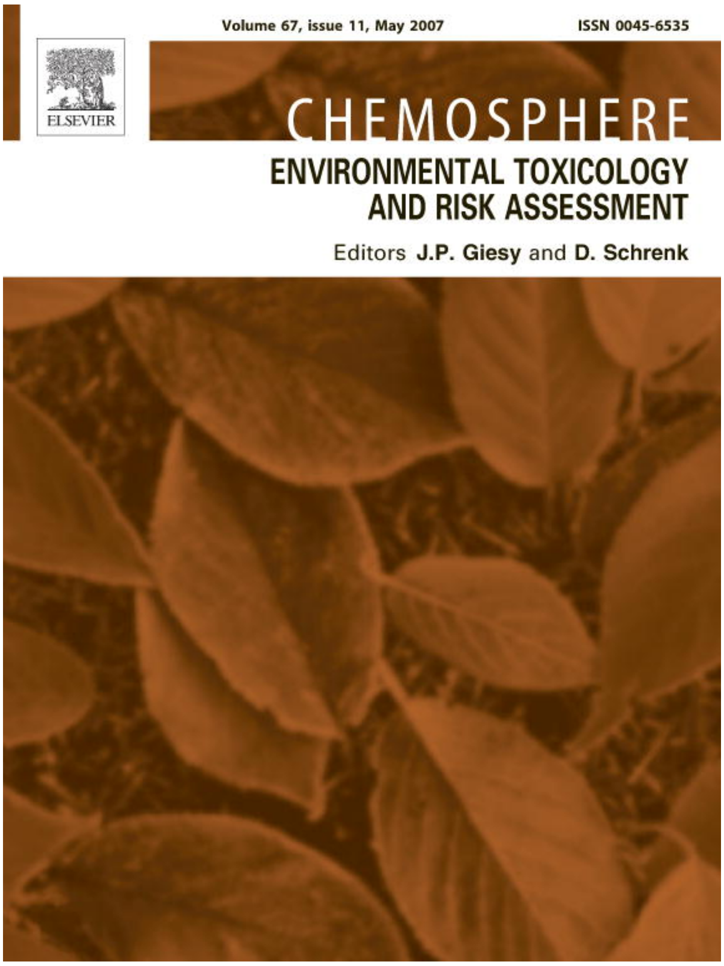

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Assessment of pesticide contamination in three Mississippi Delta oxbow lakes using *Hyalella azteca*

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Abstract

Three oxbow lakes in northwestern Mississippi, USA, an area of intensive agriculture, were assessed for biological impairment from historic and current-use pesticide contamination using the amphipod, *Hyalella azteca*. Surface water and sediment samples from three sites in each lake were collected from Deep Hollow, Beasley, and Thighman Lakes from September 2000 to February 2001. Samples were analyzed for 17 historic and current-use pesticides and selected metabolites. Ten-day *H. azteca* survival and growth (as length and dry weight) were measured to determine the degree of biological impairment. Maximum number of detectable pesticides in surface water from Deep Hollow, Beasley and Thighman Lakes was 10, 11, and 17, respectively. Maximum number of detectable pesticides in lake sediments was 17, 17, and 15, respectively. Bioassay results indicated no observable survival effects on *H. azteca* exposed to surface water or sediment from any lake examined and no growth impairment in animals exposed to lake sediments. However, growth was significantly impaired in surface water exposures from Deep Hollow Lake (2 sites) and Beasley Lake (1 site). Statistically significant relationships between growth impairment (length) and cyanazine, methyl parathion, λ-cyhalothrin, chlorfenapyr, and *pp*′DDE surface water concentrations in Deep Hollow Lake as well as trifluralin, atrazine, and methyl parathion in Beasley Lake were observed. Although pesticide frequency and concentrations were typically greater in sediment than surface water, bioassay results indicated decreased availability of these pesticides in sediment due to the presence of clay and organic carbon. Growth impairment observed in surface water exposures was likely due to complex interaction of pesticide mixtures that were present.
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Keywords: Growth impairment; DDT; Triazine; Organophosphate

1. Introduction

The Mississippi River basin, home to approximately 27% of the United States population, encompasses some 65% of the US harvested cropland (Snipes et al., 2004). Annual pesticide applications within this basin exceed 100000 metric tons (Kolpin, 2000). Toward the southeastern tip of this basin lies the lower Mississippi River Alluvial Plain, commonly referred to as ‘‘the Delta’’. This is one of the most intensive agricultural areas in the US (Snipes et al., 2004) and produces a variety of crops including cotton (*Gossypium hirsutum*), soybeans (*Glycine max*), corn (*Zea mays*), and rice (*Oryza sativa*). The Mississippi Delta is 18130 km^2, and it has a long growing season with conditions conducive to frequent pesticide use. Associated with this use is a concomitant potential for transport into nearby water bodies such as lakes, rivers and streams. The Mississippi Delta has numerous oxbow lakes that have been physically isolated from their respective main river channels (Knight and Welch, 2004). Oxbow lakes begin formation after river meanders erode the outer side of a river bend. According to Wetzel (1983) this erosion and concavity continues until these meanders deposit sufficient clay material to close in upon themselves. Wetzel (1983) also noted that deeper areas of these lakes are on the outer edges, while inner boundaries are typically shallower.

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Mississippi Delta oxbow lakes have been long known for their productivity and recreational value (Cooper et al., 1984) and have not escaped the detrimental effects of pesticide contamination. As a result, their popularity has decreased as water quality and fisheries have declined (Coleman, 1969). Recent attempts at rehabilitating some of these lakes to restore their productivity and recreational value have shown some success; however, there is a need for assessing the contaminant source (either sediment and/or water) and degree of remaining impairment. The purpose of this study is to ascertain the source (either sediment or water) and degree of impairment due to pesticide contamination in three Mississippi Delta oxbow lakes via chemical analyses and bioassays utilizing *Hyalella azteca*.

2. Materials and methods

2.1. Site description

The Mississippi Delta Management Systems Evaluation Area (MDMSEA) was initiated in 1995 to address impacts of various agricultural best management practices (BMPs) on water quality and fisheries of three oxbow lakes in northwest Mississippi—Deep Hollow Lake, Beasley Lake, and Thighman Lake. Deep Hollow Lake, the smallest of the three MDMSEA lakes with 8 ha of surface area, receives drainage from approximately 202 ha. It is located near Greenwood, Mississippi, in Leflore County. Loam and heavy clay soils are predominant within this watershed (Rebich, 2004). Between 1995 and 1999, the watershed surrounding Deep Hollow Lake consisted of 108 ha of woods, 51 ha of soybeans, and 43 ha of cotton (Hanks and Bryson, 2004). Beasley Lake, with a surface area of 25 ha, receives drainage from approximately 850 ha of loam to heavy clay soils. This lake is within Sunflower County, near Indianola, Mississippi. A unique feature of Beasley Lake is a 5.5 m change in elevation from the top of the watershed to the lake (Deep Hollow and Thighman have only 1.5 m changes in elevation) (Dabney et al., 2004a). According to Dabney et al. (2004b), cropping patterns within the Beasley Lake watershed remained fairly consistent between 1995 and 1999, with an average 357 ha of cotton; 118 ha of soybeans; 43 ha of corn; 10 ha of milo; and 3 ha of rice planted per year. Thighman Lake watershed, the largest of the three MDMSEA watersheds, is also in Sunflower County and drains approximately 1500 ha of cropland and catfish ponds. The lake itself is only slightly larger (9 ha) than Deep Hollow Lake. Average cropping patterns from 1995 to 1999 included 337 ha of cotton; 71 ha of rice; 519 ha of soybeans; and 401 ha of corn (Locke, 2004; Rebich, 2004).

2.2. Sample collection

Surface water and sediment samples were collected longitudinally from three sites, inflow (upstream), middle, and outflow (downstream), in each of three Mississippi Delta oxbow lakes: Deep Hollow Lake, Beasley Lake, and Thighman Lake. Surface water samples were collected at Deep Hollow in October 2000, at Beasley in March 2001, and at Thighman in February 2001. Sediment samples were collected in September 2000. Two liters of surface water (collected in amber bottles) and three shallow sediment cores (10 cm depth × 5 cm diameter) were sampled from each site, preserved on ice and transported to the USDA-ARS National Sedimentation Laboratory, Oxford, MS, for toxicity bioassays and pesticide analysis. Sediment samples were homogenized prior to bioassay and pesticide analysis distribution.

2.3. Analytical chemistry

Upon arrival, aliquots of surface water samples were immediately extracted using ethyl acetate and KCl according to Bennett et al. (2000) and Cooper et al. (2003). Aliquots of sediment samples for pesticide analysis were dried for 24 h and then extracted with ethyl acetate according to Moore et al. (2000) and Bennett et al. (2000). Surface water and sediment samples were analyzed for 17 current and historic-use pesticides and selected associated metabolites. Analytical chemistry was conducted according to Bennett et al. (2000) using a Hewlett-Packard 6890 gas chromatograph equipped with dual HP 7683 ALS autoinjectors. Extraction efficiencies of all fortified samples (both water and sediment) analyzed for quality assurance/quality control were $\geqslant 90\%$.

2.4. Bioassays

Ten-day static, nonrenewal, whole sediment and surface water toxicity tests using laboratory reared *Hyalella azteca* were conducted, with modifications, according to methods described by Suedel and Rodgers (1994), Deaver and Rodgers (1996) and USEPA (1994) protocol. All toxicity tests were initiated within 24 h of sample arrival. Organisms 4–5 d old were collected for the experiment. Each surface water exposure consisted of 200 ml from a lake sample placed in three replicate exposure chambers (250 ml borosilicate glass beakers) per site. Ten *H. azteca* were placed in each exposure chamber along with three, 2 cm diameter maple leaf discs as substrate and food. Additional feeding of 1 ml of a 1:1 suspension rabbit chow:Tetramin® flake food ($10\ \mathrm{mg\ l^{-1}}$) occurred at test initiation. Each sediment exposure consisted of 40 g wet weight sediment from a lake sample placed in three replicate exposure chambers per site and 160 ml overlying water obtained from the University of Mississippi Field Station (UMFS). Feeding regime for sediment exposures was identical to surface water exposures. Toxicity tests were conducted in a Powers Scientific, Inc. Animal Growth Chamber with a 16:8 (light:dark) h photoperiod and a set temperature of 20 ± 1 °C. Control and overlying water, free from priority pollutants, was obtained from UMFS (Moore et al., 1998). Likewise, control sediment was collected from UMFS (Deaver and Rodgers, 1996). Measured physical and chemical water characteristics for surface water tests were temperature, pH, dissolved oxygen, conductivity, hardness, alkalinity, turbidity, total solids, dissolved solids, suspended solids, filterable orthophosphate, total orthophosphate, ammonium-N, and nitrate-N (APHA, 1998) (Table 1). Measured physical and chemical surface water characteristics for sediment tests were temperature, pH, dissolved oxygen, conductivity, hardness, and alkalinity (APHA, 1998) (Table 1). Bioassay endpoints measured were survival and growth (as body length and dry weight). Body length was measured using an Olympus DP11 digital camera and ImagePro® Plus v.4.1 image analysis software (Media Cybernetics, 1999).

2.5. Statistical analyses

Data were analyzed using descriptive statistics and one-way analysis of variance (ANOVA) with Dunnett's multiple range test versus controls on survival and growth (length and dry weight). If data failed parametric assumptions, a Kruskal–Wallace one-way ANOVA on ranks with Dunn's multiple range test versus controls was utilized. Linear regression was performed on growth (as length) versus pesticide concentration when significant impairment was observed. Statistical significance level was set at 5% ($P \leqslant 0.05$) for all analyses (Steel et al., 1997). Data analysis was conducted using SigmaStat® v.2.03 statistical software (SPSS, 1997).

Table 1
Mean ± SD physical and chemical water characteristics for each Mississippi Delta oxbow lake aqueous and sediment exposures

Parameter	Control	Deep Hollow	Beasley	Thighman
Water				
Temperature (°C)	21.2 ± 1.2	20.7 ± 1.3	23.0 ± 1.3	19.8 ± 1.7
pH (s.u.)	7.7 ± 0.4	8.3 ± 0.3	8.0 ± 0.1	7.4 ± 0.5
Dissolved oxygen (mg l^{-1})	7.8 ± 0.8	7.6 ± 0.9	8.0 ± 0.2	9.0 ± 0.7
Conductivity (μmhos cm^{-1})	464 ± 37	417 ± 109	239 ± 140	133 ± 14
Hardness (mg l^{-1} as $CaCO_3$)	140 ± 33	174 ± 23	80 ± 32	60 ± 9
Alkalinity (mg l^{-1} as $CaCO_3$)	100 ± 27	120 ± 0	57 ± 14	43 ± 9
Turbidity (NTU)	17 ± 12	58.7 ± 16	276 ± 33	532 ± 101
Total solids (mg l^{-1})	47 ± 25	232 ± 20	274 ± 22	551 ± 75
Dissolved solids (mg l^{-1})	32 ± 7	191 ± 10	42 ± 14	85 ± 22
Suspended solids (mg l^{-1})	15 ± 18	41 ± 21	232 ± 17	467 ± 78
Filterable PO_4^- (μg l^{-1})	8 ± 6	103 ± 130	172 ± 30	60 ± 30
Total PO_4^- (μg l^{-1})	30 ± 10	252 ± 60	1200 ± 100	1190 ± 180
Ammonia (μg l^{-1})	40 ± 40	95 ± 40	180 ± 20	340 ± 100
Nitrate (μg l^{-1})	290 ± 130	59 ± 40	190 ± 40	370 ± 70
Sediment				
Temperature (°C)	20.1 ± 0.9	20.2 ± 0.6	19.9 ± 0.7	19.3 ± 0.7
pH (s.u.)	7.5 ± 0.6	7.0 ± 0.2	7.3 ± 0.3	7.0 ± 1.4
Dissolved oxygen (mg l^{-1})	8.5 ± 1.0	8.7 ± 0.2	7.9 ± 1.2	7.2 ± 1.4
Conductivity (μmhos cm^{-1})	606 ± 126	400 ± 41	324 ± 47	403 ± 39
Hardness (mg l^{-1} as $CaCO_3$)	151 ± 17	114 ± 9	83 ± 23	105 ± 23
Alkalinity (mg l^{-1} as $CaCO_3$)	86 ± 11	54 ± 17	43 ± 28	46 ± 17

3. Results and discussion

3.1. Pesticide concentrations

Pesticide analysis revealed variation in surface water samples among sites within the three lakes (Table 2) as well as differences between lakes. Of the 17 pesticides and metabolites examined, a maximum of 10 were detected in Deep Hollow Lake, 11 in Beasley Lake, and all 17 in Thighman Lake. The historic-use organochlorine pesticide, DDT (dichloro diphenyl trichloroethane) and its metabolites DDE (dichloro diphenyl dichloroethylene) and DDD (dichloro diphenyl dichloroethane) were observed at all sites in all three oxbow lakes (Table 2). Surface water concentrations of DDT and metabolites observed in this study are comparable with another intensively studied Mississippi Delta oxbow lake, Moon Lake, conducted from 1982 to 1985 (Cooper, 1991a). These results provide additional confirmation that organochlorine pesticides are persistent (Willis and McDowell, 1982) and support the claim by Cooper (1991a) that watershed soils and sediments will continue to release these contaminants into the 21st century. Although Thighman had the greatest number of detected current-use pesticides, both Deep Hollow and Beasley had greater concentrations of certain triazine herbicides, cyanazine [2-(4-chloro-6-ethylamino-1,3,5-triazin-2-ylamino)-2-methylpropionitrile] and atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine), respectively, as well as the organophosphate insecticide methyl parathion (*O*,*O*-dimethyl-*O*-*p*-nitrophenyl phos- phorothioate) and pyrrole insecticide chlorfenapyr [4-bromo-2-(4-chlorophenyl)-1-(ethoxymethyl)-5-(triflouromethyl)-1H- pyrrole-3-carbonitrile]. Cooper (1991b) observed similar patterns in surface water concentrations of methyl parathion in Moon Lake, Mississippi, an intensively cultivated Mississippi Delta oxbow lake watershed.

The insecticide chlorphenapyr, applied under a 1995 Section 18 permit, was briefly used on cotton in the Mississippi Delta. In 1999, the USEPA concluded that chlorphenapyr posed too great a risk for continued application. Chlorfenapyr was detected at all sites in Deep Hollow and Beasley Lakes as well as two of three sites at Thighman Lake (Table 2).

Mississippi Delta sediments were characterized as predominantly loam to sandy-loam with typically less than 10% clay. Total organic carbon ranged from 0.99% to 2.04% but was primarily between 1.5% and 2% (Table 3). Sediments from at least one site in both Deep Hollow and Beasley lakes contained detectable amounts of all 17 analytes, whereas only 15 analytes were detected at all three sites in Thighman (Table 3). For sediment, as with the

Table 2
Pesticide, metabolite (M), and limit of detection (LOD) concentrations ($\mu g\ l^{-1}$) in three Mississippi Delta oxbow lake aqueous samples

Pesticide	LOD	Deep Hollow Lake			Beasley Lake			Thighman Lake		
		1	2	3	1	2	3	1	2	3
Alachlor	5.00×10^{-4}	BD	BD	BD	BD	BD	BD	0.008	0.008	0.004
Metolachlor	0.001	BD	BD	BD	0.027	0.037	0.091	0.122	0.175	0.066
Pendimethalin	5.00×10^{-4}	BD	BD	BD	BD	BD	BD	0.003	0.003	0.002
Trifluralin	0.001	BD	BD	BD	0.003	0.002	0.002	0.002	0.004	0.001
Atrazine	0.001	BD	BD	BD	0.187	BD	BD	0.081	0.108	0.033
Cyanazine	5.00×10^{-4}	1.72	1.34	1.64	BD	BD	0.018	0.012	0.023	0.003
*pp′*DDT	0.001	0.045	0.052	0.058	0.056	0.061	0.085	0.073	0.038	0.023
*pp′*DDD (M)	1.00×10^{-4}	0.006	0.005	0.011	0.021	0.023	0.032	0.017	0.013	0.007
*pp′*DDE (M)	1.00×10^{-4}	0.006	0.004	0.005	0.006	0.007	0.009	0.002	0.003	0.001
Dieldrin	1.00×10^{-4}	BD	BD	BD	BD	BD	BD	0.002	0.002	0.001
Chlorpyrifos	1.00×10^{-4}	BD	BD	BD	BD	BD	BD	0.001	0.003	0.001
Methyl parathion	0.001	0.091	0.088	0.088	0.106	0.105	BD	0.033	0.081	0.033
Fipronil	1.00×10^{-4}	0.008	BD	0.007	0.009	0.010	0.011	0.007	BD	BD
Fipronil sulfone (M)	1.00×10^{-4}	0.012	BD	0.011	0.010	BD	0.011	0.002	0.003	0.002
λ-cyhalothrin	1.00×10^{-4}	0.010	0.009	0.011	0.008	0.007	0.007	0.013	0.007	0.003
Bifenthrin	1.00×10^{-4}	0.002	0.002	0.011	BD	BD	BD	0.095	0.028	0.008
Chlorfenapyr	5.00×10^{-4}	0.026	0.022	0.024	0.007	0.008	0.009	BD	0.004	0.002

BD = below detection limit.

Table 3
Sediment characteristics, and pesticide, metabolite (M) and limit of detection (LOD) concentrations ($\mu g\ kg^{-1}$ as dry weight) in three Mississippi Delta oxbow lake sediment samples

Character/pesticide	LOD	Deep Hollow Lake			Beasley Lake			Thighman Lake		
		1	2	3	1	2	3	1	2	3
Silt (%)	N/A	82.2	95.4	92.0	90.2	85.0	67.8	83.4	93.2	91.0
Clay (%)	N/A	4.00	4.30	8.00	9.80	15.0	2.80	4.80	6.80	8.50
TOC (%)	N/A	1.32	1.79	1.67	1.95	1.87	0.990	1.93	2.04	1.81
Alachlor	5.00×10^{-4}	2.12	1.06	1.25	1.21	1.29	1.27	1.81	2.95	1.58
Metolachlor	0.001	10.6	9.09	8.73	3.54	6.32	4.01	8.45	5.76	2.47
Pendimethalin	5.00×10^{-4}	BD	3.15	3.47	4.89	1.90	10.7	2.11	2.14	2.46
Trifluralin	0.001	1.07	0.561	1.88	0.592	0.386	1.07	BD	BD	BD
Atrazine	0.001	BD	27.4	1.31	22.5	BD	BD	20.2	6.66	11.7
Cyanazine	5.00×10^{-4}	2.35	3.59	1.83	2.75	1.35	2.91	2.47	2.49	1.24
*pp′*DDT	0.001	7.43	18.1	14.2	17.0	9.44	11.1	15.4	7.39	13.5
*pp′*DDD (M)	1.00×10^{-4}	4.25	14.0	23.1	26.3	6.72	21.9	5.19	3.66	5.48
*pp′*DDE (M)	1.00×10^{-4}	3.65	9.73	83.4	31.5	78.0	8.33	5.51	2.56	2.33
Dieldrin	1.00×10^{-4}	1.20	2.46	2.65	2.26	BD	2.76	1.57	1.26	1.60
Chlorpyrifos	1.00×10^{-4}	0.858	1.05	0.842	0.700	0.918	2.45	0.593	BD	1.36
Methyl parathion	0.001	26.3	29.7	26.9	33.0	26.0	36.5	24.9	26.0	25.7
Fipronil	1.00×10^{-4}	2.41	3.06	3.88	3.56	2.57	3.96	2.28	2.57	2.26
Fipronil sulfone (M)	1.00×10^{-4}	BD	1.53	1.96	1.89	1.37	1.73	BD	BD	BD
λ-cyhalothrin	1.00×10^{-4}	1.58	1.87	2.07	3.19	BD	1.82	2.03	3.26	1.58
Bifenthrin	1.00×10^{-4}	0.123	3.26	2.50	1.80	0.349	2.16	1.68	0.565	0.76
Chlorfenapyr	5.00×10^{-4}	1.39	1.52	1.58	1.65	1.43	2.03	1.57	1.52	1.38

BD = below detection limit.

surface water phase, DDT and its metabolites DDE and DDD were detected at all sites in all three oxbow lakes (Table 3). Previous studies of sediment contamination with DDT (and metabolites) in Mississippi Delta oxbow lakes were comparable to this study (Cooper, 1991a; Moore et al., 2004). However, Cooper's (1991a) study of Moon Lake conducted from 1982 to 1985 had more than twice the concentration of DDT (and metabolites) in lake sediments (mean 235 $\mu g\ kg^{-1}$) than the present study (mean 50 $\mu g\ kg^{-1}$), alluding to a slow but measurable decrease in sediment organochlorine pesticide levels in the region. Current-use pesticide levels in sediments were greatest for methyl parathion at all sites in all lakes examined (Table 3). Cooper (1991b) noted only sporadic detection of methyl parathion in sediments of Moon Lake and Moore et al. (2004) observed concentrations in two of three Mississippi Delta lakes examined that were approximately 10 times less than those of the present study. The primary reason for greater detections of methyl parathion in this study is more intensive land cultivation surrounding the three study lakes with concomitantly greater amounts of pesticide in runoff from adjacent agricultural fields.

3.2. Bioassays

Hyalella azteca survival was unaffected by exposure to either water or sediment from any of the three Mississippi Delta oxbow lakes examined (Table 4). In addition, no growth impairment was observed from exposure to sediments from any of the three lakes, rather enhanced growth (as length) occurred in at least one site in each lake (Table 4). Differences in effects between sediment and surface water exposures were evident at the sub-lethal level, measured as growth. Growth, as length, was significantly impaired in animals exposed to water from Deep Hollow Lake (sites 1, 2) and Beasley Lake (site 1) but not Thighman Lake (Table 4). Linear regression analysis showed significant relationships between animal growth (length) and cyanazine ($R^2 = 0.41$, $P = 0.025$), methyl parathion ($R^2 = 0.45$, $P = 0.017$), λ-cyhalothrin ($R^2 = 0.43$, $P = 0.021$), chlorfenapyr ($R^2 = 0.45$, $P = 0.017$), and *pp′*DDE ($R^2 = 0.44$, $P = 0.019$) surface water concentrations in Deep Hollow Lake (Fig. 1). Significant relationships were also observed between growth (length) and trifluralin ($R^2 = 0.51$, $P = 0.009$), atrazine ($R^2 = 0.84$, $P < 0.001$), and methyl parathion ($R^2 = 0.40$, $P = 0.028$) surface water concentrations in Beasley Lake (Fig. 2). No significant relationships were observed between growth (length) and surface water pesticide concentrations in Thighman Lake.

Table 4
Mean ± SD survival and growth (as length and dry weight) of *Hyalella azteca* exposed to three Mississippi Delta oxbow lake water and sediments

Lake	Site	Survival (%)	Length (mm)	Dry weight (mg)
Water				
Deep Hollow	Control	100 ± 0	2.36 ± 0.35	0.02 ± 0.00
	1	80 ± 10	2.05 ± 0.35[a]	0.01 ± 0.00
	2	90 ± 10	2.09 ± 0.28[a]	0.02 ± 0.00
	3	93 ± 6	2.22 ± 0.41	0.01 ± 0.01
Beasley	Control	100 ± 0	3.21 ± 0.19	0.03 ± 0.01
	1	93 ± 6	2.54 ± 0.15[a]	0.02 ± 0.01
	2	97 ± 6	3.09 ± 0.09	0.04 ± 0.01
	3	100 ± 0	3.13 ± 0.01	0.02 ± 0.01
Thighman	Control	97 ± 6	2.79 ± 0.36	0.02 ± 0.00
	1	97 ± 6	2.73 ± 0.03	0.02 ± 0.00
	2	90 ± 10	2.91 ± 0.03	0.02 ± 0.01
	3	100 ± 0	2.92 ± 0.23	0.02 ± 0.01
Sediment				
Deep Hollow	Control	100 ± 0	2.46 ± 0.16	0.02 ± 0.01
	1	93 ± 6	2.93 ± 0.12[a]	0.02 ± 0.01
	2	100 ± 0	3.08 ± 0.18[a]	0.03 ± 0.00
	3	100 ± 0	2.85 ± 0.18[a]	0.02 ± 0.01
Beasley	Control	93 ± 6	2.63 ± 0.11	0.03 ± 0.01
	1	93 ± 6	3.06 ± 0.16[a]	0.03 ± 0.01
	2	83 ± 12	2.71 ± 0.27	0.03 ± 0.01
	3	93 ± 6	2.52 ± 0.11	0.02 ± 0.00
Thighman	Control	100 ± 0	2.50 ± 0.13	0.03 ± 0.00
	1	90 ± 0	3.02 ± 0.10[a]	0.03 ± 0.01
	2	97 ± 6	2.76 ± 0.08	0.02 ± 0.01
	3	93 ± 6	2.60 ± 0.17	0.02 ± 0.01

[a] Statistically significant versus control ($P < 0.05$).

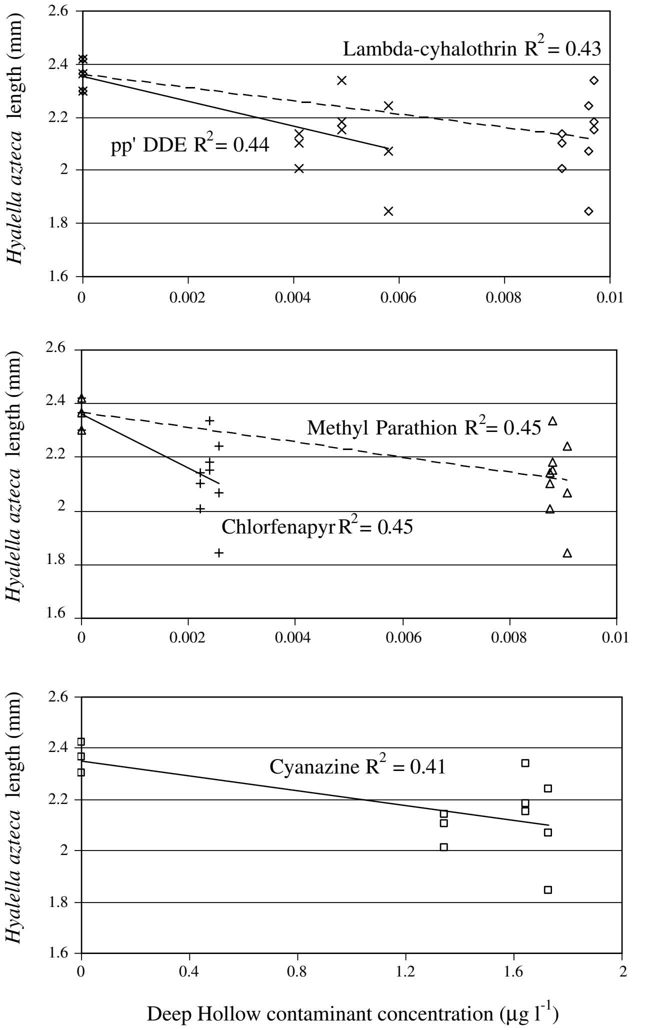

Fig. 1. Relationships between *Hyalella azteca* growth (as length in mm) and Deep Hollow Lake aqueous contaminant concentrations.

Water from all three lakes had some level of pesticide contamination. While Deep Hollow Lake had the least number of pesticides present and Thighman Lake the greatest, total pesticide concentration was greatest in Deep Hollow Lake primarily due to much greater concentrations of one pesticide, cyanazine. Individually, surface water herbicide concentrations were well below published effects concentrations (Giddings and Lenwood, 1998; Solomon and Chappel, 1998; Steen et al., 1999) and nearly all insecticide concentrations were also below published effects concentrations (Lotufo et al., 2000; Solomon et al., 2001). However, in all three sites where *H. azteca* growth was impaired, both triazine herbicides and organophosphate insecticides were present. Several studies attributed detrimental synergistic effects on aquatic invertebrates, including *H. azteca* (Pape-Lindstrom and Lydy,

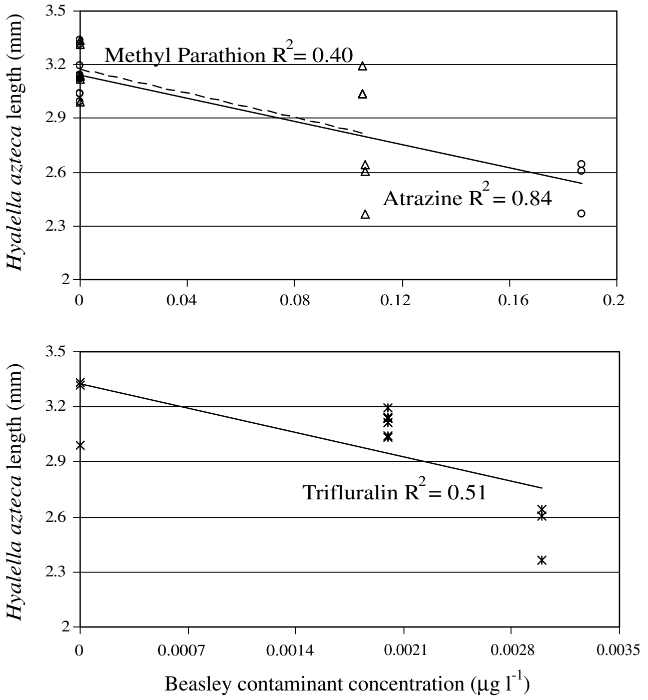

Fig. 2. Relationships between *Hyalella azteca* growth (as length in mm) and Beasley Lake aqueous contaminant concentrations.

1997; Belden and Lydy, 2000; Anderson and Lydy, 2002; Jin-Clark et al., 2002) to mixtures of these two pesticide classes and in this study significant relationships were observed between growth and concentrations of pesticides from both classes. Anderson and Lydy (2002) observed significant mortality in *H. azteca* after 96 h exposure to methyl parathion/atrazine mixture under laboratory conditions with concentrations approximately 10-fold greater than those observed in this study. While Thighman Lake also had detectable amounts of both pesticide classes, concentrations apparently were not great enough to affect growth.

Pesticide contamination in lake sediments was similar for all three oxbow lakes. Moore et al. (2004) observed lesser levels of pesticide contamination in sediments from other oxbow lakes within the same region as the current study. Differences can be attributed to more intensive agricultural land-use surrounding lakes in the current study than those examined by Moore et al. (2004). Despite the greater contamination in oxbow lake sediments noted in this study, the similarity in survival and growth responses observed in *H. azteca* exposed to contaminated sediment from other oxbow lakes in the same region (Moore et al., 2004) suggests pesticides at these reported concentrations are not bioavailable. Sediment texture can influence the availability of certain pesticides that often strongly bind to materials such as clay and organic matter (Weber and Weed, 1974; Ankley et al., 1994; Kruger et al., 1996). Mississippi Delta soils and associated oxbow lake sediments are typically comprised of loam and silty-clay with 1–2% organic carbon content (Snipes et al., 2004). More specifically, Beasley Lake had mean soil properties of 1.65% organic carbon, 30% clay, and 16% sand (Gaston et al., 2001). Deep Hollow Lake soil properties ranged from 0.7% to 1.5% for organic carbon and 10% to 34% clay (Staddon et al., 2004). Despite conditions conducive to significant pesticide transport via suspended sediment into Mississippi Delta oxbow lakes (e.g., long growing season, frequent pesticide use, rainfall amounts exceeding 120 mm annually, and farming practices), soil and concomitant sediment properties in and around Mississippi Delta water bodies limit the bioavailability of some pesticides and mitigating pesticide mixture effects.

4. Conclusions

Both surface water and sediment phases of the three lakes examined had greater levels of current-use pesticide contamination than other previously studied Mississippi Delta oxbow lake watersheds due to more intensive cultivation and the concomitantly greater amounts of pesticide runoff from adjacent agricultural fields. Historic-use organochlorine pesticide concentrations within the surface water phase were comparable to levels observed in the region 15 years previously, however, sediment phase levels were less than half those observed 15 years ago indicating a slow but measurable decrease in sediment organochlorine pesticide levels for the area.

Based upon responses of *H. azteca* to both sediment and surface water phases, the source of continued impairment in Deep Hollow and Beasley Lakes was from water contaminated with a complex mixture of herbicides, insecticides and metabolites most likely due to runoff from adjacent agricultural fields. Data from previous studies and relationships observed among the selected pesticides and organism responses implicate the combination of triazine herbicides and organophosphate pesticides as the primary source of impairment. The lack of observed impairment in the test organisms exposed to lake sediment suggests pesticides at these reported concentrations are not bioavailable due, in part, to sediment characteristics.

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