Reducing Atrazine Losses: Water Quality Implications of Alternative Runoff Control Practices

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ABSTRACT

Water quality is being affected by herbicides, some allegedly harmful to human health. Under scrutiny is atrazine (1-chloro-3-ethylamino-5-isopropylamino-2,4,6-triazine), a commonly used herbicide in corn (*Zea mays* L.) and sorghum [*Sorghum bicolor* (L.) Moench] production. Concentrations of soluble and adsorbed atrazine losses sometimes exceed the safe drinking water standard of 3 μg L^{-1} established by the USEPA. This study assesses the protective implications of runoff control structures and alternative crop farming practices to minimize atrazine losses. Using a computerized simulation model, APEX, the following four practices were the most effective with respect to the average atrazine loss as a percent of the amount applied: (i) constructing sediment ponds, 0.09%; (ii) establishing grass filter strips, 0.14%; (iii) banding a 25% rate of atrazine, 0.40%; and (iv) constructing wetlands, 0.45%. Other atrazine runoff management options, including adoption of alternative tillage practices such as conservation and no-till as well as splitting applications between fall and spring, were marginally effective.

Maintaining a safe and high-quality water supply is critically important for rural towns and small communities using surface water reservoirs or shallow wells for drinking water. Common impairments to water quality in agrarian settings allegedly arise from nonpoint sources such as applications of commercial fertilizers, animal manure, herbicides, and other select inputs used in farm and ranch production activities. In 1991, the U.S. Geological Survey developed a comprehensive water quality program, the National Water Quality Assessment, which found pesticides in 95% of the streams and 60% of shallow wells in agricultural areas (Hamilton and Miller, 2002). Recently, quantities of nutrients and pesticides in excess of the maximum contamination levels (MCL) developed by USEPA have been detected in public drinking water supplies of selected rural communities ranging from north-central to south-central Texas, the region of interest in this study.

Small rural watersheds with reported breaches of safe drinking water standards are usually characterized by one or more of several factors including intensive farming and ranching practices, concentrated livestock feeding activities, moderate to high seasonal and annual rainfall, conducive topography and soil conditions causing runoff into surface waters or leaching into ground water, and inadequate soil conservation production practices and on-farm impounding structures to restrict water flow on farms and ranches within the watershed.

The primary objectives of this study are to (i) validate the APEX simulation model using historical crop yields and edge-of-field atrazine runoff measurements and (ii) estimate the effects of alternative structural impoundments and crop production practices on atrazine losses compared with current crop production practices.

These objectives will be attained by using a computerized crop production simulation model, APEX, to simulate crop yields and atrazine losses over the long run using alternative best management practices (BMPs) that, in turn, affect water quality.

While many have investigated the effects of tillage practices, filter strips, and alternative crops in rotations, the alternatives evaluated did not always reduce atrazine runoff. In Iowa, Baker and Johnson (1979) reported increases in atrazine losses using no-till of 6 and 98% on silty loam soils at different sites over conventional tillage but ridge tillage reduced runoff losses 24 and 21% at the same sites, respectively. In Maryland, Kentucky, and Pennsylvania, reductions of 29 to 100% atrazine were reported using no-till on loam and silty loam soils (Glen and Angle, 1987; Hall et al., 1991; Witt and Sander, 1990). Filter strips using switchgrass reduced dissolved atrazine losses 52% compared with 41% with bare soil strips (Mersie et al., 1999). In Texas on a clay soil, Senseman et al. (2002) reported that buffalograss [*Bouteloua dactyloides* (Nutt.) Columbus] filter strips trapped 35% of the atrazine applied, and somewhat lower percentages of atrazine metabolites in a 1-h rainfall simulation study. Hoffman (personal communication, 1997) found that grass and wheat (*Triticum aestivum* L.) filter strips decreased atrazine losses in 1993–1994 significantly but no-till practices on cropland from a large storm event in 1997 increased losses. On a similar soil, Hoffman et al. (1995) reported that contour filter strips reduced atrazine losses 44 to 50%.

While no-till has resulted in mixed effects on atrazine losses, Hall et al. (1983) found that incorporating surface-applied atrazine was highly effective in reducing runoff losses. Additionally, they reported that planting

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Published in J. Environ. Qual. 33:7–12 (2004).

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Abbreviations: BMP, best management practice; MCL, maximum contamination level.

6-m-wide filter strips of oats (*Avena sativa* L.) also reduced atrazine runoff losses from 91% with an application of 2.2 kg ha^{-1} to 65% at twice the rate of application.

For an example of an atrazine-contaminated large water supply, in 1989 the Hoover Reservoir was found to have elevated levels of atrazine above the MCL of 3 μg L^{-1} (Williams and Miller, 1992). The SWRRBWQ (Simulator for Watershed Resources in Rural Basins-Water Quality) model (Arnold et al., 1991) was used to evaluate the probabilities that alternative management practices in the watershed would reduce atrazine losses to the reservoir below the USEPA drinking water standard. Simulations for 100 yr of no-till and conservation tillage practices indicated that the MCL would be equal or less than 3 μg L^{-1} 35% and 25% of the time, respectively, compared with 42% using conventional tillage practices.

Using the APEX (Agricultural Policy/Environmental eXtender) model (Williams et al., 2000) to simulate the effects of buffers along streams, a possible reduction in atrazine loss of 14% was reported (Z. Qui, personal communication, 2000). Miller et al. (1995) assessed several herbicides for losses in irrigation runoff in Canada. Similar to atrazine, hexazinone [3-cyclohexyl-1-methyl-6-(dimethylamino)-*s*-triazine-2,4(1*H*,3*H*)-dione] (Velpar; DuPont, Wilmington, DE) is highly soluble and was found to be highest in concentration during the first continuous flow (flood) irrigation, whereas using surge irrigation reduced the concentration in the initial runoff by one-half. The highest atrazine concentrations were found to be significantly below the USEPA standard for drinking water (USEPA, 1989a, 1989b). Koo and Diebel (1996) used the GLEAMS (Ground Loading Effects of Agricultural Management Systems) model (Leonard et al., 1987) to simulate the effects of either substituting select crops such as alfalfa (*Medicago sativa* L.), soybean [*Glycine max* (L.) Merr.], or small grains for corn and sorghum, or by reducing the proportion of cropland in corn and sorghum. Atrazine losses in both runoff and sediment decreased significantly. Economic effects on profits, and risk (variability) of returns, however, varied by selection of crop and rotation.

Nationally, Osteen and Kuchler (1986) estimated that a ban on corn pesticides including atrazine would increase net farm income by \$1.1 billion by decreasing herbicide costs and increasing corn prices due to declining yields. Consumer surplus would, however, decrease \$1.9 billion because of higher food prices. Richardson et al. (1999) analyzed the economic effects of a nationwide herbicide ban on representative farms of major crop production areas including Corn Belt grain and grain–hog farms where atrazine is commonly used for corn. Both grain farms in Iowa and Missouri realized increases in cash receipts from rising corn prices as a result of a 31% decline in corn yields and a 30% reduction in herbicide expenses. These factors resulted in excess of a 50% increase in profits. Present value of net worth increased 17 and 9%, respectively. Similarly, Indiana and Missouri grain–hog farms increased the present value of net worth 26 and 8%, respectively.

WATER QUALITY BACKGROUND OF THE STUDY AREA

The Texas Natural Resource Conservation Commission identified the 1996 Clean Water Act (CWA) 303(d) problems in 142 of 368 classified water segments in Texas. Of these, 62 segments are of nonpoint sources only and 43 of both nonpoint and point sources. The CWA requires the state to address all problems identified on the 303(d) list. Causes of impairment include fecal coliform detections in 117 segments, dissolved oxygen problems in 38 segments, metal contaminants in 28 segments, organic compounds in 19 segments, and dissolved solids in 19 segments (Texas Natural Resource Conservation Commission, 1997).

The study area, the Aquilla Watershed in Hill County of central Texas, is characterized by mixed crop and livestock production on clay and clay loam soils having slow infiltration and high runoff characteristics. This study focuses on corn and grain sorghum production. Atrazine is a common herbicide used for seasonal weed control in these two crops.

Recently, Aquilla Lake water quality was found to exceed the MCL for atrazine in treated drinking water. The watershed contributing water to Aquilla Lake covers 65 811 ha, of which 39 487 ha are cropland or 60% of the watershed; 21% is pasture, hay, and grassland; 13% is deciduous and evergreen forest; and 6% is urban, commercial, industrial, transportation, and residential land uses (J. Jeske, personal communication, 2000). Cropland allocation for different crops was based on information from Aquilla Watershed producers reported in the Aquilla Creek representative farm report (Richardson et al., 1999). According to the report, 36% of total cropland is sorghum, 29% corn, 18% wheat, and 17% cotton (*Gossypium hirstum* L.). Atrazine is only used for weed control in corn and sorghum production with the common application rate of 1.68 kg ha^{-1}. Other herbicides including Treflan [2,6-dinitro-*N*,*N*-dipropyl-4-(trifluoromethyl)-benzamine; Dow AgroSciences, Indianapolis, IN] and Telone II (1,3-dichloropropene; Dow AgroSciences) were used for weed control in cotton and Roundup (glyphosate; Scotts, Columbus, OH) was used for weed control before wheat seeding.

CHARACTERIZATION OF THE AQUILLA CREEK WATERSHED

To create a digitized characterization of the Aquilla Watershed, information relating to the watershed geographic area, soils, land uses, and digital elevation data for mapping is essential. These geographic information system layers were obtained from the USDA Natural Resources Conservation Service (NRCS) in Temple, TX. Based on this data, the watershed was divided into 44 nonuniformly sized sub-areas.

Soil Type and Cropping System Delineation for Sub-Areas

The dominant soil and land use in each sub-area was determined with U.S. Geological Survey and USDA-

NRCS databases. Additionally, an aerial map provided a second avenue for identifying land use for each sub-area in the watershed since the cropland and non-cropland could be visually recognized and determined. The soil data included all soil types and associated areas in each sub-area (USDA Soil Conservation Service, 1975). The soil type having the largest land area or percentage was selected as the dominant soil in the sub-area. The next step was to determine the cropping systems being produced. The USDA National Resource Inventory (USDA-NRI) survey data for 1996–1999 described crops produced and their associated soil type in Hill County. Though it seems that each of these crops such as corn, sorghum, cotton, and wheat could be planted on a variety of soil types, some general linkages were established between crop and soil type. For instance, a majority of corn and cotton was grown on Heiden or Houston Black soils (both fine, smectitic, thermic Udic Haplusterts) and the majority of sorghum on Houston Black clay and Wilson (fine, smectitic, thermic Oxyaquic Vertic Haplustalfs) and Lott (fine-silty, carbonatic, thermic Udorthentic Haplustolls) clay loams. By contrast, the majority of wheat was produced on Wilson soil.

Additionally, year-to-year cropping patterns were indicated in the USDA-NRI dryland crop rotations indicating the dominant cropping systems. These were assigned to sub-areas that were identified as dominantly cropland sub-areas and other sub-areas were considered rangeland. Twenty-one production systems including various crops as well as grasses were developed for simulation. Commonly used crop rotations were: cotton–cotton–cotton–sorghum, a 4-yr rotation; corn–sorghum, a 2-yr rotation; sorghum–wheat graze-out, a 2-yr rotation; sorghum–sorghum–cotton, a 3-yr rotation; corn–sorghum–wheat, a 3-yr rotation; corn–corn–sorghum, a 3-yr rotation; and corn–corn–wheat, a 3-yr rotation. Cattle were allowed to graze on rangeland as well as on some wheat fields designated as sorghum–wheat graze-out areas. Grazing rates varied based on the grass yields. In general, 4 ha head^{-1} was used for tall native grasses, 13.75 ha head^{-1} for short to medium height native grasses, and 3.25 ha head^{-1} for the winter grazing period for wheat.

In the base simulation, typical herbicide application and cultural practices were used for each crop rotation. Atrazine was not incorporated immediately after application, a common practice. Immediate incorporation following application was one of the atrazine runoff control options to be compared with the base situation. The first simulated tillage following atrazine application in the base simulation was a field cultivator for weed control 15 d afterward. Other important information needed for accurate simulation of the estimated atrazine losses by runoff and erosion included land slope and slope length as well as channel size and slope. These parameters were developed using a computerized-interface procedure that uses digital elevation methods to calculate the coefficients. Additionally, the computerized calculation procedure also generated channel routing information, indicating the stream flow paths from one sub-area to the next through the watershed. Detailed watershed information by sub-area was then developed to ensure that crops, crop rotations, and cultural practices typical of those in the watershed were appropriately placed on the correct soils for enhanced simulation accuracy of crop yields.

THE APEX MODEL

The Agricultural Policy/Environmental eXtender model (APEX) simulates cropping system and cultural practices and their environmental effects for whole-farm situations, which is a larger scale of simulation than APEX's predecessor, the field-level EPIC model (Williams et al., 1998). APEX is a daily time-step crop simulation–environmental impact model. Of the many variables in an ecosystem, it uses soils data, climatic data, cultural practices, cropping systems, and management data. A farm may be subdivided into several fields, soil types, landscapes, or any other desirable configuration.

Manure may be applied as solid or liquid. Confined feeding areas may contain a lagoon to catch runoff and wash water. Effluent from the lagoon is applied automatically to a designated field(s). Solid manure is scraped from the feeding area and stockpiled for automatic application. When an application is triggered, it is applied to the field having the lowest soluble phosphorus concentration in the top 50 mm of the designated fields. Additionally, the system can be supplemented with manure produced off-farm, applied either automatically or manually at specific times and rates. Manure is also applied automatically to grazed fields by livestock activity. A variety of livestock including cattle, swine, and poultry may be simulated since manure production per day is dimensioned as kg head^{-1} and manure ingredients are pre-specified as percentage of mineral organic nitrogen and phosphorus as well as percentage ammonia nitrogen.

More than 100 crops have the potential of being simulated in continuous single or multiple-crop rotations. The results include daily, monthly, and yearly projections for each sub-area in the watershed and the total watershed of crop yields; runoff; percolation; water and wind erosion; nutrient uptake, storage, and losses; pesticide degradation, storage, and losses; and grazing interactions with forage consumption, erosion, runoff, nutrient cycling, and nutrient and pesticide losses. Other data include inter-field runon–runoff, subsurface flow, pond and reservoir storage, stream and reach routing, and water transfer. It incorporates alternative tillage practices, commercial fertilizer and manure application practices, irrigation, grain and hay harvesting, and grazing of forages. All major crops, several minor crops and vegetables, and a few grasses and trees can be simulated over time.

Validation of APEX Using Controlled Experiment Runoff Measurements and Historical Crop Yields

Pantone et al. (1996), at the USDA Grassland, Soil, and Water Conservation Laboratory (Temple, TX), conducted an atrazine runoff experiment comparing no-

Table 1. Validation of simulated crop yields.

Crop	Producers	Simulated
	Mg ha^{-1}	
Corn	6.28	6.25
Cotton	0.56	0.563
Sorghum	5.61	5.66
Wheat	3.03	3.15

till and chisel tillage on a Houston Black clay soil. Of the atrazine applied to chisel-tilled corn, there was less than 2% in runoff loss and less than 0.03% in sediment loss. Similarly, the base situation for the Aquilla Watershed simulated with typical chisel-tillage corn operations but heterogeneous soils and crop rotations resulted in an average total loss of 1.98% of that applied.

For further validation, estimates of average crop yields were provided by a panel of farmers from within the Aquilla Watershed. According to the Aquilla representative farm report, the farm panel's average corn yield was estimated to be 6.28 Mg ha^{-1}; sorghum, 5.61 Mg ha^{-1}; cotton, 0.56 Mg ha^{-1}; and wheat, 3.03 Mg ha^{-1} (Richardson et al., 1999). The APEX-simulated yields for the 1988–1999 period were within 5% of the estimated crop yields provided by the panel (Table 1).

The previous results are sufficient validation of the APEX model in the absence of accurate in-stream measurements of atrazine losses. Following validation of APEX, the method of analysis for each of the alternative runoff control practices includes simulating 30 randomly generated weather patterns resulting in different rainfall and wind distributions for 12-yr periods each. (Twelve years were necessary to provide continuous simulated crop yields for an adequate period for a future long-term economic analysis.) The atrazine losses in runoff and sediment are averaged for the 360 observations of each alternative and compared with those of the base situation.

For the purposes of this study, several BMPs were developed for evaluation. A detailed outline of them is given in Table 2, but briefly they include:

- Base: Use conventional tillage (mostly disk tillage) with no immediate incorporation of atrazine.
- Alternative 1: Incorporate atrazine immediately after application by disk tillage.
- Alternative 2: Establish filter strips of bermudagrass down-slope of cropland areas.
- Alternative 3: Adopt conservation tillage to maintain crop residues, minimizing soil erosion and runoff.
- Alternative 4: Construct sediment retention ponds at confluences of tributaries with major creeks to reduce soluble atrazine losses in runoff and sediment.
- Alternative 5: Apply atrazine in split applications in late fall and early spring, resulting in a 50% rate per application.
- Alternative 6: Apply atrazine at planting time in bands resulting in a 75% decrease in the application rate.
- Alternative 7: Adopt no-tillage practices for corn and plant Roundup-ready corn varieties.
- Alternative 8: Construct wetlands upstream from Aquilla Lake.

EFFECTS OF ALTERNATIVE BEST MANAGEMENT PRACTICES ON ATRAZINE RUNOFF

Atrazine loss as defined in this project is the total percentage lost in runoff plus sediment of the amount of atrazine applied in implementing a runoff control strategy. Comparisons of loads in runoff and particulate are not valid since the total atrazine applied in the watershed varies depending on the control. The comparable gauge is the percentage lost of that applied.

Losses do not include those caused by deep percolation below the root zone since the focus of the study was on surface water quality, not ground water quality. Most of the soils in the watershed are high in clay content and are characteristically slow in infiltration rates, enhancing runoff and minimizing percolation losses. Adding runoff and sediment losses leaving the watershed outlet (or those entering the Aquilla Lake reservoir) constitutes the reported atrazine losses in Table 3, which were then used to calculate the percentage loss based on the annual aggregated application rate for all crops in the watershed. (In an example corn–wheat rotation, the average annual atrazine application would be 0.84 kg ha^{-1} yr^{-1} when applying 1.68 kg ha^{-1} yr^{-1} on corn and none on wheat.)

The simulation results indicated that atrazine losses with the alternative treatments in the Aquilla Watershed were generally low, less than 2% of the total application amount (Table 3). This is consistent with previous experiment findings (Pantone et al., 1996). Sediment-transported atrazine losses were much less important and represented less than 0.03% of the total amount applied. In this study, the base simulation resulted in 1.977% loss by runoff and 0.001% in sediment for the watershed.

Among the BMPs, the percentage lost of the total

Table 2. Strategies for atrazine runoff control, Aquilla Watershed.

Strategy	Atrazine application	Timing of application	Land treatment
Base	1.68 kg ha^{-1} on sorghum and corn	spring	unincorporated
Alternative 1	1.68 kg ha^{-1} on sorghum and corn	spring	incorporated with disk tillage
Alternative 2	1.68 kg ha^{-1} on sorghum and corn	spring	unincorporated, filter strips
Alternative 3	1.68 kg ha^{-1} on sorghum and corn	spring	unincorporated plus conservation tillage
Alternative 4	1.68 kg ha^{-1} on sorghum and corn	spring	unincorporated, sediment ponds at confluences of major creeks
Alternative 5	0.84 kg ha^{-1} twice on corn and sorghum	spring and fall	unincorporated, split applications
Alternative 6	0.42 kg ha^{-1} on corn and sorghum	planting	incorporated, banded applications
Alternative 7	1.68 kg ha^{-1} on corn and sorghum	spring	unincorporated, planting of Roundup-ready no-till corn
Alternative 8	1.68 kg ha^{-1} on corn and sorghum	spring	unincorporated, constructed wetlands in-stream

Table 3. Yearly average atrazine losses by atrazine runoff control strategy, Aquilla Watershed.

Atrazine runoff control strategy	Item	Total	Range
		kg ha^{-1}	
Base: spring-applied, unincorporated	applied	0.639839	–
	runoff loss	0.012647	0.001237–0.034060
	sediment loss	0.000009	0.000000–0.000045
	total loss	0.012656	0.001237–0.034105
	loss as % of applied	1.98%	0.19–5.33%
Alternative 1: spring-applied, incorporated	applied	0.639839	–
	runoff loss	0.007966	0.003186–0.019625
	sediment loss	0.000009	0.00–0.000027
	total loss	0.007975	0.003186–0.019652
	loss as % of applied	1.25%	0.50–3.07%
Alternative 2: spring-applied, buffer strips	applied	0.639839	–
	runoff loss	0.000872	0.000347–0.002029
	sediment loss	0.000000	0.00–0.0000000
	total loss	0.000872	0.000347–0.002029
	loss as % of applied	0.14%	0.05–0.32%
Alternative 3: spring-applied, conservation tillage	applied	0.639839	–
	runoff loss	0.008749	0.003462–0.02414
	sediment loss	0.000009	0.00–0.000018
	total loss	0.008758	0.003462–0.02414018
	loss as % of applied	1.37%	0.54–3.77%
Alternative 4: spring-applied, with sediment ponds located at confluences of streams with major creeks	applied	0.639839	–
	runoff loss	0.000579	0.000169–0.001415
	sediment loss	0.000000	0.00–0.0000000
	total loss	0.000579	0.000169–0.001415
	loss as % of applied	0.09%	0.03–0.22%
Alternative 5: spring and fall split application	applied	0.639839	–
	runoff loss	0.009835	0.006070–0.034060
	sediment loss	0.000009	0.00–0.000027
	total loss	0.009844	0.006070–0.034087
	loss as % of applied	1.53%	0.94–5.30%
Alternative 6: banded application, 25% rate	applied	0.159960	–
	runoff loss	0.000632	0.000338–0.001068
	sediment loss	0.000000	0.00–0.000009
	total loss	0.000632	0.000338–0.001077
	loss as % of applied	0.40%	0.21–0.67%
Alternative 7: spring-applied, Roundup-ready corn varieties	applied	0.639839	–
	runoff loss	0.011615	0.004646–0.029539
	sediment loss	0.000009	0.00–0.000009
	total loss	0.011624	0.004646–0.029548
	loss as % of applied	1.82%	0.73–4.62%
Alternative 8: spring-applied, with constructed in-stream wetlands	applied	0.639839	–
	runoff loss	0.002857	0.000872–0.008660
	sediment loss	0.000000	0.00–00000000
	total loss	0.002857	0.000872–0.008660
	loss as % of applied	0.45%	0.14–1.35%

amount applied in runoff and sediment ranged from 0.09 to 1.98%. The following list ranks the BMPs from lowest to highest in atrazine losses and the simulated yearly percentage loss of the amount applied:

1. Alternative 4: Construct sediment ponds at confluences of tributaries and major creeks; 0.09%.
2. Alternative 2: Establish grass filter strips downslope of cropland areas; 0.14%.
3. Alternative 6: Apply banding at a 25% rate of atrazine at planting time; 0.40%.
4. Alternative 8: Construct wetlands in-stream where possible; 0.45%.
5. Alternative 1: Incorporate atrazine at time of application by disk tillage; 1.25%.
6. Alternative 3: Enhance residue levels by adopting conservation tillage, substituting disk tillage with field cultivator tillage; 1.37%.
7. Alternative 5: Implement fall–spring split applications (1/2-rate per application); 1.53%.
8. Alternative 7: Adopt no-tillage corn and plant Roundup-ready corn varieties; 1.82%.
9. Base: Use conventional disk tillage with no incorporation of atrazine following the application; 1.98%.

All BMPs use the common practice of non-incorporation of 1.68 kg ha^{-1} spring-applied atrazine and use conventional disk operations in preparing land for corn and sorghum except, of course, in the individual cases of the third-ranked BMP of banding a 25% rate at planting time; the fifth-ranked BMP, which immediately incorporates spring-applied atrazine by disking at application time; the sixth-ranked BMP, which substitutes the field cultivator for the disk; and the seventh-ranked BMP, which applies 1/2-rate split applications in the fall and spring.

These results suggest five major implications. First, constructing sediment ponds at confluences of tributaries with the main channel and building in-stream wetlands can be significant in cutting atrazine encroachment in Aquilla Lake, largely due to the fact that ponds and wetlands have the capability to slow or retain atrazine flows.

Second, similar logic can be used for the reason that grass filter strips reduce atrazine losses. Obviously, the amount of atrazine runoff reduction is contingent upon the number of constructed sediment ponds in a watershed area and the width of the filter strips over which runoff occurs. In this study, 20 sediment ponds were simulated in the Aquilla Watershed and 10% of the cropland was assumed for filter strips down-slope of each cropland area.

Third, using herbicide banding is environment-friendly regarding atrazine losses since the rate applied is reduced significantly, 75% in this case. Weed pressures in the furrow will, however, require additional row cultivation, adding to the tillage costs and marginally to runoff and sediment losses.

Fourth, incorporating atrazine at the time of application cuts atrazine losses by enhancing soil adsorption, which stabilizes atrazine in the soil, thereby decreasing the potential of atrazine loss from runoff.

Fifth, since atrazine losses are largely influenced in the Aquilla Watershed by runoff in lieu of sediment (except when occasional heavy rainfall events occur on a bare, highly erodible soil surface), conservation tillage and no-tillage, which focus on minimizing soil erosion, are not highly effective in reducing atrazine losses compared with other remedial measures.

LIMITATIONS

The major limitation is the absence of long-term in-stream and reservoir atrazine measurements with which the APEX model could be further validated. Future research should use any new in-stream and reservoir measurements for improved model validation.

ACKNOWLEDGMENTS

The Texas State Soil and Water Conservation Board (Temple, TX) is recognized for their outstanding and continuing support in completing this research despite a breach of funding mid-project by the Texas Commission on Environmental Quality (Austin, TX).

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