Contributing Area and Concentration Effects on Herbicide Removal by Vegetative Buffer Strips

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Abstract
Deteriorated water quality due to nonpoint source pollution from herbicides is one of the environmental problems receiving attention this decade. One off-site best management practice (BMP) being suggested to improve water quality is vegetative buffer strips. This study was conducted on a Storden loam soil, under simulated rainfall (6.35 cm/h), to determine the effects of nominal inflow concentration (0.1 and 1.0 mg/L) and the ratio of drainage area to vegetated buffer strip area (simulated to be 15:1 and 30:1) on the efficiency of vegetative buffer strips (12.2 m long) in removing herbicides dissolved in runoff water. Four treatments (2 ¥ 2 factorial) replicated three times were included in the study. Three inflow samples (each integrated over 15 min) and nine outflow samples (each integrated over 5 min) were collected from each plot and analyzed for three herbicides. Reductions of 41, 39, and 38% from plots having a relative area ratio of 15:1, and 37, 35, and 34% from plots having a relative area ratio of 30:1 were measured, respectively, for atrazine, metolachlor, and cyanazine. Although the percentage of removal decreased for the larger area ratios for each herbicide, the decreases were not significant. Reductions of 29, 30, and 28% from plots having 0.1 mg/L nominal inflow concentration, and 49, 44, and 45% from plots having 1.0 mg/L nominal inflow concentration were measured, respectively, for atrazine, metolachlor, and cyanazine. The differences between reductions for the nominal inflow concentrations were significant. Using a bromide tracer, it was determined that the major factor in reduction of herbicide transport was infiltration of inflow into the vegetative buffer strips.

Keywords
Buffer strips, Filter strips, Herbicide, Runoff, Water quality, Management practices

Disciplines
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CONTRIBUTING AREA AND CONCENTRATION EFFECTS ON HERBICIDE REMOVAL BY VEGETATIVE BUFFER STRIPS


ABSTRACT. Deteriorated water quality due to nonpoint source pollution from herbicides is one of the environmental problems receiving attention this decade. One off-site best management practice (BMP) being suggested to improve water quality is vegetative buffer strips. This study was conducted on a Storden loam soil, under simulated rainfall (6.35 cm/h), to determine the effects of nominal inflow concentration (0.1 and 1.0 mg/L) and the ratio of drainage area to vegetative buffer strip area (simulated to be 15:1 and 30:1) on the efficiency of vegetative buffer strips (12.2 m long) in removing herbicides dissolved in runoff water. Four treatments (2 × 2 factorial) replicated three times were included in the study. Three inflow samples (each integrated over 15 min) and nine outflow samples (each integrated over 5 min) were collected from each plot and analyzed for three herbicides. Reductions of 41, 39, and 38% from plots having a relative area ratio of 15:1, and 37, 35, and 34% from plots having a relative area ratio of 30:1 were measured, respectively, for atrazine, metolachlor, and cyanazine. Although the percentage of removal decreased for the larger area ratios for each herbicide, the decreases were not significant. Reductions of 29, 30, and 28% from plots having 0.1 mg/L nominal inflow concentration, and 49, 44, and 45% from plots having 1.0 mg/L nominal inflow concentration were measured, respectively, for atrazine, metolachlor, and cyanazine. The differences between reductions for the nominal inflow concentrations were significant. Using a bromide tracer, it was determined that the major factor in reduction of herbicide transport was infiltration of inflow into the vegetative buffer strips. Keywords: Buffer strips, Filter strips, Herbicide, Runoff, Water quality, Management practices.

Deteriorated water quality due to nonpoint source pollution is one of the environmental problems receiving attention this decade, with concerns for human health and the effects on wildlife, livestock, and aquatic ecosystems. Transport of sediment, nutrients, and pesticides from agricultural land (Prere, 1976) in the forms of nitrogen, phosphorus, carbon, total suspended solids, and microbial populations from animal waste application and disposal sites (Khaleel et al., 1980) causes major water quality concerns. To reduce nonpoint source pollutant transport and improve water quality, various in-field and off-site BMPs (Best Management Practices) have been suggested according to the type and mechanism of loss of the pollutant. For pesticides, which are transported to water resources primarily by overland flow, vegetative buffer strips (which are also known as buffer strips, vegetative filter strips, grassed strips or filters, and filter strips) are listed as one of the off-site BMPs. For the herbicides atrazine (in 1993) and cyanazine (in 1994) the labels were rewritten requiring a 20.1-m (66 ft) long buffer strip where runoff from a treated area directly enters a water resource, although the buffer strip does not have to be vegetated. Vegetative buffer strips are bands of planted or indigenous grass located downslope from croplands or other potential sources of pollution (NCASL, 1992). Vegetative buffer strips do not receive chemical applications and also are cited as an economical BMP for creating a more environmentally sound ecosystem.

The potential removal mechanisms associated with vegetative buffer strips for pollutants in runoff involve changes in flow hydraulics that enhance the opportunity for infiltration of runoff water, deposition of sediment, filtration of suspended sediment by vegetation, pollutant adsorption onto in-place soil and dead and living plant surfaces, and absorption of soluble pollutants by plants (NCASL, 1992). However, limited data exist on the actual effects of vegetative buffer strips in reducing the transport of the pollutants, especially for herbicides. Herbicide application to agricultural lands generally is required for adequate weed control, particularly when conservation or minimum tillage is used for erosion control. Soil-applied herbicides usually are retained to a large degree in the surface soil, and herbicides classified as weakly to moderately adsorbed are mostly lost in solution with runoff water.

In an earlier study of the effects of vegetated buffer strips on runoff, sediment transport, and herbicide removal, Wauchope et al. (1990) reported that one-third less rain was needed for bare plots to produce the same runoff as for the grassed plots in a rainfall simulation study. Aasmussen et al. (1977) conducted a grassed-waterway study on the

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reduction of 2,4-D load in surface runoff. By using simulated rainfall on 24.4-m long waterways, incoming suspended sediment was reduced by 98 and 94% for dry and wet antecedent conditions, respectively. The total losses of 2,4-D from the plots were 2.5 and 10.3% for the dry and wet plots, respectively. Only about 30% of the 2,4-D that entered the top of the waterway reached the bottom. In a similar study, Rhode et al. (1980) determined surface runoff losses of trifluralin from treated fields and how vegetated buffer strips reduced runoff transport. Annual losses, as percentages of that applied, were low (0.17 and 0.03%) for two years of measurement under natural rainfall. When runoff caused by rainfall simulation was directed onto vegetated buffer strips, trifluralin losses were reduced by 96% if the buffer strip was dry and by 86% if it was pre-wetted. Over half of this reduction was attributed to adsorption on vegetation, organic matter, and soil. Hall et al. (1983) determined atrazine surface-runoff losses from treated corn fields with and without an oat strip at the slope base. Atrazine loss without the oat strip or incorporation was 3.5% of that applied. With the oat strip, loss was reduced by more than a factor of 10 to 0.33%. Pre-plant incorporation reduced losses even further over a preemergence application.

Mickelson and Baker (1993), in a rainfall simulation study on the effect of vegetative buffer-strip length on atrazine transport, found reductions of 31.7 and 55.4% for 4.6- and 9.1-m lengths, respectively, with no significant difference in reduction whether the runoff contained sediment or not. Arora et al. (1993) reported that for the first field-runoff event after herbicide application, an average of 12.5% atrazine, 27.3% metolachlor, and 21.1% cyanazine was retained for a 15:1 area ratio (drainage area to vegetated buffer-strip area); corresponding values for a 30:1 area ratio were 9.3, 15.3, and 7.2%.

Dillaha et al. (1989) conducted a study to investigate the performance of vegetative filter strips as an agricultural nonpoint source pollution-control measure. They concluded that vegetative filter strips are ineffective on steeper hill slopes; they become ineffective under concentrated flow conditions with time; and when sediment was deposited higher than the adjacent field, flow parallel to the strips took place that reduced their effectiveness.

The National Council of the Paper Industry for Air and Stream Improvement (NCASL, 1992) published a technical bulletin on the effectiveness of buffer strips in reducing sediment, nutrient, and pesticide transport and losses occurring from silvicultural operations. Velocity of water flow, size distribution of incoming sediment, slope and slope length of the source area, slope and slope length of the buffer strips, vegetation characteristics, flow depth and vegetation height, pesticide properties, and water quality were stated as critical factors responsible for determining the effectiveness of buffer strips. It was concluded that due to the variety of ongoing chemical, physical, and biological processes, buffer strips have high potential to reduce the transport of nutrients, pesticides, and sediment with surface runoff. They pointed out that specific site factors (e.g., soil type, topography, vegetation in buffer area, and the nature of the surface water being protected) should be considered when designing buffer strips.

The studies cited here reflect the pollutant-removal capability of vegetative buffer strips. However, data from realistic field-oriented studies are still needed to evaluate the performance of vegetative buffer strips under different conditions related to: drainage area to vegetated buffer-strip-area ratios, bare buffer strips versus vegetated buffer strips, type of buffer strip vegetation, vegetation density, slope of buffer strips, buffer strip width, efficiency of buffer strips with respect to time, herbicide application rate, herbicide concentration in inflow, soil erodibility within the buffer strip, and site preparation method. The objectives of this study were to determine:

1. The effectiveness of vegetative buffer strips and the process(es) important in reducing herbicide transport with surface runoff.
2. The effect of the area ratio (drainage area relative to vegetated buffer strip area) on the efficiency of the vegetative buffer strips for herbicide removal.
3. The effect of herbicide concentration in inflow on the efficiency of the vegetative buffer strips for herbicide removal.

METHODS AND MATERIALS

An experimental area 4 km west of Iowa State University, Ames, Iowa, was surveyed, and 12 plots with dimensions of 1.5 m wide x 12.2 m long (maximum length possible due to the limits of the rainfall simulator used) were established during the summer of 1993. The vegetative buffer-strip plots were laid out within a previously established, grassed waterway area consisting of mostly Storden loam soil (32.1% sand, 18.4% coarse silt, 21.0% fine silt, 28.7% clay, and 5.8% organic matter) and having approximately 2 to 3% land slope. The individual plots were positioned with the length dimension parallel to the slope and were isolated with metal borders driven (7.6 cm deep) into the ground with joints sealed with soil berms to prevent leakage into or out of the plots. Metal collectors were installed at the downslope end over 30-cm-deep drained pits to allow runoff samples to be collected and flow measurements to be made manually.

The treatments involved two nominal herbicide-inflow concentrations (0.1 and 1.0 mg/L) and two area ratios (drainage area to vegetated buffer strip area, simulated to be either 15:1 or 30:1). The four treatments in the 2 x 2 factorial, replicated three times, were laid out in a randomized block design, thus there were 12 plots, grouped in sets of four, with treatments randomized within each set. A 15.2-m-diameter, rotating, overhead-boom rainfall simulator as described by Swanson (1965) was used to apply the simulated rainfall at 6.35 cm/h for 1 h on two plots at a time. A schematic diagram of the relative position of the plots and rainfall simulator is shown in figure 1.

The herbicides atrazine, metolachlor, and cyanazine, and a conservative anion tracer in the form of potassium bromide (KBr) were individually measured out and mixed in 3030 L of water in each of two 3785-L tanks to form either a 0.1- or 1.0-mg/L solution for the herbicides and a 100-mg/L solution for bromide. These solutions were pumped and metered from the tanks onto the upper ends of the plots to simulate field runoff.

The inflow was added to the upper end of the vegetative buffer strip plots through a 7.5-cm diameter perforated PVC pipe laid across the 1.5-m plot width to simulate runoff uniformly entering the buffer strips. The inflow was
Assuming runoff at the rate of 1.22 cm/h from upslope drainage areas 15 or 30 times larger than the vegetative watershed areas, these inflow rates would represent added to the upper end at either 57 or 114 L/min. Assuming runoff at the rate of 1.22 cm/h from upslope watershed areas, these inflow rates would represent drainage areas 15 or 30 times larger than the vegetative buffer-strip area, respectively. To determine this assumed runoff rate, it was estimated that runoff would begin 15 min into the rain (6.35 cm/h) and that at that point about 20% of the rain would run off. This representation of a runoff event is somewhat arbitrary, being a compromise between the desire to have a standard set of conditions (experimentally feasible) that allows comparisons between treatments to be made and the complex nature of actual field hydrographs. The times to runoff of 15 min and the rate of runoff of 1.2 cm/h are rough averages of two previous rainfall simulation studies (one published: Baker and Laflen, 1979) conducted by the authors of this manuscript on similar soils at the same rainfall intensity (6.35 cm/h). Three rainfall simulations (on six plots) were performed each day on 10 and 11 August 1993. A simulation was comprised of 60 min of rain with 45 min of inflow beginning 15 min after the rain started. No natural rainfall occurred during the two-day study.

Three 1-L samples of inflow for chemical analysis, each integrated over a 15-min period, were collected during inflow at the upslope end; inflow rates were continuously metered using a Great Plains Industries digital flowmeter (range: 11.4 to 114 L/min) and adjusted to the required rate through the use of a valve. Due to variability in chemical concentrations with time expected in outflow samples, up to nine 1-L samples, each integrated over a 5-min period (following initiation of runoff), were taken at the downslope end. Runoff rates for each plot were determined gravimetrically by collecting all of the outflow over a measured time interval and weighing it. Six rain water samples also were taken. The inflow, outflow, and rain samples were transported immediately to a refrigerated storage room (5°C). The runoff water samples (essentially free from sediment) were analyzed shortly after collection and the Department of Agricultural and Biosystems Engineering Water Quality Laboratory at Iowa State University. The three herbicides, atrazine, metolachlor, and cyanazine were extracted and analyzed by using gas chromatography, and bromide was analyzed by using high pressure liquid chromatography as described below.

All inflow, outflow, and rain samples were first filtered (through a 15-cm-diameter medium porosity, slow flowrate, 5-μm-pore-size filter paper). Herbicides were extracted from the filtered samples by using toluene. The 1.0 mg/L nominal concentration inflow/outflow water samples were extracted for atrazine, metolachlor and cyanazine as follows: a well-shaken 100-g aliquot was weighed into a 250-mL boiling flask, and about 50 mL of toluene was added by weight (43.3 g). The mixture was shaken on an orbital shaker at 250 rpm for 1 h, allowed to separate for 30 min, and then the less dense toluene was decanted. The 0.1 mg/L nominal concentration inflow/outflow water samples were extracted by using the same procedure, except that a 150-g aliquot and 20 mL of toluene were used. A 150-g aliquot and 5 mL of toluene were used to extract rain samples. All extracts were stored in a refrigerator at 5°C prior to analysis.

The extracts from the water samples were analyzed by using a Tracor 560 gas-liquid chromatograph equipped with a model 702 N-P thermionic detector and Tracor 770 auto sampler. The carrier gas was helium with a flowrate of 18 cc/min; reaction gases were hydrogen with a flow rate of 3.5 cc/min and air with a flow rate of 100 cc/min. Column oven-temperature was held constant at 160°C, with an inlet temperature of 246°C and a detector temperature of 246°C. The herbicides were separated by using a 3% OV-1, 0.63-cm-diameter x 1.8-m-long packed column. Data acquisition was performed by using a Spectra-Physics 4270 integrator and Fisher Recordall 5000 strip-chart recorder.

The water samples also were analyzed for bromide. The inflow, outflow, and rainfall samples were filtered (through a 13-mm-diameter, syringe filter, medium porosity, slow flow rate, 0.45-μm-pore-size filter paper) and analyzed by using high performance liquid chromatography with a HIC-6A ion chromatograph, Spectroflow 400 solvent delivery system, and Micromeritics 728 auto sampler. A 3mM potassium phthalate (KCC₆H₄O₄, KHP) carrier-solution at 3.8 pH was pumped at the rate of 1.20 mL/min at a pressure of 8700 kPa. Data acquisition was again performed by using a Spectra-Physics 4270 integrator and Fisher Recordall 5000 strip-chart recorder.

Runoff volumes were calculated for each 5-min sample-interval from the average of the flow rates at the beginning and end of each 5-min period, and these values were summed over all sample-intervals to give total plot-runoff volumes. Total inflow and outflow were calculated over the last 45 min of the rainfall simulation (leaving out the 15-min wetting period when no outflow occurred). The total amount of inflow plus rainfall that infiltrated into the vegetative buffer strips was determined with inflow/rainfall/outflow data. Since bromide is a conservative tracer and only is found in traces in the atmosphere (and in soil and rain water), the amount of inflow that infiltrated in the plots was calculated by using the bromide data. It is assumed that the only bromide loss was through the loss of inflow; therefore, bromide loss
(i.e., 1 minus the ratio of outflow bromide amount over inflow bromide amount, multiplied by 100) was equal to the percentage of inflow infiltrated. Equilibrium infiltration rates over the last 20 min also were calculated.

Inflow/outflow herbicide concentration data were combined with inflow/outflow water-volume data to determine the herbicide masses and to calculate herbicide removal by the vegetative buffer strips. For each of the three replications of the four treatments, the percentage of atrazine, metolachlor, and cyanazine removal were determined. Herbicide losses by infiltration (percentage of bromide loss) and by adsorption including other processes (total percentage of herbicide loss minus percentage of bromide loss) also were estimated.

The vegetative population density of each plot was determined by taking three random samples and counting the number of tillers by type within a 0.3 x 0.3-m square metal frame. The buffer strips contained 100% Bromegrass (Bromus inermis), and the average tiller population was 7.01 million tillers/ha. The average grass height at the time of simulation was roughly 20 cm.

An analysis of variance at the 10% significant level ($\alpha = 10\%$) was performed on total infiltration and herbicide loss data to evaluate the effects of area ratio and concentration level. Statistical analyses also were performed on infiltration results and herbicide losses for steady state or equilibrium conditions that appeared to occur during the last 20 min of the storm. The SAS ANOVA program for randomized block design, assuming normal populations and independently testing for area ratio and concentration level treatment effects, was used for the statistical analysis (SAS, 1983).

**RESULTS AND DISCUSSION**

Table 1 shows hydrologic data for outflow volume and the percentages of infiltration of rainfall, inflow, and rainfall plus inflow for the rainfall simulation imposed on the 12 vegetated-buffer-strip plots. For the 15:1 area ratio, the amount of infiltration during the 45-min inflow period (average of 6.2 cm for six plots) was slightly more than the amount of the rainfall (4.8 cm). For the 30:1 area ratio, infiltration (average of 9.2 cm for six plots) was somewhat greater than for the 15:1 area ratio, likely due to the greater depth of pondage, with pondage extending over a greater portion of the somewhat uneven vegetative-buffer-strip surface. The results indicate that the amount of inflow has some effect on both the amount and percentage of total infiltration because about 34% of the rain plus inflow infiltrated for the 15:1 area ratio; whereas, the corresponding number was 29% for the 30:1 area ratio. However, the differences were not statistically significant at the 10% level. Table 1 shows that when the concentration increased from 0.1 mg/L to 1.0 mg/L, the total infiltration increased for both area ratios, but again the difference was not significant at the 10% level. However, in this instance, there is no reason to believe that herbicide concentration should have any effect on infiltration. Table 1 also shows a negative value for the percentage of rain that infiltrated for the treatment with a 30:1 area ratio and 1.0 mg/L inflow concentration. This is not realistic, but could result from expected analytical errors in bromide analyses of up to ±10% that could result in estimation of more inflow infiltration than total infiltration.

The rain (plus inflow after 15 min) and outflow rates are plotted as a function of time for the 15:1 and the 30:1 area ratios in figure 2. For the first 15 min, only rain was added (wetting period) with inflow added after 15 min for the next 45 min for both the 15:1 and 30:1 area ratios. The average times to the start of runoff were 6.7 and 4.0 min after beginning the addition of inflow for the 15:1 and 30:1 area ratios, respectively. Outflow started later for the 15:1 area ratio due to the lower inflow rate. Figure 2 shows that outflow increased with time until about 40 min into the rain, and then was fairly constant. The observed trends can be explained by the fact that all the rain infiltrated during the 15-min wetting period, and, for a short while, the capacity of the soil to infiltrate water exceeded the rain-plus-inflow rate, at least for the 15:1 area ratio. The 4.0 min from the beginning of inflow to the beginning of outflow for the 30:1 area ratio is about the travel time of water flowing through the vegetated buffer strips (a flow velocity of 3 m/min was measured for vegetated plots in a similar study using dye). Later in the run, the infiltration capacity of the soil decreased to a nearly constant value, and outflow was nearly constant. The average steady-state

<table>
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<tr>
<th>Treatments</th>
<th>Area Ratio*</th>
<th>Inflow Conc (mg/L)</th>
<th>Outflow (cm)</th>
<th>Inflow (%)</th>
<th>Outflow (%)</th>
<th>Total (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15:1</td>
<td>0.1</td>
<td>13.3 (1.8)</td>
<td>6.9 (15.2)</td>
<td>35.6 (8.1)</td>
<td>28.2 (10.0)</td>
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<td></td>
<td>15:1</td>
<td>1.0</td>
<td>11.2 (4.3)</td>
<td>13.9 (29.3)</td>
<td>47.9 (21.2)</td>
<td>39.2 (23.2)</td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td></td>
<td>10.4</td>
<td>41.8</td>
<td>33.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>30:1</td>
<td>0.1</td>
<td>24.4 (0.5)</td>
<td>17.1 (15.7)</td>
<td>25.4 (4.5)</td>
<td>24.2 (1.6)</td>
</tr>
<tr>
<td></td>
<td>30:1</td>
<td>1.0</td>
<td>21.5 (1.8)</td>
<td>-5.7 (20.0)</td>
<td>40.1 (4.5)</td>
<td>33.3 (5.6)</td>
</tr>
<tr>
<td>Overall Average</td>
<td></td>
<td></td>
<td>5.7</td>
<td>32.8</td>
<td>28.8</td>
<td></td>
</tr>
</tbody>
</table>

* Simulated drainage to vegetated buffer strip area ratio.
† Percentage of 4.8 cm of rain applied during 45 min inflow period; rain infiltration calculated from difference between total and inflow infiltration amounts (a negative value is not realistic, but can result from errors in the bromide analytical data).
‡ Percentage of 13.7 cm of inflow added in 45 min for 15:1 area ratio (27.4 cm for 30:1 area ratio); calculated from bromide data.
§ Percentage of total infiltration was taken as $1 - \{\text{outflow}/(\text{inflow + rain})\} \times 100$.
II Standard deviation in parentheses.

Figure 2—Hydrology of vegetative buffer strips for 15:1 and 30:1 area ratios.
equilibrium infiltration for the last 20 min of each run was 1.5 cm (19% of rain plus inflow) for the 15:1 area ratio; the corresponding value for the 30:1 area ratio was 2.5 cm (17% of rain plus inflow).

Considering just the process of infiltration, at one extreme, if all the water that infiltrated was inflow water (with herbicide at 0.1 or 1.0 mg/L nominal concentration) and all the runoff was the remaining inflow plus rain water, at the 15:1 area ratio (inflow of 13.7 cm, rain of 4.8 cm, and average infiltration of 6.2 cm) average herbicide removal from just infiltration would be 45%. At the other extreme, if all the water that infiltrated was rainfall containing no herbicide (4.8 cm), the remaining portion of infiltration was from inflow, and all the runoff was inflow water, then herbicide removal from just infiltration would be 11%. Corresponding extreme values for the 30:1 area ratio (inflow of 27.4 cm, rain of 4.8 cm, and average infiltration of 9.2 cm) would be 34 and 16%, respectively. For three out of four treatments, the removal values (given in table 2) fall within the limit of calculated extremes, so it is feasible (although not likely, as shown by the bromide data) that infiltration alone could account for all of the removal. However, for the fourth treatment (30:1 area ratio and 1.0 mg/L nominal inflow concentration), the percentage of removal exceeded the maximum calculated extreme that could be accounted for by infiltration only (i.e., the unlikely case where only inflow water infiltrated, with no rain water infiltrating). Therefore, a process that reduced herbicide concentrations, such as adsorption onto the soil and dead/living vegetation, also was causing some herbicide removal.

Figure 3 shows the average bromide concentrations in outflow samples relative to concentrations in the corresponding inflow samples for the two area-ratio treatments (15:1 and 30:1). The span around each average value is ±1 standard deviation (for six values), and the horizontal lines represent the concentration if the inflow was diluted by rain (i.e., a dilution factor of 0.742 for the 15:1 area ratio and 0.852 for the 30:1 area ratio). Figure 3 indicates that, initially, proportionately more inflow than rain infiltrated; whereas, near the end of the run time the percentage of rain and inflow that infiltrated were nearly equal. During higher initial infiltration rates, inflow added to the top of the plot has more opportunity for infiltration than rainfall distributed uniformly over all of the plot. At lower infiltration rates, later in the run, this effect is decreased; in addition, it is possible that rain falling on higher, unponded surface-areas increases the opportunity for infiltration over inflow confined to ponded areas.

Average herbicide inflow and removal from inflow by the vegetative buffer strips are shown in table 2 for atrazine, metolachlor, and cyanazine for all four treatments. The inflow amounts are shown as kg/ha (based on the area of the buffer strips), and removal values are listed in terms of percentage of inflow amounts. The herbicide removal by the individual vegetative buffer strips for atrazine, metolachlor, and cyanazine ranged from 26 to 50%. Differences between herbicide removal values were not significant at the 10% level. The percentage of removal for all three herbicides increased with increasing concentration (from 0.1 mg/L to 1.0 mg/L) within the same area ratio. These increases were significant at the 10% (and 5%) level. For the same concentration, (either 0.1 mg/L or 1.0 mg/L), increased area ratio (from 15:1 to 30:1) decreased the percentage of herbicide removal for all three herbicides. However, in general the decreases due to area ratio were not significant at the 10% level; the only exception was for atrazine for the 0.1 mg/L nominal concentration.

The average inflow and removal values for herbicides during the last 20 min of the run, when infiltration was nearly steady-state, are shown in table 3 for atrazine, metolachlor, and cyanazine for all four treatments. These data illustrate what happens after the vegetative buffer strips become more nearly saturated, and can be used to predict the results for longer rainfall-runoff events. The average herbicide removal by the vegetative buffer strips during this period for atrazine, metolachlor, and cyanazine ranged from 11 to 39%. As with the total run, the percentage of removal for the last 20 min for all three herbicides increased with increasing concentration (from 0.1 mg/L to 1.0 mg/L) for both the 15:1 and 30:1 area ratios. These differences were significant at the 10% significance level. A comparison of percentage of infiltration of inflow in table 2 with the percentage of herbicide removal in table 4 for the whole run, and a similar comparison of values in table 3, show that herbicide removal for all herbicides and treatments generally was dominated by the amount of infiltration; the greater the

![Figure 3](image-url)
infiltration the greater the removal. However, particularly for the 1.0 mg/L nominal inflow concentration, for all three herbicides and both area ratios, an additional process such as adsorption to in-place soil or to living or dead plant tissue, reducing concentrations and further increasing removal, was indicated.

To determine if adsorption was a significant process, two comparisons were made using bromide data. First, a comparison of total removal of bromide to total removal values for each herbicide was made. Because bromide is a soluble anion, not adsorbed, and moves readily with water, the difference between bromide-removal and herbicide-removal values should indicate the possible degree of adsorption. As shown in table 4, bromide and herbicide removal values were not much different (with expected analytical errors in herbicide and bromide analyses of up to ±10%, subtraction of herbicide and bromide loss reductions to estimate herbicide removal by adsorption could, and did, result in some negative values). The second comparison was made on a sample-by-sample basis: relative herbicide concentrations (ratio of outflow sample concentrations and corresponding inflow concentrations) were divided by relative bromide concentrations for atrazine, metolachlor, and cyanazine. Average relative atrazine concentrations ±1 standard deviation are shown in figures 4 and 5 for the 15:1 and 30:1 area quotients, respectively; data for metolachlor and cyanazine were quite similar. Table 5 shows average relative concentrations with their respective standard deviations. The quotients are less for the 1.0 mg/L nominal inflow concentration in all six herbicide-area ratio comparisons with the 0.1 mg/L nominal inflow concentration, with difference for three of these comparisons being statistically significant. This shows a concentration effect, where at higher nominal inflow concentration removal is greater. At this higher concentration, the vegetative buffer strips also show potential for a small amount of adsorption, as ratios are less than 1.0 for all six values at 1.0 mg/L nominal inflow concentration (statistically less in four cases).

<table>
<thead>
<tr>
<th>Area</th>
<th>Inflow Conc</th>
<th>Steady-state Infiltration*</th>
<th>Inflow</th>
<th>Removal</th>
<th>Inflow</th>
<th>Removal</th>
<th>Inflow</th>
<th>Removal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>(mg/L)</td>
<td>(%)</td>
<td>(kg/ha)</td>
<td>(%)</td>
<td>(kg/ha)</td>
<td>(%)</td>
<td>(kg/ha)</td>
<td>(%)</td>
</tr>
<tr>
<td>15:1</td>
<td>0.1</td>
<td>11.9 (7.75)†</td>
<td>0.080 (0.01)</td>
<td>10.8 (8.38)</td>
<td>0.081 (0.01)</td>
<td>13.8 (3.94)</td>
<td>0.080 (0.01)</td>
<td>11.8 (7.25)</td>
</tr>
<tr>
<td>15:1</td>
<td>1.0</td>
<td>25.7 (19.23)</td>
<td>0.667 (0.07)</td>
<td>39.1 (20.28)</td>
<td>0.640 (0.05)</td>
<td>30.7 (25.61)</td>
<td>0.567 (0.07)</td>
<td>30.5 (23.02)</td>
</tr>
<tr>
<td>30:1</td>
<td>0.1</td>
<td>15.4 (8.03)</td>
<td>0.130 (0)</td>
<td>14.5 (9.06)</td>
<td>0.131 (0.01)</td>
<td>15.4 (10.66)</td>
<td>0.116 (0.01)</td>
<td>12.0 (10.66)</td>
</tr>
<tr>
<td>30:1</td>
<td>1.0</td>
<td>19.1 (2.38)</td>
<td>1.456 (0.23)</td>
<td>38.7 (8.21)</td>
<td>0.869 (0.87)</td>
<td>28.5 (12.95)</td>
<td>0.987 (0.08)</td>
<td>29.8 (9.24)</td>
</tr>
</tbody>
</table>

* Percentage of total volume added at steady-state of 2.1 cm rain (6.3 cm/in. for 0.33 h) and inflow of 6.1 cm for 15:1 or 12.2 cm for 30:1 area ratio.
† Standard deviation in parentheses.

Figure 4—Relative atrazine concentrations for 0.1 and 1.0 mg/L nominal inflow concentrations and 15:1 area ratio.

Figure 5—Relative atrazine concentrations for 0.1 and 1.0 mg/L nominal inflow concentrations and 30:1 area ratio.

Table 4. Herbicide removal by adsorption

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Inflow Conc (mg/L)</th>
<th>Inflow Infiltration* (Bromide Loss) (%)</th>
<th>Atrazine Adsorption† (%)</th>
<th>Metolachlor Adsorption† (%)</th>
<th>Cyanazine Adsorption† (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area Ratio</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15:1</td>
<td>0.1</td>
<td>35.6 (8.15)‡</td>
<td>-4.4 (5.66)</td>
<td>-4.1 (0.92)</td>
<td>-5.5 (2.89)</td>
</tr>
<tr>
<td>15:1</td>
<td>1.0</td>
<td>47.9 (21.15)</td>
<td>0.4 (2.55)</td>
<td>-1.2 (4.55)</td>
<td>-1.3 (2.19)</td>
</tr>
<tr>
<td>30:1</td>
<td>0.1</td>
<td>25.4 (4.51)</td>
<td>1.0 (1.98)</td>
<td>2.0 (0.76)</td>
<td>0.2 (2.55)</td>
</tr>
<tr>
<td>30:1</td>
<td>1.0</td>
<td>40.1 (4.50)</td>
<td>7.4 (6.49)</td>
<td>1.7 (6.75)</td>
<td>2.3 (4.65)</td>
</tr>
</tbody>
</table>

* Amount of inflow infiltration is assumed equal to bromide removal or loss.
† Reduction by adsorption (and/or possible other processes) is assumed equal to total loss reduction minus infiltration (negative values may be due to measurement error).
‡ Standard deviation in parenthesis.

Table 5. Relative herbicide concentrations divided by relative bromide concentrations

<table>
<thead>
<tr>
<th>Area Ratio</th>
<th>Inflow Conc (mg/L)</th>
<th>Atrazine Average*</th>
<th>Metolachlor Average*</th>
<th>Cyanazine Average*</th>
</tr>
</thead>
<tbody>
<tr>
<td>15:1</td>
<td>0.1</td>
<td>1.07 (0.13)</td>
<td>1.08 (0.15)</td>
<td>1.11 (0.21)</td>
</tr>
<tr>
<td>15:1</td>
<td>1.0</td>
<td>0.87 (0.05)</td>
<td>0.87 (0.04)</td>
<td>0.90 (0.04)</td>
</tr>
<tr>
<td>30:1</td>
<td>0.1</td>
<td>0.99 (0.02)</td>
<td>0.96 (0.03)</td>
<td>1.00 (0.03)</td>
</tr>
<tr>
<td>30:1</td>
<td>1.0</td>
<td>0.86 (0.10)</td>
<td>0.97 (0.08)</td>
<td>0.96 (0.09)</td>
</tr>
</tbody>
</table>

* Average of nine samples taken over 45 min for each of three replications.
† Standard deviation in parenthesis.
CONCLUSIONS

Vegetative buffer strips were found to be effective in reducing runoff volumes for the conditions of this study. The average infiltration of inflow plus rain was calculated to be 34 and 29% for 15:1 and 30:1 area ratios, respectively. Forty minutes into the rainfall simulation, the average steady state infiltration was 19 and 17% of inflow plus rain for the 15:1 and 30:1 area ratios, respectively. No significant difference was observed for either total infiltration or steady state infiltration among area ratio treatments or concentration level treatments.

The average herbicide removal by the vegetative buffer strips for atrazine, metolachlor, and cyanazine ranged from 26 to 50%. Average herbicide reductions of 41, 39, and 38% from plots having a relative area ratio of 15:1, and 37, 35, and 34% from plots having a relative area ratio of 30:1 were found, respectively, for atrazine, metolachlor, and cyanazine. Differences between area ratios or between herbicides were not significant. Herbicide reductions of 29, 30, and 28% from plots having 0.1 mg/L nominal inflow concentration and 49, 44, and 44% from plots having 1.0 mg/L nominal inflow concentration were measured, respectively, for atrazine, metolachlor, and cyanazine. The differences between nominal inflow concentrations were significant.

Vegetative buffer strips were effective in increasing infiltration, reducing runoff, and also diluting herbicide concentrations in inflow through rain that fell on the vegetated buffer strips. Vegetative buffer strips were found to be more effective for herbicide removal in the earlier part of a storm. Infiltration was found to be the most important herbicide removal mechanism associated with vegetative buffer strips. For the herbicides tested under the conditions of this study, adsorption or other processes that reduced concentrations were believed to be active at greater herbicide concentrations, but were not dominant, reducing herbicide losses from 0 to less than 10% compared to 25 to 48% reductions due to infiltration.

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REFERENCES


