1990). If present concentrations are similar to those in 1984, the concentrations of Hg in raccoon livers found in this study could be accounted for through the consumption of fish. Mercury concentrations of 1 to 1.5 μg/g dry weight in the diet, which are in the range of those found in fish from the Savannah River, have been associated with reproductive impairment in wildlife (Barr 1986; Scheuhammer 1991).

Potential impacts from Hg appear to be more of an overall concern for the lower Savannah River ecosystem, rather than just to the dredge-disposal areas, although the effects of drainage and rewetting of dried dredged sediments on availability and transport of Hg may be important (Bodaly *et al.* 1984; Kelly *et al.* 1997). Availability of mercury appears to be associated with aquatic/wetland habitats where methylation processes are enhanced (Gilmour *et al.* 1992) and may account for the significant differences seen in Hg levels in raccoons from the river/wetland system compared to the more upland area. The environmental effects of Hg are also influenced by Se (Cuvin-Aralar and Furness 1991), but the significance of this ameliorating effect on Hg toxicity is not known for the Savannah River system.

Conclusions

Sediments from several locations within the lower Savannah River system demonstrated toxicity to *H. azteca*. These sites were located in Back River near the Savannah National Wildlife Refuge maintenance area and in Tidal Creek and Middle River, which receive drainage, seepage, or overflow from dredge-disposal areas. Reduced survival in sediments from some sites was attributed to reduced water quality, such as ammonia, alkalinity, and/or salinity. Increased mortality of test animals from solid-phase sediment and pore-water tests after exposure to ultraviolet light indicated that some sediments in Front and Back Rivers may be contaminated with PAHs. Residues of As, Cr, Mn, Mo, Ni, and Zn exceeded ER-L values at several sites, and the distribution of stations with elevated concentrations of these metals suggests the adjacent dredge-disposal area as the point source. High concentrations of AVS, which exceeded SEM concentrations, essentially precluded the bioavailability of metals under undisturbed anaerobic conditions at most sites. However, metals exceeded AVS concentrations at several sites and may have contributed to observed toxicity. Based on metal concentrations in sediments and sediment pore-water toxicity, drainage from the dredge-disposal areas into Back River and Middle River may be reducing habitat quality in localized areas.

Laboratory bioaccumulation studies and measurement of metal residues in resident biota demonstrated availability and bioaccumulation potential of some metals. Of particular concern are Hg, Se, and Zn, which have the potential to biomagnify and cause adverse biological effects. These data suggest that predators and piscivorous birds associated with the lower Savannah River systems may be at risk from these metals that are mobilized in the dredge-disposal sediments and transferred through food chains.

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