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Application of Mathematical Modeling to Determine The Size of On-Site Grass Filters for Reducing Farm Pesticide Pollution

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ABSTRACT

This paper presents a mathematical approach for estimating the size of a grass filter area for removing pesticide residues from agricultural drainage waters. The method utilizes a water table management model, DRAINMOD, for simulating drainage waters from agricultural land and then a solute transport model, PRZM2, for simulating pesticide concentrations in drain effluent discharging from grass filters. DRAINMOD was used to estimate daily drain outflows that occurred in a 100 ha subsurface drained field in the Ottawa-St. Lawrence lowlands by running the model for a one-in-twenty year annual rainfall period. Atrazine (AZ), metolachlor (MT) and metribuzin (MZ) are the most common herbicides that are found in drainage waters. The simulated drain outflows were assumed to contain 50 µg/l of AZ, MT and MZ residues, and simulations were carried out with PRZM2 to determine the required size of grass filter area to make drainage waters safer for aquatic life and a marine habitat. It was found that no more than 6% of the farm area could be used to reduce the concentrations in drainage waters from 50 µg/l to less than 1 µg/l for the three herbicides.

Keywords: Atrazine, DRAINMOD, Grass strips, Metolachlor, Metribuzin, PRZM2, Subsurface drainage.

INTRODUCTION

Agricultural chemicals applied to cultivated fields with subsurface drains are an environmental concern with potential effects on the health of all living beings. Many pesticide residues have been detected in streams, tile drain effluent and ground water with concentrations far above the standard level for drinking water (Flury, 1996; Muir and Baker, 1976; Frank and Sirons, 1979; and Wauchope, 1978).

Soil scientists and engineers have developed technologies to reduce pollution from contaminated waters. Sand filtration has been used for the purification of drinking water (Steel and McGhee, 1979). Grass filtration (grass strips) is used in the prevention of sediment production, in the reduction of sediment yields from agricultural watersheds, in food industry wastewater treatment, in feedlot runoff treatment, and in municipal sewage effluent. Filter strips have also been evaluated for their ability to control herbicide runoff losses (Mickelson and Baker, 1993).

The combination of sand and grass filters was found to be effective in reducing herbicides from agricultural waters (Liaghat *et al*., 1996; Liaghat and Prasher, 1996) and in removing sediment from river water (Nsengiyumva *et al*., 1994). Liaghat and Prasher conducted a lysimeter and a field study to investigate the effect of soil and grass strips in reducing pesticides from contaminated waters. They applied contaminated water consisting

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of 50 μg/l of AZ, MT and MZ, on field and lysimeters. Then, they found a reduction in concentration of polluted water to less than 1 μg/l when it passed through the soil and grass filters. In such a system, polluted waters from a large agricultural drainage area are collected by a system of drain pipes, ditches and canals, and then pumped on to a smaller filtration area, underlain by a subsurface drainage system, for treatment. The water infiltrates through the grass filter into the soil profile and the treated water, coming out of tile drains from the filtration area, can be discharged to streams or other receiving waters.

The efficiency of combined systems for pesticide removal depends on meteorological data, soil characteristics, chemical properties, and mainly the size ratio of filter area to farm area. Among those, only the size of ratio can be manipulated to assess the desired level of contaminant in drainage waters. Thus, methods are needed to determine the size of filtration area for treating agricultural drainage water. Conducting field-scale experiments is expensive and time consuming. A cheaper and faster alternative is the use of computer simulation models. This article presents a computer modeling approach for determining the size of filtration area for removing pesticide residues from agricultural drainage waters. The method utilizes a water table management model, DRAINMOD, for simulating drainage waters from agricultural land and a solute transport model, PRZM2, for simulating pesticide residues in treated waters.

MODEL DESCRIPTION

DRAINMOD Simulation Model

DRAINMOD is a well known field scale water management model, developed by Skaggs (1978). Extensive field testing of DRAINMOD has been undertaken in many areas of Canada and the US (Skaggs, 1982; Mackenzie and Prasher, 1989; and Shukla *et al*., 1994). DRAINMOD was developed for shallow water table soils and is based on a water balance in the soil profile at the mid-point between two drains. The model uses climatological records to simulate the performance of drainage and water table control systems in a field bordered by parallel ditches or subsurface drains. Input data to DRAINMOD includes soil properties, crop parameters, drainage system, site parameters, and the weather data. Soil property inputs include saturated hydraulic conductivity for each layer, relationships between drainage volume and water table depth, and information concerning upward flux from the water table. The effective root zone depth as a function of time is also an input. In general, the basic time increment used for simulation in the model is one hour. However, it could be switched to two hours or a one day period depending on drainage and evapotranspiration (ET) rates under zero rainfall conditions. During rainfall events, depth of infiltration and surface runoff are predicted in three-minute increments. The number of trafficable days, sum of excess water table rises above a 300 mm depth (SEW_{30}), and planting data are estimated and stress-day-index methods are used to calculate yield response to excessive and deficient soil water conditions. Output of model predictions is available on a daily, monthly, or annual basis. The performance of a given system design or management alternative can be simulated for a long period of climatological record (i.e. 20 to 40 years) to consider the effects of the year-to-year and seasonal variability.

PRZM2 Simulation Model

The PRZM2 model provides a state-of-the-art deterministic simulation for movement of solutes in porous media for steady-state, transient, and multi-layered conditions. It simulates the fate of pesticides in crop root and vadose zones taking into account the effects of agricultural management practices. PRZM2 links two subordinate models: PRZM and VADOFT, to predict pesticide transport and transformation down through the crop root and unsaturated zones.

PRZM (Pesticide Root Zone Model) is a well known continuous simulation model, which was developed at the EPA Laboratory in Athens, Georgia, by Carsel *et al.* (1985). PRZM is a one-dimensional finite-difference model, which accounts for pesticide fate in the crop root zone. PRZM is able to simulate multiple zones, transport and transform the parent compound and as many as two daughter species within and immediately below the plant root zone. PRZM has two major components: hydrology and chemical transport. The hydrology component calculates runoff and erosion based on the Soil Conservation Service (SCS) curve number technique and the Universal Soil Loss Equation (USLE). Evapotranspiration is estimated either directly from pan evaporation data, or based on an empirical formula. Water movement is simulated using generalized soil parameters, including field capacity, wilting point, and saturated water content. The chemical transport component can simulate pesticide application on soil or on plant foliage as well as biodegradation in the root zone. Dissolved, adsorbed, and vapor-phase concentrations in the soil are estimated by the simultaneous consideration of the processes of pesticide uptake by plants, surface runoff, erosion, decay, leaching, foliar wash-off, advection, dispersion, and retardation. PRZM2 incorporates several additional features to those simulated in the original PRZM code, in particular soil temperature simulation, volatilization and vapor phase transport in soil, irrigation simulation, microbial transformation, and a method of characteristics (MOC) algorithm to eliminate numerical dispersion.

VADOFT is a one-dimensional, finite element code that solves Richard's equation for flow in the unsaturated zone. VADOFT simulates the movement of pesticides within and below the plant root zone and assesses subsequent groundwater contamination. VADOFT can also simulate the fate of two parent and two daughter products. Transport processes include hydrodynamic dispersion, advection, linear equilibrium sorption, and first-order decay. The model simulates infiltration or recharge rate and solute mass flux entering the saturated zone.

PRZM2 predictions are made on a daily basis. Output can be summarized for a daily, monthly, or annual period. Daily time series values of various fluxes can be reported to sequential files during program execution for subsequent analysis.

MATERIALS AND METHODS

Field Site

In order to determine the size ratio of filtration area to farm area, a field site with St-Amable sandy soil (Ferro-Humic podzol) was selected at Macdonald Campus of McGill University to simulate the drain outflows and pesticide residues in drainage waters flowing out of the farm and filtration areas. This farm was chosen because several soil properties and pesticide characteristics (Table 1) had been measured at that site in previous studies (Liaghat *et al.*, 1996). The soil consists of 91.3% sand, 4.2% silt, 3.5% organic matter content; the bulk density of the soil is 1.4 g/cm^3.

Atrazine and metolachlor herbicide are normally applied to the corn-growing area of Quebec in pre- or post-emergence applications at a rate of 2.4 and 2.7 kg/ha of active ingredient, respectively, and metribuzin herbicide is applied on potato farms in Quebec at a rate of 1 kg/ha of active ingredient. Drainage water from the corn-growing area drains into a small lake.

Design Procedure

The procedure contains two components; hydrology and test analysis. These components are explained in more detail in the following sections.

Hydrology

Forty years of annual rainfall data (1955 to 1995), measured at the Dorval Airport weather station (Montreal, Quebec, Canada), were used to predict a 1-in-20 year annual rainfall. The rainfall data was sorted in a descending order and a 1-in-20 year annual rainfall was chosen to use its daily rainfall and maximum and minimum temperatures for running the DRAINMOD model. The concept of 1-in-20 year annual rainfall was to consider the worst case scenario of rainfall that could occur on site. The 1-in-20 year annual rainfall is a conservative return period for any drainage project (Smedema and Rycroft, 1983). The year 1972, with an annual rainfall of 685 mm, was the one with a 20-year return period.

DRAINMOD was used to estimate the daily drainage water (runoff and subsurface drainage water) that would occur in a 100 ha subsurface drained field by running the model for 1972 meteorological data. The drainage parameters required are drain spacing, drain depth, and drainage coefficient, which were 20 m, 1 m, and 10 mm/day, respectively. These are common values for southern Quebec agricultural lands (Brougthon, 1972).

Daily rainfall and maximum and minimum temperatures were entered into DRAINMOD as the weather input data. Hydraulic conductivity of the soil was measured to be 3 m/day. Soil moisture retention data was measured in the laboratory by Haines Funnel and pressure plate apparatuses.

Test Analyses

The filtration area was tested for two purposes: a) infiltration test in which the filtration site was tested for the maximum infiltration rate and its size was increased so as to pass all drainage water draining from a 100 ha agricultural farm; and b) the trapping test; in which the filtration site was tested for trapping herbicides and its size was increased so as to trap most of the pesticides in drainage waters and bring the levels down to acceptable levels that would be safe for aquatic life.

Infiltration Test

In our case, the filtration area should be able to accommodate daily drainage waters from a 100 ha agricultural farm. Therefore, the pumping rate should be equal to or less than the infiltration rate of the filtration site in order to eliminate storage needs for drainage waters. The pumping rate depends on size of the filtration area and it can be expressed as follows:

$$R_p = R_d \times 100 / A \qquad (1)$$

where, R_p is the pumping rate (mm/day per ha), R_d the drain outflow rate from agricultural land (mm/day), and A the size of filtration area (ha).

Drain spacing and drain depth for the filtration site were chosen to be 10 m and 1 m, respectively. The drainage coefficient was calculated from Equation 2 (Kirkham, 1949), which describes drain flow in homogeneous and saturated soils.

$$Q = 2\pi K\,(t + h - r) / \ln(2h / r) \qquad (2)$$

Where, Q is the flow into a unit length of drain per unit time (m/day), K the hydraulic conductivity (m/day), t the depth of water ponded on the soil surface (m), h the depth from soil surface to center of drain (m), and r the radius to outside of drain (m).

Use of Equation 2 assumes that drainage is limited by the rate of soil water movement to the lateral drains and not by the hydraulic capacity of the drain tubes or of the outlet. The maximum depth of water ponded on the filtration area was chosen to be 0.3 m. Therefore, the drainage coefficient was calculated to be 0.7 m/day. Usually, the size of the drain tubes is chosen to provide a design flow capacity, also known as the drainage coefficient. The drainage coefficient (m/day) for a given slope and size of drain can be obtained from Manning's equation, expressed as follows.

$$Q = 86{,}400\, R^{2/3}\, S^{1/2}\, A_t / (A_d\, n) \qquad (3)$$

where n is Manning's coefficient, R is the hydraulic radius (m), S the slope, A_t the cross section area of the drain pipe (m^2), A_d the area of the drained area (m^2) that is equal to L x S in which L is the length of drain pipe (m) and S is the drain spacing (m).

Manning's coefficient, slope, length, and size of drain pipes for the filtration area were 0.015, 0.0025, 100m, and 0.15m, respectively. Therefore, the drainage coefficient, estimated by Manning's equation, was 0.25 m/day.

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Table 1. chemical properties of atrazine, metolachlor, and metribuzin

Property	Atrazine	Metolachlor	Metribuzine	Source
Solubility (mg/l)	33	530	1220	Wauchope *et al*., 1991
Partition Coef., K_d (ml/g)	2.7	5.0	1.6	Liaghat *et al*., 1996
Soil half life (day^{-1})	60	90	40	Wauchope *et al*., 1991
Henry's constant	2.5E-7	3.8E-7	9.8E-8	PRZM Manual

However, a conservative input value for the drainage coefficient was set at 0.2 m/day.

The investigation started with A = 1 ha and the DRAINMOD model was used to evaluate this test for every day of the year. The result of this test showed a runoff water occurrence on the filtration area, indicating that a 1 ha filtration area is not able to pass all drainage water flowing out of a 100 ha field. Therefore, the size of filtration area was increased to 2 ha and DRAINMOD model was run again to evaluate the new size of filtration area.

Trapping Test

It was assumed that the simulated drain outflows from the farm area (100 ha) contained 50μg/l of atrazine, metolachlor, and metribuzin residues, and simulations were carried out with PRZM2 to determine the required size of the grass filter area to make drainage water safer for aquatic life and the marine habitat. The nodal spacing for PRZM was chosen to be 1 cm and pesticide movement was simulated to a depth of 100 cm, which is equal to the drain depth. Plant growth was introduced to the simulation model by inducing cropping soil conditions over the simulation period. The root depth and plant uptake factor for the grass strips were chosen to be 15 cm and 0.3, respectively.

Soil properties, such as organic matter content and bulk density, were previously measured to be 3.5% by weight and 1400 kg/m^3, respectively (Liaghat *et al*., 1996). Values of decay rate, solubility and partitioning coefficient for the three herbicides are given in Table 1. The dispersion coefficients for the three herbicides were set at zero, as suggested by the PRZM Manual.

RESULTS AND DISCUSSION

DRAINMOD was run with 1972 meteoro-

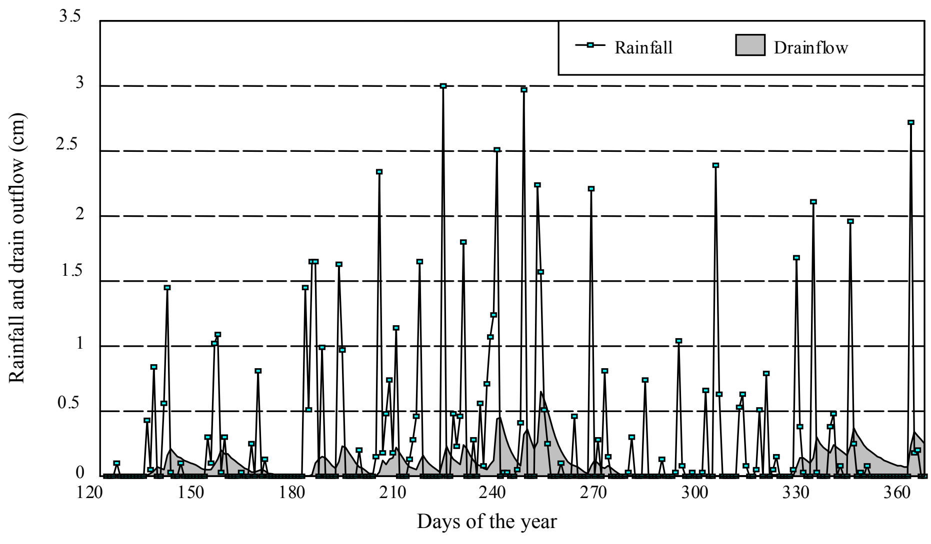

Figure 1. Daily rainfall and simulated drain outflow per unit area for 1972.

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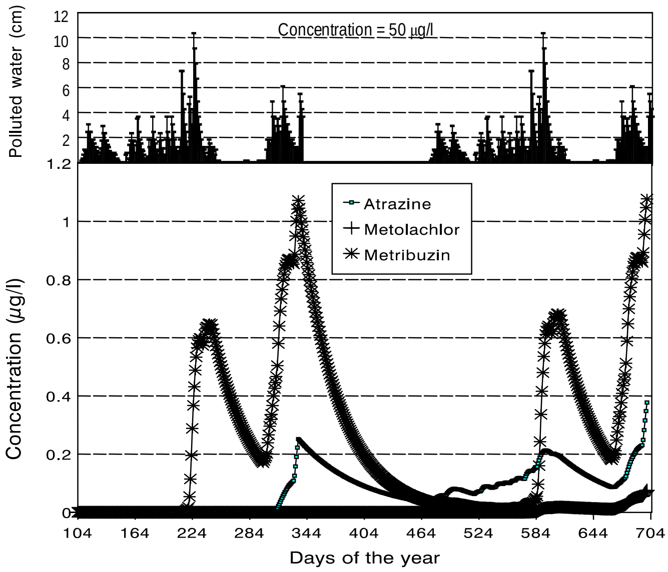

Figure 2. Predicted pesticide concentrations in treated water escaped from filtration area on a daily basis.

logical data to simulate the daily drain outflow from the 100 ha agricultural field. Figure 1 shows the daily rainfall and drain outflows as simulated by DRAINMOD for 1972. It shows that the drains would have flown continuously during the summer, thus representing a worst case scenario for this analysis.

The drainage coefficient for the filtration area, using Equations 2 and 3, was estimated to be 0.7 and 0.25 m/day, respectively. This indicates that the drainage or infiltration rate for the soil was limited by the discharge capacity of the drain pipes, and not by the rate of soil-water movement towards the drains.

The infiltration test had revealed that filtration area of at least a 2 ha is required in order to pass all drainage water through the soil profile without causing any surface runoff. The trapping test was performed for the 2 ha filtration area, running the PRZM2 model. However, the efficiency of the filtration area was found to be inadequate in lowering the concentration level of pesticides in drainage waters to the maximum acceptable level of 1 µg/l for aquatic life. Therefore, this test was also performed for 3, 4, 5, and 6 ha filtration areas and for two consecutive years, assuming that the 1-in-20 year annual rainfall occurred in two consecutive years. This represents the worst case scenario for an agricultural fields in this region. Figure 2 shows simulated pesticide concentrations in treated water from a 6 ha filtration area on a daily basis. This figure shows that the concentrations are less than 1 µg/l on all the days, with the exception of a few days during the two year period for metribuzin herbicide. This indicates that 6% of the farm area can be used to bring down the concentration level in drainage waters from 50 µg/l to less than 1 µg/l for the three herbicides under local meteorological conditions. In Figure 2, the high concentration levels belong to metribuzin herbicide which has a higher water solubility and a lower soil sorption coefficient. The low concentration levels belong to metolachlor herbicide, which has a higher soil sorption coefficient. The concentration levels of atrazin herbicide lie in between. This indicates that a smaller filtration area is needed for reducing herbicides with low water solubility and a high soil sorption coefficient.

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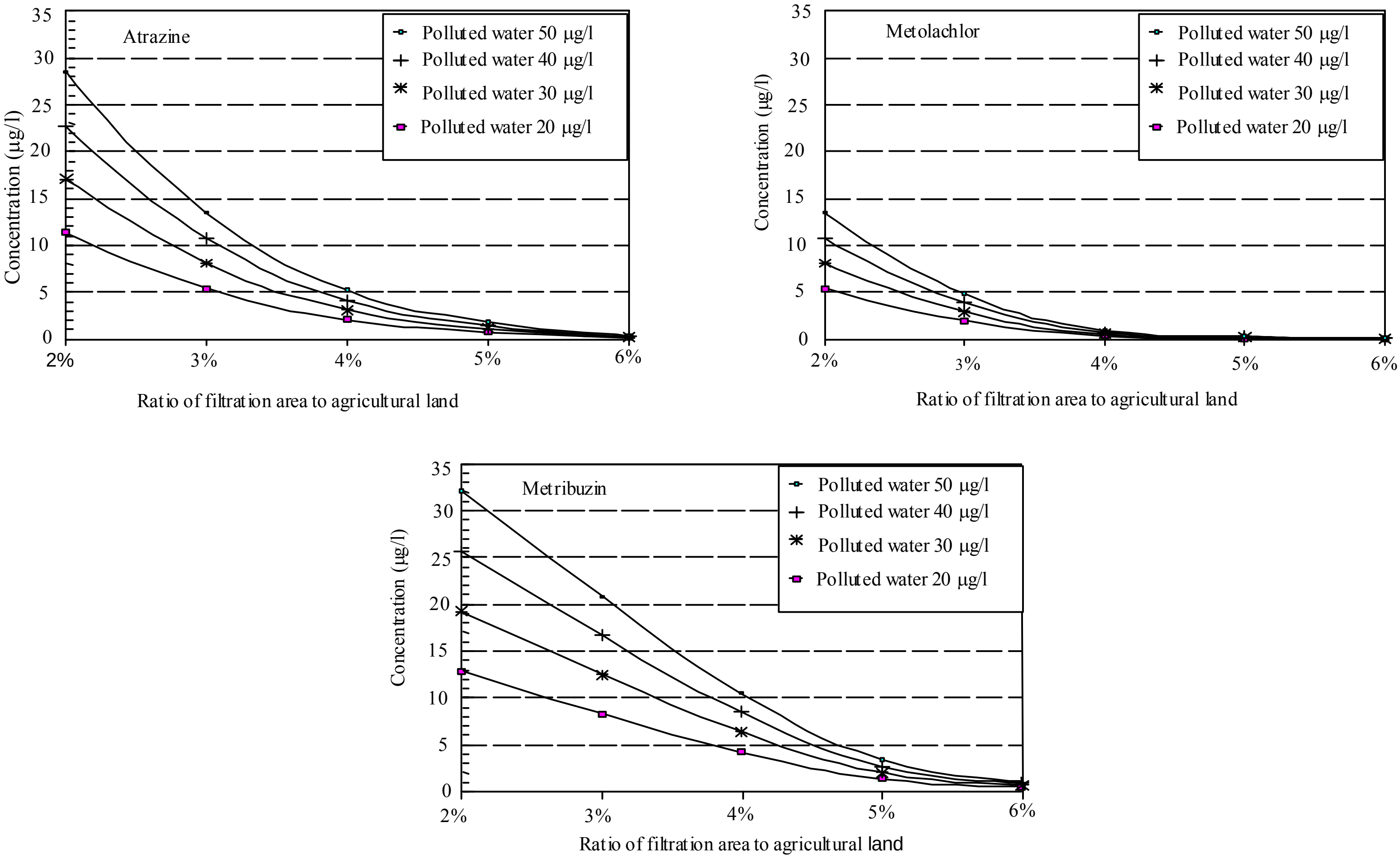

Figure 3. Maximum concentration level of atrazine, metolachlor, and metribuzin in treated water for the different filtration size and different contaminant levels of drainage waters.

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Determination of the size of filtration area was also determined for different levels of contaminants, such as 20, 30, and 40 μg/l, that may be found in drainage waters under various circumstances. Figure 3 illustrates the maximum concentration levels of atrazine, metolachlor and metribuzin in treated water according to the size ratio (filtration area to farm area) and the level of contaminant in drainage water. Knowing the contaminant level in polluted water and the maximum acceptable level, one can determine the size of filtration area from this figure.

It should be noted that a worst case scenario was considered in this study, with contaminant levels in drainage waters at 50 μg/l. In actual practice, the concentrations will fluctuate, depending on the time of year. In addition, the contaminant level in drainage waters during wet years, or following heavy rainfalls, would be low due to a dilution effect, while the total loss of pesticides may be greater for such years.

One should also note that the simulation was performed such that the system does not require any on-site water storage. However, in many regions, natural lakes or ponds are available and may be used for storage of polluted drainage waters during heavy rainfalls and, later on, may be pumped on to the filtration area. This can reduce the required size of the filtration area.

CONCLUSIONS

A computer modeling approach was used to determine the size of filtration area required for removing pollutants from agricultural drainage waters. DRAINMOD and PRZM2 models were used to determine the required size of filtration area for an agricultural farm in Southwestern Quebec for a 1-in-20 year rainfall period. The results of this study show that no more than 6% of farm area can be used to reduce pesticide concentration in drainage waters from 50 μg/l to less than 1 μg/l. This procedure can also be used at other sites in determining the required size of filtration area.

In this study, the 6% of land area for the filtration site was obtained based on a worst case scenario. However, it may be noted that the actual land area required for filtration will be less than 6% since this figure was derived for a 1-in-20 year annual rainfall event and by assuming 50 μg/l pesticide concentrations in drainage waters. The herbicide concentration in drainage waters will seldom remain at a 50 μg/l level throughout the drainflow period, especially when the high rainfall occurs. In most cases, it will be much less than 50 μg/l, and thus a smaller area will be needed for filtration purposes. The mathematical approach given in this paper can only be used to perform these types of analyses.

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استفاده از مدلهاي رياضي بمنظور تخمين اندازه فيلترهاي چمني جهت كاهش آلودگي‌هاي كشاورزي

ع. لياقت و اس. او. پراشر

چكيده

اين مقاله يك روش رياضي براي تخمين اندازة فيلتر چمني جهت كاهش آلودگي‌هاي كشاورزي از زه‌آبها ارائه مي‌دهد. در اين روش از يك مدل مديريتي سطح ايستابي بنام DRAINMOD ، به منظور برآورد حجم زه‌آبها از اراضي كشاورزي و از يك مدل حركت املاح بنام PRZM2 براي تخمين غلظت سموم در زه‌آبهاي تصفيه شده توسط فيلتر چمني استفاده شده است. براي تخمين زه‌آبهاي روزانه در يك سال پرباران با دورة برگشت ۲۰ ساله كه از يك مزرعه ۱۰۰ هكتاري مجهز به سيستم زهكشي در اراضي سنت لورنت اتاوا (كانادا) اتفاق مي‌افتد، مدل DRAIMOD استفاده گرديد. آترزين (AZ) ، متالكلور (MT) و متري بيوزين (MZ)، مهمترين علفكشهايي موجود در آبهاي زهكشي منطقه مي باشند. در اين تحقيق بقاياي علف كشهاي مذكور (MZ, MT, AZ) در زه‌آبهاي برآورد شده توسط مدل ۵۰ ميكرو گرم در ليتر فرض گرديد. با استفاده از مدل PRZM2 شبيه‌سازي‌هائي به منظور تعيين اندازه فيلتر چمني مورد نياز كه آلودگي

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زه‌آبها را تا حد قابل قبولي براي زندگي آبزيان تصفيه نمايد، انجام شد. نتايج تحقيق نشان مي‌دهد كه به منظور كاهش غلظت علف كشها در زه‌آبهاي منطقه از سطح ۵۰ ميكروگرم در ليتر به يك ميكروگرم در ليتر، لازم است تا كمتر از ٦ درصد اراضي كشاورزي براي فيلتر چمني اختصاص يابد.

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