USE OF A CONSTRUCTED WETLAND TO REDUCE NONPOINT-SOURCE PESTICIDE CONTAMINATION OF THE LOURENS RIVER, SOUTH AFRICA

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Abstract—The Lourens River, Western Cape, South Africa, and its tributaries situated in an intensively cultivated orchard area receive pesticide contamination during rainfall-induced runoff and during spraydrift. A 0.44-ha constructed wetland, built in 1991 in one of the tributaries (summer flow 0.03 m^3 per second), was studied in order to assess its effectiveness in reducing nonpoint-source agricultural pesticide contamination. Even high levels of particle-associated azinphos-methyl (43 µg per kilogram), chlorpyrifos (31 µg per kilogram) and prothiofos (6 µg per kilogram) introduced via runoff were not detectable in the outlet suspended-particle samples. Recovery of water-diluted azinphos-methyl contamination at inlet concentrations of about 0.55 µg per liter during spraydrift indicated much less retention, approximately 51 percent. Comparison of *in situ* bioassays of bloodworms (*Chironomus* spec.) above and below the wetland revealed a reduction of contamination in terms of toxicity from 41 to 2.5 percent. TSS, ortho-phosphate, and nitrate were retained in the wetland with trapping efficiencies of 78, 75, and 84 percent, respectively.

INTRODUCTION

Agriculture is a source of sediment, nutrient, and pesticide input into surface waters (Cooper 1993). Rainfall-related runoff and spraydrift are two major sources for the agricultural nonpoint-source pollution of surface waters (Groenendijk and others 1994). The fact that nonpoint-source pollutants are recognized as the single greatest threat to surface waters (Loague and others 1998) has heightened concerns about sustainable agriculture and has highlighted the need for measures to minimize input and risk (Mainstone and Schofield 1996).

Constructed wetlands have been suggested and used as a potential risk-reduction strategy for nonpoint-source pollution (Hammer 1992, Mitsch 1992, Van der Valk and Jolly 1993). Whereas the fate and retention of nutrients and sediments in wetlands is understood quite well (Hammer 1992, Van der Valk and Jolly 1993), the same cannot be said of agrochemicals (Baker 1993). Only very few studies refer to the potential of wetlands for removal of herbicides and some other organic chemicals (Kadlec and Hey 1994, Lewis and others 1999, Wolverton 1987). Since wetlands have a high ability to retain and process material, it seems reasonable that constructed wetlands as buffer strips between agricultural areas and receiving surface waters could mitigate the impact of pesticides in this runoff (Rodgers and Dunn 1993).

During the last decades, a shift to lower 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 (Tharme and others 1997). No information is available on the extent to which toxic substances are responsible for the degradation of the Lourens River. In order to minimize the input of sediment into the Lourens River, a small flow-through constructed wetland was built in 1991 into one of the tributaries. Constructed wetlands have been used so far in South Africa mainly for wastewater treatment (Wood 1990).

The aim of the present study is to assess the effectiveness of a small constructed wetland for control of nonpoint-source pesticide input into the Lourens River. Retention is assessed for particle-associated pesticide input via runoff and for water-diluted pesticide input following drift during spray application. Sediment- and nutrient-trapping efficiencies are evaluated, and the effects of the wetland in terms of toxicity alteration are addressed using an *in situ* exposure bioassay.

MATERIALS AND METHODS

Study Region and Climate Conditions

The Lourens River rises at an altitude of 1080 m in the Hottentots Holland Nature Reserve and flows in a southwesterly direction for about 20 km before discharging into False Bay at Strand (34°06´ S., 18°48´ E.). The river is surrounded by intensive farming activities (orchards and vineyards) in its middle reaches after leaving a naturally vegetated fynbos area and before flowing through the town of Somerset West. The Lourens River has a total catchment area of approximately 92 km^2 and receives a mean annual rainfall of 915 mm.

The orchards mainly consist of pears, plums, and apples (total growing area: 4 km^2). The pesticide application period starts in the study area´s orchards in early August and ends at the end of January (pears) or end of March (apples). Organophosphorous (OP) insecticides like azinphos-methyl and chlorpyrifos are used between October and February quite frequently on pears and plums. Endosulfan is applied mainly to apple orchards.

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The constructed wetland studied in the present investigation is located in one of the tributaries shortly before its entry into the Lourens River. This tributary has an average width and depth of 0.89 m by 0.30 m and a current velocity of about 0.1 m per second. Average discharge in the tributary is 0.03 m^3 per second in January and 0.32 m^3 per second in July.

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

Separate studies revealed that the Lourens River receives contamination from the surrounding farming areas via rainfall-related runoff and via spraydrift during spray application. Runoff produced concentrations of particle-associated chemicals as high as 244 µg per kilogram azinphos-methyl, 69 µg per kilogram chlorpyrifos and 245 µg per kilogram total endosulfan. Spraydrift-related pesticide input elevated the levels of water-diluted pesticide in the Lourens River to about 0.04 µg per liter azinphos-methyl, with peak concentrations at about 1.7 µg per liter in those tributaries receiving spraydrift directly. Effectiveness of pesticide retention in the constructed wetland was studied for both scenarios—runoff and spraydrift.

Description of the Constructed Wetland

The constructed wetland was built in 1991 into one of the southeastern tributaries draining the surrounding farmland to prevent nonpoint-source pollution with suspended particles from entering the Lourens River. The catchment area of the wetland comprises about 15 ha of orchard, 10 ha of pasture land, and 18 ha of forest. The tributary flows longitudinally through the wetland, which has a length of 134 m and a maximum width of 36 m giving a total area of 0.44 ha. The actual water depth is between 0.3 and 1 m. The first 30 m of the wetland are free of vegetation, and the remaining area is covered mainly with *Typha capensis* Rohrb. (60 percent coverage), *Juncus kraussii* Hochst (10 percent coverage), and *Cyperus dives* Delile (5 percent coverage).

Sampling Program and Analysis

Two sampling stations were used: inlet sampling was done in the tributary about 5 m before its entry into the wetland; outlet sampling took place in the tributary about 7 m below the wetland. Standard sampling procedure included measurement of discharge, suspended particles, and nutrients as well as taking of water and suspended sediments for pesticide analysis. Discharge was calculated on the basis of standard formulas (Maniak 1992) using velocity measurements along cross-section profiles. Turbidity was measured with a turbidity meter (Dr. Lange) allowing measurements between 1 and 200 NTU. To calibrate the turbidity measurements as described by Gippel (1995), certain samples were filtered through preweighed Whatman GF/F (0.45 mm pore-size) glass microfibre filters and dried at 60 °C for 48 hours. The filter paper was then reweighed to determine total suspended solids (TSS). Ortho-phosphate and nitrate were measured with photometric test kits from Merck, Ingelheim. Discharge, TSS, and nutrients were measured during periods with high-flow conditions between December 1998 and June 1999 (n = 17 measurements).

Suspended sediments were taken to describe particle-associated pesticide contamination following runoff events. Time-integrating samples were obtained from continuously operating suspended particle samplers (Liess and others 1996) installed in the stream bottom. Suspended sediments were taken out about every 2 weeks between December 14, 1998, (10:00 h; before rainfall event) and May 17, 1999, and were analyzed for pesticides.

Samples of water for pesticide analysis were collected at the inlet and outlet site in 3-L glass jars during spray application on January 11, 28, and 29, 1999. A previous experiment with the introduction of a tracer (Rhodamin B) 200 m above the wetland (spraydrift deposition site) was undertaken on January 7 during the same hydrological conditions (discharge: 0.026 m^3 per second) to determine the starting point and duration of sampling intervals at the inlet and outlet station of the wetland used for the pesticide sampling. As a result, a 1-hour composite sampling starting 15 minutes after introduction of spraydrift (200 m above the wetland) was done at the inlet station, whereas 5-hour composite sampling was performed at the outlet station starting 4.5 hours after introduction of spraydrift. This sampling design has been found to enable an integrated sample of more than 85 percent of the pesticide load to be obtained at both stations. Water samples (500 to 900 ml) were solid-phase extracted (SPE) within 10 hours after sampling using C18 columns (Chromabond) that had been previously prepared with 6 ml methanol and then 6 ml water. The columns were air-dried for 30 minutes and kept at –18 °C until analyzed.

Analyses were performed at the Forensic Chemistry Laboratory of the Department of National Health, Cape Town. Pesticide residues were extracted from suspended sediment samples using methanol. Extracts were passed through a C18 column (Chromabond) and eluted with 2 ml hexane and then 2 ml dichloromethane. Measurements were done by means of gas chromatographs (HP 5890) with electron-capture, nitrogen-phosphorus, and flame-photometric detectors. Water samples were eluted from SPE columns and measured as well in a GC. The following detection limits were obtained for water and suspended sediments: 0.01 µg/l and 0.1 µg per kilogram dw.

Exposure Bioassays

Bloodworms (*Chironomus* spec.) were used as a test organism. Animals were obtained from a clean water pond at Somerset West water treatment plants. The organisms were collected 1 hour before the exposure started. At each site, four plastic beakers (9 cm in diameter by 13 cm in height) containing 20 4^{th}-instar larvae were installed in the stream. The front and rear walls of the beakers were made of netting (0.5 mm mesh) to allow water to flow through (current: 0.11±0.02 m per second). In each box, 5 g of mud provided material for constructing the larval tubes. Mortality was measured after a 24-hour exposure period. Two trials were performed, one during a day without any spray application from December 12, 10:00 hour, to December 13, 10:00 hour, and one during azinphos-methyl application resulting in spraydrift into the tributary (December 28, 10:00 hour, to December 29, 10:00 hour).

RESULTS

Sediments and Nutrients

Results obtained for inlet-outlet-measurements of suspended sediments and nutrients are summarized for high-discharge conditions in table 1. Trapping efficiency was calculated by dividing the concentration difference (inlet minus outlet) by the inlet concentration and expressing it as a percentage. TSS, ortho-phosphate, and nitrate levels were reduced by the constructed wetland by 78, 75, and 84 percent. Despite the high inlet concentrations, absolute values for all three parameters at the outlet station were quite low, indicating the effectiveness of the wetland.

Particle-Associated Pesticides

The concentrations of azinphos-methyl, chlorpyrifos, and prothiofos in suspended particles sampled at the inlet station during periods with rainfall-induced runoff events are summarized in table 2. Azinphos-methyl concentration in the inlet sample was 43.3 µg per kilogram during an interval with a high-rainfall event in December. During the same interval, prothiofos was present in the inlet sample at a level of 6 µg per kilogram. Chlorpyrifos occurred at a relatively low concentration of 0.6 µg per kilogram following a small rainfall event in February but at elevated concentrations up to 31.4 µg per kilogram during April and May rainfall events. None of the three OP insecticides were detectable in the outlet samples at any time, indicating a 100-percent retention of particle-associated pesticides that were introduced into the tributary via runoff.

Table 1—Mean (n = 17 measurements, ± SE) total suspended solids and nutrient concentrations of water at the inlet and outlet of the constructed wetland as well as trapping efficiency during high discharge conditions (0.175 ± 0.03 m³ per second) typical of rainfall conditions between 2 and 35 mm per day

	Inlet	Outlet	Trapping efficiency
	- - - - - - - - mg/L	*- - - - - - -*	*Percent*
TSS	105 ±14	23.0 ±1.9	78.1
Ortho-phosphate	.88 ± .15	.22 ± .02	75
Nitrate	1.84 ± .37	.3 ± .03	83.7

TSS = total suspended solids.

Water-Diluted Pesticides

The effectiveness of retention of water-diluted pesticide was estimated during spraydrift events following application of azinphos-methyl (table 3). Inlet concentrations varied during the three trials between 0.36 and 0.69 µg per liter in the 1-hour composite samples. Five-hour composite samples taken at the outlet contained levels between 0.02 and 0.03 µg per liter. Average concentrations detected in the composite samples and discharge (0.026 m^3 per second) were used to calculate chemical loads for both stations. Retention was calculated by dividing the load difference (inlet minus outlet) by the inlet load and expressing it as a percentage. Retention ranged between 44 and 60 percent and was, on average, 51 percent.

Exposure Bioassay

Mortality of bloodworms exposed for 24 hours *in situ* at the inlet and outlet of the constructed wetland is shown in table 4. During periods without spraying activity, the average mortality was = 1.25 percent. In the 24-hour period during spraydrift trial 1, the mortality at the inlet station was elevated considerably to 41.3 percent, whereas the mortality at the outlet station stayed low at 2.5 percent.

DISCUSSION

Sediment and Nutrient Trapping Efficiency

As expected, considerable reductions of sediment and nutrient loads were observed in the wetland. Retention of TSS was 78 percent during the wet period, when, on average, 105 mg per liter TSS entered the wetland. Cooper and Knight (1991) reported a 78-percent trapping efficiency of a 1.1-ha detention reservoir during storms with inflow TSS concentrations of 800 mg per liter or greater. A 2.1-ha

Table 2—Rainfall and concentrations of different OP insecticides associated with suspended particles that were continously sampled above the constructed wetland during intervals with rainfall-induced runoff events (none of the suspended particles sampled during the same intervals at the outlet station contained any detectable pesticide levels)

Rainfall characteristics		Suspended particles-sampling interval	Contamination of inlet station samples	
Date	Intensity		Substance	Concentration
	mm/d			*µg/kg*
12/14/98	18.4	12/14–12/29/98	Azinphos-methyl	43.3
02/26/99	2	02/15–03/01/99	Chlorpyrifos	.6
04/19/99	18.8	03/31–04/19/99	Chlorpyrifos	31.4
04/21/99	29.8	04/19–05/17/99	Chlorpyrifos	23.9
12/14/98	18.4	12/14–12/29/98	Prothiofos	6

Table 3—Concentration of azinphos-methyl in composite samples taken during spraydrift at the inlet and outlet of the constructed wetland. Inlet samples represent 1-hour composite samples, whereas outlet samples represent 5-hour composite samples (retention was calculated based on calculation of chemical load)

Event	Inlet	Outlet	Retention
	- - - - - - - *µg/L* - - - - - - -		*Percent*
1	0.69	0.07	49
2	.36	.04	44
3	.62	.05	60

Table 4—Mortality (± SE; n = 4) of *Chironomus* spec. exposed for 24 hours at the inlet and outlet of the constructed wetland during a period without any spraying activity and during an azinphos-methyl spraydrift event

	Inlet	Outlet
Without spraying (%)	1.25 ± 1.25	0
During spraydrift (%)	41.3 ± 2.4	2.5 ± 1.4

constructed wetland receiving constant volumes of nonpoint-source agricultural and urban pollution reduced suspended solids with inlet concentrations of 50 mg per liter by 78 percent and those of 123 mg per liter by 95 percent (Kadlec and Hey 1994). Lower trapping efficiency observed in the present study may be due to the small wetland size and the fact that the wetland is a flow-through wetland without any water storage capacity and with water inflow rates that vary over time between 0.016- and 0.522-m^3 per second.

Trapping efficiencies during wet conditions for ortho-phosphate (0.9 mg per liter) and for nitrate (1.8 mg per liter) were 75 and 84 percent. Similar results (72 percent and 82 percent) have been found in the 1.1-ha Morris Pond, MS (Cooper and Knight 1990) and in Des Plaines Wetlands, IL, where total P reduction averaged 74 percent and nitrate reduction 78 percent (Kadlec and Hey 1994).

The TSS and nutrient-trapping efficiency is still quite high, although the wetland has never been dug out during the 7-year period since it was built. This indicates the sustainability of constructed wetland use as a strategy for the long-term improvement of water quality.

Retention of Particle-Associated Pesticides: Runoff Scenario

The constructed wetland acted as a very effective sink for sediment-associated pesticides during the study period. Azinphos-methyl (43 µg per kilogram), chlorpyrifos (31 µg per kilogram), and prothiofos (6 µg per kilogram) detected in the suspended particles of the inlet water were never present in the outlet suspended particles. Although it was thought that wetlands have a high potential to reduce specifically sorbed chemical load (Rodgers and Dunn 1993), this fact had not previously been demonstrated for insecticide fate in small constructed wetlands. It is likely that one major reason for the effectiveness in retaining particle-associated chemicals is the sedimentation of suspended particles in the wetland areas with reduced-flow conditions. As discussed above, TSS were removed at a rate of 78 percent during wet weather conditions. However, the 100-percent retention detected for all of the three organophosphate pesticides cannot be explained just by sedimentation processes. Dilution, decomposition, and microbial metabolism may account for the remaining chemical retention (Rodgers and others 1999). The effectiveness of pesticide retention in wetlands may differ with season due to changes in water temperature and flow as well as wetland abiotic and biotic conditions (Spongberg and Martin-Hayden 1997). There is still a need for further studies to demonstrate the long-term fate of insecticide runoff in constructed wetlands.

Retention of Water-Diluted Pesticides: Spraydrift Scenario

Levels of azinphos-methyl during spraydrift were between 0.36 and 0.69 µg per liter in the inflow water, whereas maximal concentrations in the outflow were at about 0.07 µg per liter. It follows that the retention for this pesticide entering the wetland in the water phase was as high as 51 percent. There are no other studies dealing with the retention of water-diluted insecticide input in constructed wetlands. However, the implementation of retention ponds in agricultural watersheds was examined as one strategy to reduce the amount and toxicity of runoff-related insecticide pollution discharging into estuaries (Scott and others 1999). For atrazine, a removal rate between 25 and 95 percent was demonstrated in the Des Plaines Wetland cells (Kadlec and Hey 1994). Reduction of atrazine concentration in water was 11 to 14 percent in 230-m flow-through wetland mesocosms (Detenbeck and others 1996). Processes important for removal of nonpoint-source pesticide runoff in wetlands may include adsorption, decomposition, and microbial metabolism (Rodgers and others 1999). The macrophytes present in the wetland may play an important role in providing an enlarged surface area for sorption as well as microbial activity and due to chemical metabolism within the plants (Wetzel 1993).

Toxicological Evaluation

In situ exposure of bloodworms during spray deposition clearly indicated an increased 24-hour mortality at the inlet station in comparison to an only slightly elevated mortality at the outlet station. It follows that the constructed wetland makes an important contribution in that it reduces the toxicity of azinphos-methyl in the tributary water by 94 percent before it enters the Lourens River. That is, I attribute the observed reduction of toxicity to the wetland and conclude that it would be much lower if the tributary water were to flow over the same distance (230 m) via a conventional channel into the Lourens River. Azinphos-methyl concentrations measured in the inlet water were in the range of acutely toxic concentrations for various crustacean species including *Gammarus fasciatus* Say (Sanders 1972) and *Hyalella azteca* Saussure (Ankley and Collyard 1995). They exceeded the 96-hour LC_{50} of *Chironomus tentans* Fabricius, which is 0.37 µg per liter (Ankley and Collyard 1995). According to prevous experiments, the 24-hour LC_{50} for the chironomid species used in the present study is approx. 7.3 µg per liter.

On the basis of the 24-hour LC_{50} and the azinphos-methyl concentration measured in the field, it is not possible to explain the observed mortality of exposed bloodworms. Similar differences between toxicological reactions in the field and those predicted from laboratory toxicity tests at the same contaminant levels have been described by other authors as well. Matthiesen and others (1995) observed 100 percent mortality of caged *Gammarus pulex* L. following exposure to a peak concentration of 27 µg per liter carbofuran, which exceeded the 24 hour LC_{50} of 21 µg per liter only for a period of 3 to 5 hours. Baughman and others (1989) expected differences in measured and real exposure concentrations to be a reason for higher mortalities in *in situ* bioassays than predicted from laboratory data.

CONCLUSION

It was shown that the investigated wetland is capable of reducing the load and toxicity of nonpoint agricultural pesticide pollution. Keeping in mind the relative importance of runoff-related pesticide contamination associated with suspended particles, constructed wetlands can be regarded as a very effective tool for the reduction of nonpoint agricultural pesticide contamination in small streams.

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