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Effectiveness of a Constructed Wetland for Retention of Nonpoint-Source Pesticide Pollution in the Lourens River Catchment, South Africa

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Constructed wetlands have been widely used to control both point- and nonpoint-source pollution in surface waters. However, our knowledge about their effectiveness in retaining agricultural pesticide pollution is limited. A 0.44-ha vegetated wetland built along a tributary of the Lourens River, Western Cape, South Africa, was studied to ascertain retention of runoff-related agricultural pollution. Total suspended solids, orthophosphate, and nitrate were retained in the wetland in the proportions 15, 54, and 70%, respectively, during dry weather conditions (with rainfall less than 2 mm/d) and 78, 75, and 84% during wet conditions (with rainfall between 2 and 35 mm/d). Retention of water-diluted azinphos-methyl introduced via runoff at a level of 0.85 μg/L was between 77 and 93%. Chlorpyrifos and endosulfan were measured during runoff in inlet water at 0.02 and 0.2 μg/L, respectively. However, both pesticides were undetectable in the outlet water samples. During a period of 5 months, an increased concentration of various insecticides was detected in the suspended particles at the wetland inlet: azinphos-methyl, 43 μg/kg; chlorpyrifos, 31 μg/kg; and prothiofos, 6 μg/kg. No organophosphorus pesticides were found in the outlet suspended-particle samples, highlighting the retention capability of the wetland. A toxicological evaluation employing a *Chironomus* bioassay in situ at the wetland inlet and outlet revealed an 89% reduction in toxicity below the wetland during runoff.

Introduction

During the last three decades, the multiple functions and value of vegetated ponds or wetlands have been widely recognized (*1*). Among their ecological importance as ecotones between land and water (*2*) and as habitats with great diversity and heterogeneity (*3*), specifically constructed wetlands are used extensively for water quality improvement. Initially wetlands were employed mainly to treat point-source wastewater (*4*), followed later by an increased emphasis on nonpoint-source urban (*5*) and agricultural runoff (*6*).

While the fate and retention of nutrients and sediments in wetlands are understood quite well, the same cannot be claimed for agrochemicals (*7*). Only very few studies refer to the potential of wetlands for removal of herbicides and some other organic chemicals (*8*−*10*). Since wetlands have a high ability to retain and process material, it seemed reasonable that constructed wetlands, acting as buffer strips between agricultural areas and receiving surface waters, could mitigate the impact of pesticides in this runoff. The effectiveness of wetlands for reduction of hydrophobic chemicals, e.g., most insecticides, should be as high as for suspended particles and phosphorus since these chemicals enter aquatic ecosystems mainly in particle-associated form following surface runoff (*11*, *12*).

Along with improvement of the chemical water quality, wetlands may considerably improve the ecological situation by reducing concentrations and loads of pesticides. Such effects can be studied either under experimental conditions using mesocosms (*13*) or in the field employing organisms in situ (*14*). There is now a need to link measurements of a wetland's toxicant retention effectiveness with studies on nonpoint-source pesticide contamination and its biological impact. The following study was undertaken for this purpose.

During recent decades, a decrease in water quality in Western Cape rivers has been observed. This shift has also occurred in the middle and lower reaches of the Lourens River and is attributed to intensified agriculture, sediment input, and loss of indigenous vegetation (*15*). However, no information exists about the extent to which toxic substances from the orchard plots in the surroundings are responsible for the degradation of the Lourens River.

To minimize the input of sediment into the Lourens River, a vegetated siltation pond was constructed in 1991 along one of the tributaries. The aim of the present study is to assess the effectiveness of this constructed wetland for control of sediments, nutrients, and pesticides originating from rainfall-induced edge-of-field runoff. Results were compared for typical dry and wet weather conditions. Toxicological effects of the wetland were addressed by means of an in situ exposure bioassay.

Materials and Methods

Study Region and Climate Conditions. The Lourens River originates at an altitude of 1080 m in a naturally sclerophyllous vegetation area (fynbos) and flows in a southwesterly direction for approximately 20 km before discharging into False Bay at Strand (34°06′ S, 18°48′ E). The catchment region is characterized by intensive farming, with orchards and vineyards in its middle reaches. The Lourens River has a total catchment area of approximately 92 km^2 and receives an annual mean rainfall of 915 mm. Approximately 87% of its 35×10^6 m^3 mean annual discharge occurs during the winter months between April and October (*15*), as is characteristic of the region's Mediterranean climate. The main soil type is silty loam.

The 400-ha orchard area consists mainly of pears, plums, and apples. The pesticide application period in the study area's orchards proceeds from early August and continues until the end of March. Organophosphorus (OP) insecticides, such as azinphos-methyl and chlorpyrifos, are applied between October and February quite frequently to pears and plums. Endosulfan is applied mainly in apple orchards.

The constructed wetland studied in the present investigation is located along one of the tributaries shortly before its entry into the Lourens River. This tributary has an average width and depth of 0.89 m × 0.30 m and a current velocity

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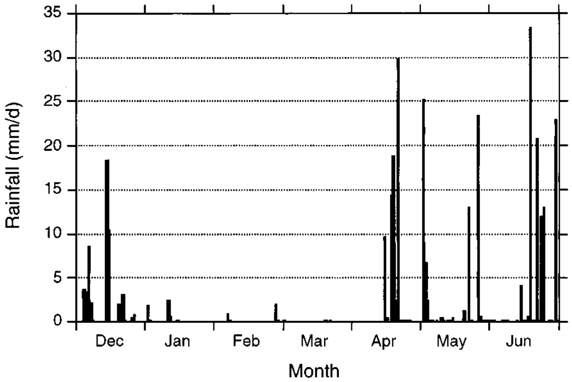

FIGURE 1. Rainfall during the study period. Pesticide application was carried out until the end of January in orchards situated in the catchment area of the constructed wetland. Rainfall in the middle of December resulted in a major runoff event within the pesticide application period.

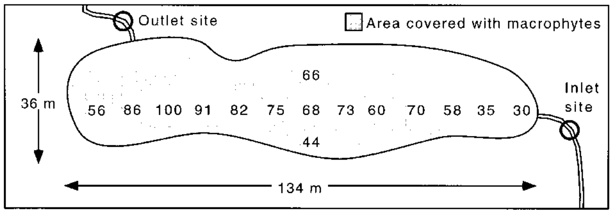

FIGURE 2. Schematic view of the wetland showing size, vegetation coverage, and sampling sites. The numbers indicate the water depths (cm) along a longitudinal and vertical transect.

of approximately 0.1 m/s. It has a total length of approximately 1.8 km and flows from a dam through a forest area for 800 m and then into pasture land for 400 m before flowing through the orchard area for a further 600 m. Average discharge in the tributary is 0.03 m^3/s in January and 0.32 m^3/s in July.

The study period lasted from December 1998 to June 1999. A heavy rainfall event resulting in edge-of-field runoff during the pesticide application period occurred on December 14, 1998 (Figure 1). The period between January and the middle of April was characterized by low rainfall (dry period), while the following months were characterized by high rainfall (wet period).

Description of the Wetland. The wetland was built in 1991 along one of the Lourens River tributaries, specifically being constructed to prevent nonpoint-source pollution with suspended particles from entering into the Lourens River. It is situated 15 m before the tributary discharges into the Lourens River (see Figure 2). The inlet and outlet of the tributary are formed by concrete tubes with a diameter of 0.7 and 0.6 m. The catchment area of the wetland comprises approximately 15 ha of orchard, 10 ha of pasture land, and 18 ha of forest. The tributary flows in a longitudinal direction through the wetland. The wetland has a length of 134 m and a width of 36 m, giving a total area of 0.44 ha. The present water depth varies between 0.3 and 1 m, which is much lower than the initial depth of approximately 1.5 m at time of construction, indicating the extent of particle sedimentation within the wetland. The first 30 m of the wetland is free of vegetation, and the remaining area is covered mainly with *Typha capensis* Rohrb (60% coverage), *Juncus kraussii* Hochst (10% coverage), and *Cyperus dives* Delile (5% coverage).

Sampling Procedure and Analysis. Two main sampling stations were used: inlet sampling was carried out in the tributary approximately 5 m before its entry into the wetland, while outlet sampling took place in the tributary approximately 7 m below the wetland. Standard sampling procedure included measurement of discharge, several physicochemical water quality parameters, and collection of water and suspended sediment samples for pesticide analysis. Discharge was calculated, on the basis of standard formulas, from velocity measurements along cross-sectional profiles. Total suspended solids were measured using a turbidity meter (Dr. Lange, Duesseldorf, Germany). Turbidity readings were calibrated as described by Gippel (*16*). Temperature and pH were measured with portable electronic meters (WTW, Weilheim, Germany). Orthophosphate and nitrate levels were measured with photometric test kits from Merck, Ingelheim, Germany. Discharge and physicochemical parameters were measured during varying flow conditions between December 1998 and June 1999 in order to describe a dry ($n = 21$ days) and a wet ($n = 17$ days) period.

Samples of water for pesticide analysis were collected at the inlet and outlet site in 3-L glass jars at 1-h intervals during the rainfall event on December 14, 1998. Water samples (500−900 mL) were solid-phase extracted (SPE) within 10 h after sampling, using C18 columns (Chromabond). The columns were air-dried for 30 min and kept at −18 °C until analysis (*17*).

Suspended sediments were obtained from continuously operating suspended-particle samplers (*18*) installed in the stream bottom. Suspended-particle samplers were emptied approximately every 2 weeks between December 14, 1998, and May 17, 1999, and were analyzed for pesticide content. On December 14, 1998, the suspended-particle samplers were installed before the rainfall event.

Analysis was performed by the Forensic Chemistry Laboratory of the Department of National Health, Cape Town. Pesticides from suspended sediment samples were extracted with methanol and concentrated using C18 columns. Measurements were done using gas chromatographs (HP 5890) fitted with standard HP electron-capture, nitrogen−phosphorus, and flame-photometric detectors (*17*). Concentrations for sediments were expressed as micrograms per kilogram dry weight (dry wt). The following detection limits were obtained for water and suspended sediments: 0.01 μg/L and 0.1 μg/kg dry wt. Spiked recovery efficiencies were between 79 and 106%.

In Situ Exposure Bioassays. Midges (*Chironomus* sp.) were used as a test organism. Animals were obtained from a clean water pond at Somerset West Water Treatment Plant. The organisms were collected 1 h before the exposure started. At each site, four replicate exposure beakers containing 20 fourth instar larvae were placed in the stream. Mortality was measured after a 24-h exposure period. Two trials were performed: one during a day without any rainfall beginning at 10 a.m., December 12, and one during the rainfall-related runoff event (from 10 a.m. December 14 to 10 a.m. December 15). Another set of four exposure beakers was employed during the second trial at a site in the tributary flowing through the wetland approximately 300 m upstream of the orchard area to serve as a control without pesticide contamination but with increased TSS levels. The in situ exposure methodology is outlined in detail in Schulz and Liess (*14*).

Results and Discussion

Sediment and Nutrient Retention. Results obtained for measurements of discharge and physicochemical water quality parameters were separated into two groups according to the discharge (Table 1). Dry period values refer to days with less than 2 mm rainfall and discharge less than 0.05 m^3/s, while wet period values describe situations with 2−35 mm/d of rainfall and a discharge of more than 0.05 m^3/s. TSS levels increased during the wet period by a factor of approximately 5, while orthophosphate and nitrate levels were twice as high during the wet period. TSS, orthophosphate, and nitrate levels were reduced by the wetland by 15,

TABLE 1. Discharge and Physicochemical Water Quality Parameters of Water at Inlet and Outlet of Wetland during Low and High[a] Discharge Typical of Dry[b] and Wet[c] Weather

	dry period ($n = 21$)		wet period ($n = 17$)	
	inlet	outlet	inlet	outlet
discharge (m^3/s)	0.027 ± 0.002	0.025 ± 0.002	0.175 ± 0.03	0.166 ± 0.03
TSS (mg/L)	21.7 ± 0.8	18.4 ± 0.6	105 ± 14	23.0 ± 1.9
temp (°C)	21.3 ± 0.6	21.1 ± 0.7	15.7 ± 0.5	16.1 ± 0.4
pH	6.8 ± 0.001	6.7 ± 0.001	7.2 ± 0.1	6.7 ± 0.001
orthophosphate (mg/L)	0.46 ± 0.07	0.21 ± 0.02	0.88 ± 0.15	0.22 ± 0.02
nitrate (mg/L)	0.83 ± 0.12	0.25 ± 0.06	1.84 ± 0.37	0.3 ± 0.03

[a] >0.05 m^3/S. [b] Rainfall <2 mm/d. [c] Rainfall between 2 and 35 mm/d.

54, and 70%, respectively, during the dry period. Retention levels during the wet period were much higher, averaging 78, 75, and 84%, respectively. Despite the higher inlet concentrations during the wet period, absolute values for all three parameters at the outlet station remained constant during the dry and wet period, indicating the effectiveness of the wetland. The temperature difference between inlet and outlet was less than 0.5 °C. The inlet-sample pH levels increased to 7.2 during the wet period. However, outlet readings remained constant at pH 6.7 during all flow conditions measured.

In a study by Cooper and Knight (*19*), a 78% trapping efficiency of a 1.1-ha detention reservoir during storms with inflow TSS concentrations of 800 mg/L or greater was reported. Kadlec and Hey (*9*) demonstrated that a 2.1-ha constructed wetland receiving constant volumes of nonpoint-source agricultural and urban pollution reduced TSS concentrations of 50 mg/L by 78% and those of 123 mg/L by 95%. The lower trapping efficiency observed in this study may be due to the small size of the wetland and the fact that the wetland is a flow-through pond without any water storage capacity. The water inflow rates vary over time between 0.016 and 0.522 m^3/s.

Similar nutrient retentions (72% and 82%) have been obtained in the 1.1-ha Morris Pond, MS, by Cooper and Knight (*20*) and in Des Plaines wetlands, IL, where total P reduction averaged 74% and nitrate reduction averaged 78% (*9*).

The overall effect of the wetland on the outlet water quality is very positive, with TSS levels as low as 23 mg/L and orthophosphate and nitrate concentrations of 0.2 and 0.3 mg/L, respectively. The initial purpose, keeping suspended solid input via the tributary from entering the Lourens River, is fulfilled by the wetland. The TSS and nutrient trapping efficiency is still quite high although the wetland has never been dug out during the 7-yr period since its construction. This indicates the sustainability of constructed wetland use as a strategy for the long-term improvement of water quality.

Pesticide Retention during a Runoff Event. A heavy rainfall event followed by edge-of-field runoff commenced at 3 p.m. on December 14, 1998, and continued until 8 a.m. on December 15, 1998. Total rainfall during this event was 28.8 mm/d, of which approximately 80% occurred in an initial period between 3 p.m. and 9 p.m. on December 14, 1998. The last rainfall before this date had been on December 7, 1998, with 2.2 mm/d, and the last heavy rainfall ≥10 mm/d occurred on December 5, 1998.

Discharge, TSS, and pesticide concentrations in water samples increased during the December 14, 1998, rainfall event (Figure 3). The increase in TSS was initially detected from 4:30 p.m. and was still detactable at 7:30 p.m. A maximum TSS value of 180 mg/L in the inlet was measured 2.5 h after the commencement of rainfall. All outlet levels measured remained constantly below 15 mg/L. Azinphos-methyl was detected in the inlet samples between 4:30 p.m. and 7:30 p.m. and attained a maximum of 0.85 µg/L at 6:30 p.m. Approximately 0.06 µg/L of azinphos-methyl was detected in the outlet between 5:30 p.m. and 7:30 p.m., giving a retention value between 77 and 93%. Chlorpyrifos and endosulfan (α, β, and S) reached maximum concentrations of 0.02 and 0.2 µg/L in the inlet samples. Both pesticides were undetectable in any of the outlet samples.

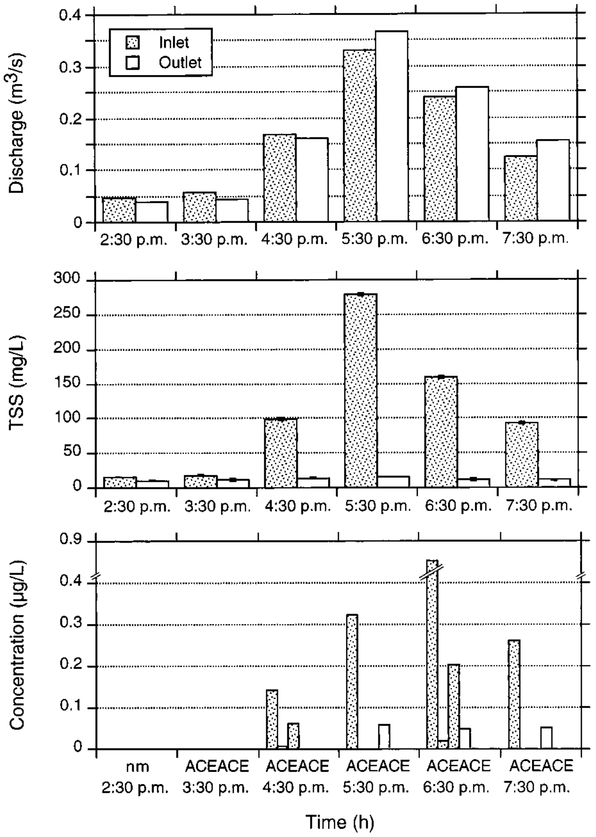

FIGURE 3. Discharge, total suspended solids (TSS) (± SE; $n = 3$) and concentration of azinphos-methyl (A), chlorpyrifos (C), and total endosulfan (E) in inlet and outlet water of the wetland during a rainfall event on December 14, 1998. Rainfall began at 3 p.m. and yielded a total of 18.4 mm on December 14, 1998. Zero values for pesticides denote that concentrations were below detection limit; nm = not measured; no analyses were performed on the 2:30 p.m. samples.

Kadlec and Hey (*9*) reported for atrazine a removal rate between 25 and 95% in the Des Plaines wetland cells. According to a study in 230-m flow-through wetland mesocosms (*13*), the reduction of atrazine concentration in water was 11−14%. There are almost no other studies in the open literature dealing with the retention of runoff-related insecticide input in constructed wetlands. However, the implementation of retention ponds in agricultural watersheds was examined by Scott et al. (*21*) as one strategy to reduce the amount and toxicity of runoff-related insecticide pollution discharging into estuaries. The usefulness of aquatic plants

TABLE 2. Concentrations (μg/kg) of Different OP Insecticides in Suspended Particles Continously Sampled above and below the Wetland[a]

	inlet			outlet[b]		
date	azinphos-methyl	chlorpyrifos	prothiofos	azinphos-methyl	chlorpyrifos	prothiofos
Dec 29, 1998	43.3	nd	6	nd	nd	nd
Jan 11, 1999	22.5	nd	3.2	nd	nd	nd
Jan 25, 1999	17.9	nd	2	nd	nd	nd
Feb 15, 1999	0.9	0.2	0.5	nd	nd	nd
Mar 1, 1999	1.2	0.6	0.7	nd	nd	nd
Mar 15, 1999	nd	0.2	0.5	nd	nd	nd
Mar 31, 1999	nd	nd	0.8	nd	nd	nd
April 19, 1999	nd	31.4	nd	nd	nd	nd
May 17, 1999	nd	23.9	nd	nd	nd	nd

[a] Dates refer to the end of each sampling interval. The first sampling interval began before the rainfall event on December 14, 1998. [b] Outlet sample from March 15, 1999, contained 2.1 μg/kg total endosulfan.

for removal of the insecticide mevinphos from water was described by Wolverton and Harrison (*8*).

Processes important for removal of nonpoint-source pesticide runoff in wetlands may include adsorption, decomposition, and microbial metabolism (*22*). The macrophytes present in the wetland may play an important role in providing an increased surface area for sorption as well as for microbial activity. Furthermore, they may contribute directly to chemical metabolism (*3*). The South African macrophyte species *T. capensis* and *J. kraussii* have already been employed for wastewater treatment (*23*). It was demonstrated that emergent vegetation reduces the resuspension of sediments in wetlands (*24*). However, it should be considered that the potential of wetlands to reduce toxicants can also lead to unwanted long-term accumulation of chemicals, as documented for natural wetland areas (*25*).

Pesticide Retention during Longer Time Periods. The concentrations of azinphos-methyl, chlorpyrifos, and prothiofos in suspended particles sampled over the 5-month period following the rainfall-induced runoff event in the middle of December are summarized in Table 2. Maximum daily rainfall between the middle of December and the end of March was 3 mm, illustrating that no further runoff had occurred during this period. The first rainfall event of the wet season was on April 15, 1999, followed by several days of heavy rainfall (Figure 1). Azinphos-methyl concentrations in the inlet samples declined from an initial concentration of 43.3 μg/kg to nondetectable levels within a 3-month period. Prothiofos was present in inlet samples even after a 3.5-month period at a level of 0.8 μg/kg, in comparison to an initial concentration of 6 μg/kg (Table 2). Chlorpyrifos occurred only at levels up to 0.6 μg/kg during February and March and was present with increased concentrations up to 31.4 μg/kg during April and May. None of the three OP insecticides was detectable in the outlet samples at any time. The outlet sample taken on March 15, 1999, contained 2.1 μg/kg of the organochlorine insecticide endosufan.

Although it had been assumed that wetlands have a high potential to reduce specifically sorbed chemical load (*26*), this fact had not yet been demonstrated for insecticide fate in constructed wetlands. It is likely that one major reason for the effectiveness in retaining particle-associated chemicals is the sedimentation of suspended particles, which occurs in the wetland areas due to reduced flow conditions. As discussed above, TSS were removed at a rate of 78% during wet weather conditions. The 100% retention detected for all of the three organophosphate pesticides indicates that the particles leaving the wetland may be entrained antecedent sediments. Dilution, decomposition, and microbial metabolism may also account for pesticide retention (*22*). The present study also indicated a concentration of 2.1 μg/kg total endosulfan in one suspended-particle sample taken in the outlet of the wetland. Endosulfan was not detected in the respective inlet samples, which means that resuspension processes within the wetland must be responsible for the output. The effectiveness of pesticide retention in wetlands may differ with season due to fluctuations in water temperature and flow as well as wetland abiotic and biotic conditions (*27*). There is still a need for further studies to demonstrate the long-term fate of insecticide runoff in constructed wetlands.

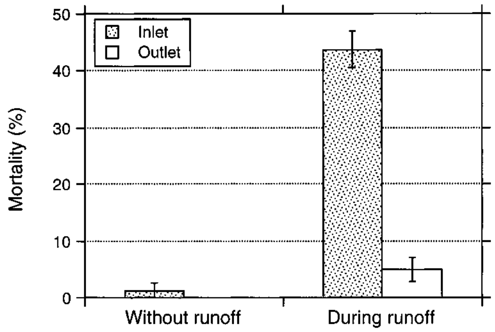

FIGURE 4. Mortality ($\pm$ SE; $n = 4$) of *Chironomus* sp. exposed for 24 h in both the inlet and the outlet of the wetland during a period without any edge-of-field runoff and during the runoff event on December 14, 1998.

Toxicological Evaluation. Mortality of midges exposed for 24 h in situ in the inlet and outlet of the wetland is illustrated in Figure 4. During periods without runoff (TSS, <19 mg/L), the average mortality was ≤1.25%. In the 24-h period beginning at 10 a.m. on December 14, 1998, the average mortality of exposed midges was 43.7% at the inlet station, in comparison to 5% at the outlet. Mortality at a control site in the same tributary upstream of the orchard area was 3.8 ± 1.3%. This site revealed no detectable pesticide contamination but had increased levels of TSS (maximum, 198.1 ± 0.8 mg/L).

It can therefore be deduced that the wetland performs an important role in reducing the toxicity of azinphos-methyl in the tributary water by 89% before it enters the Lourens River. Azinphos-methyl concentrations of 0.85 μg/L in the inlet water were higher than acute toxic concentrations for various species of crustaceans such as *Gammarus fasciatus* Say (*28*) and *Hyalella azteca* Saussure (*29*). They also exceeded the 96-h LC$_{50}$ of *Chironomus tentans* Fabricius, which is 0.37 μg/L (*29*). The 24-h LC$_{50}$ for the chironomid species used in the present study is 7.3 μg/L (R. Schulz, unpublished data).

Therefore it is not possible to explain the observed mortality of exposed midges based on the 24-h LC$_{50}$ and the azinphos-methyl concentrations measured in the field. Similar differences between toxicological reactions in the field and those predicted from laboratory toxicity tests at the same contaminant levels have been described as well by other authors. Matthiesen et al. (*30*) observed 100% mortality of caged *G. pulex* following a peak concentration of 27 μg/L carbofuran, which exceeded the 24-h LC_{50} of 21 μg/L only for a period of 3−5 h. Baughman et al. (*31*) expected differences between measured and real exposure concentrations to be a reason for higher mortalities in in situ bioassays than predicted from laboratory data.

Increased suspended-particle concentrations may cause mortality in bioassay exposure of aquatic invertebrates (*14*). However, the high survival rate at the upstream control site, which had a strongly increased TSS level, indicates that the exposed midges did not suffer from increased suspended sediment levels. Furthermore, *Chironomus* species usually live within the sediment and therefore should be able to cope with increased levels of sedimentation.

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