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Review

Review of hydrologic assessment models for predicting pesticide leaching in Nigeria

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The need to evaluate the potential risks of pesticides usage that may lead to contamination of water resources has been the reason behind the development of models for predicting pesticide leaching in soils and watershed areas. Various assessment models have been developed in the past. For example, the vulnerability of groundwater to pesticide leaching may be evaluated by indices and overlay-based methods, by statistical analyses of monitoring data, or by using process-based models of pesticide fate. Most of these models have been applied in various parts of the world but with little or none applicability in Nigeria. Since Nigeria is an agrarian country whose soils and water resources have suffered severely from the effects of pesticide contamination, the need to inform decision on applicability of some of these models becomes paramount. This paper thus provide a descriptive synthesis of some of the models used in predicting pesticide leaching in underground water and make recommendation for their usage in assessing groundwater contamination effects resulting from agricultural processes in Nigeria.

Key words: Groundwater, model, pesticide, hydrologic, simulation, management.

INTRODUCTION

The intensification of agricultural production and the associated increased applications of agrochemicals have caused water pollution to be a serious threat to the environment, and consequently, to human and animals. Sources of water pollution are either point or nonpoint. Nonpoint source (NPS) pollution has been recognized as an important environmental problem with negative effects on agricultural productivity, and soil and water quality (USEPA, 2006). Groundwater quality concerns have resulted in the need for tools, such as computer models, to evaluate effects of interacting processes on chemical movement within and through soils. For instance, Novotny (1986) reviewed several hydrologic and water quality models and concluded that a good NPS pollution model should represent the spatial variability of the area and simulate the distributed physical process of water pollution. Studies by Vieux et al. (1989) and Arnold et al. (1990) have tried to combine different spatial data sets with distributed hydrological NPS pollution models to reduce the time and effort required for model data input.

Pesticide contaminated surface water can reach groundwater which, in turn, can reach the surface and contribute to surface-water pollution. Once in the ground water, pesticides can persist for years, rendering the water unsuitable for human and animal consumption (Ehteshami et al., 1991).

There are numerous literatures concerning pesticide contamination. Rao et al. (1985), Leonard et al. (1988), and Pionke et al. (1988) reported concentration of pesticides in their experimental field and agricultural areas in states from Florida to California. Oki and Giambelluca (1987) reported pesticide contamination and closure of water-supply wells on Oahu Island, Hawaii. Jury et al. (1987) used soil and pesticide chemical characteristics to model pesticide contamination. Their model used uniform values of soil-water content and soil bulk density and did not consider the effect of actual rainfall and irrigation water on pesticide movement and groundwater contamination. Carsel et al. (1988) used a pesticide root zone model (PRZM) as a screening procedure for aldicarb contamination in the peanut growing areas in North Carolina. Their simulations indicate a significant mass flux to groundwater. Banton and Villeneuve (1989) compared the pesticide DRASTIC index and the PRZM leaching quantity model for evaluation of groundwater vulnerability to pesticide contamination. They concluded that chemical characteristics of the potential contaminants, which are not considered in the DRASTIC index, are important.

Addiscott and Wagenet (1985) categorized pesticide leaching models into three types: 1) detailed research models such as LEACHM (Wagenet and Hutson, 1989) and RZWQM (Hanson et al., 1998), 2) management models such as GLEAMS (Leonard et al., 1987) and PRZM (Carsel et al., 1985), and 3) screening models such as PESTAN (Enfield et al., 1982).

Borah and Bera (2003) reviewed eleven watershed-scale hydrologic and non-point source pollution models based on model capability, temporal and spatial representation, mathematical strength, and applicability of hydrology, sediment, chemical, and BMP components. Numerous lumped and distributed parameter hydrologic/water quality (H/WQ) models have been developed to predict the impacts of agriculture on the quality of water, including EPIC (Erosion Productivity Impact Calculator), CREAMS (Chemicals, Runoff, Erosion from Agricultural management Systems), WEPP (Water Erosion Prediction Project), ANSWERS (Aerial Nonpoint Source Watershed Environment Response Simulation), and AGNPS (AGricultural NonPoint Source). Models can evaluate alternate management practices for controlling soil erosion, sediment transport, and loss of agrochemicals. They provide a basis for guiding management and regulatory decision-making processes. They can also be used to help plan where, when, and what to monitor, thus making monitoring more effective and less costly.

Many of these models have been used to a greater or lesser degree world-wide. However, none of these models have been used in predicting pesticide leaching in groundwater in Nigeria. Being an agrarian country that utilizes insecticides, fungicides, pesticides etc., in agricultural production, it is believed therefore that much of the surface and groundwater would have been polluted by such activities. Although much has been done on agricultural water quality studies in various parts of Nigeria, none of such studies uses any of these models. This paper thus reviews by syntheses some of the popularly used hydrologic models for predicting pesticide leaching in groundwater. This is done with the hope that researchers can replicate some of these models to test their applicability in Nigeria, thus providing farmers and decision makers and other stake holders with information useful for groundwater pollution control.

MATERIALS AND METHODS

Five models are reviewed. Three of these models (CREAMS, GLEAMS and PRZM) are physically based field scale models. The HSPF is a continuous watershed scale model while RZWQM is a process based research level model. Using qualitative technique, each of the models is synthesized based on various works available.

HYDROLOGIC MODELS FOR PREDICTING PESTICIDE LEACHING

Hydrologic simulation program-FORTRAN

The Hydrologic Simulation Program-FORTRAN (HSPF) (Johanson et al., 1984) is the most comprehensive water quality model developed to date, and has been extensively used for NPS modeling. HSPF is a continuous, watershed-scale model developed to simulate the movement of dissolved oxygen, organic matter, temperature, pesticides, nutrients, salts, bacteria, sediment, pH, and plankton from the land surface through streams, reservoirs, and groundwater. Both point and nonpoint sources can be simulated. This allows comparisons between the relative magnitudes of point and NPS pollution during water quality planning. HSPF allows the watershed to be subdivided into land segments with relatively uniform meteorologic, soils, crops, and management practices. Runoff from the land segments drains to channel reaches with uniform hydrologic properties and to larger receiving waters if they exist. It is difficult to include many land segments in the model because this greatly increases calibration and input data requirements (Butler, 2007). HSPF requires several years of historical hydrologic records for calibration, which is often a limitation for its use. Since HSPF is based on a calibrated parameter set, it is very difficult to evaluate changing watershed conditions caused by BMP implementation.

Chemicals runoff and erosion from agricultural management systems

Chemicals Runoff and Erosion from Agricultural Management Systems (CREAMS) (Knisel, 1980) is a physically-based, field-scale model developed for making relative comparisons of pollutant loads from alternate management practices. The model has been applied in many areas of the world and has been the most widely used model for field-scale assessment. The model is intended for use as a continuous simulation model, but it also can be used as an event-oriented model. The model has three basic components: hydrology, erosion/sediment transport, and chemistry.

The hydrology portion estimates runoff volume, peak runoff, infiltration, evapotranspiration, soil moisture, and percolation. The erosion component estimates sediment yield and particle-size distribution of eroded sediment. The chemistry component estimates losses of dissolved and adsorbed nitrogen, phosphorus, and pesticides in surface runoff and percolate (Butler, 2007).

The primary limitations of the model are that it is field-scale and, consequently, limited to areas with uniform soils and cropping and does not consider pollutant transport between the field and receiving waters. Testing of CREAMS has found that it is more accurate in representing average annual runoff volumes than daily or monthly runoff volumes (Smith and Williams, 1980). Losses of sediment and other pollutants would be expected to follow a similar trend. CREAMS does not require observed data for parameter calibration, but observed data can be used to adjust sensitive parameters to improve model accuracy (Leonard and Knisel, 1988). One of the most attractive features of CREAMS is its comprehensive user's manual, which documents the model's development and facilitates parameter selection.

Groundwater loading effects of agricultural management systems

The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model (Leonard et al., 1987) is a continuous simulation, physically based field scale model, that was developed to analyze how agricultural management practices, such as tillage operations, irrigation, and planting dates affect nutrient and pesticide leaching into groundwater sources (Reyes et al., 2004). The GLEAMS model is an extension of the Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS) model (Knisel, 1980; Gerwig et al., 2001).

GLEAMS uses the basic foundation of CREAMS and adds components to simulate the movement of water and chemicals within the crop root zone. At present, GLEAMS only simulates subsurface movement of pesticides, but a nitrogen model is being developed.

This model is an extraordinary water quality tool that is capable of analyzing pesticides, soil properties, climate effects, and the effect of small-scale management decisions on surrounding waterbodies (USDA, 2006). The GLEAMS model can be broken down into four major components that include: hydrology, erosion/sediment yield, pesticide transport, and nutrients (Reyes et al., 2001). A mass balance approach is used for the hydrology component of the GLEAMS model. Infiltration, runoff, irrigation, evapotranspiration and soil water movement within and through the root zone are considered under the hydrology component. The modified SCS CN method is used to calculate runoff while percolation is determined by the storage routing technique (Reyes et al., 2004). Two methods can be used to account for evapotranspiration. These methods include the Priestley-Taylor method and the Penman-Monteith method (Reyes et al., 2001). The erosion component is basically the same as the CREAMS model with minimal modifications (Leonard et al., 1987). In order to simulate erosion, the GLEAMS model utilizes the USLE and both detachment and transport processes are simulated.

Another important portion of the GLEAMS model is the nutrient component. To adequately depict the actual processes that are occurring in the environment, the model simulates both the nitrogen and phosphorus cycle (USEPA, 2006). The final main component of the GLEAMS model is the pesticide component. The GLEAMS model calculates the daily decay of the pesticide based on its half-life. From the partition coefficient, part of the pesticide is lost to runoff solution while the other is retained in the soil phase (Leonard et al., 1987).

The GLEAMS model is an excellent tool for evaluating water quality and land management decisions and there are several advantages to using this model. One advantage is that the model is fairly easy to use and has very few input requirements (USEPA, 2006). Another advantage of using this model is that it is a continuous simulation model that allows users to evaluate the effects of management scenarios over a long period of time. There are several limitations of using the GLEAMS model. One disadvantage of using the GLEAMS model is that it is a field-scale model. This means that it is limited to simulation of management on a very small scale. Another disadvantage of using this model is that it is limited to agricultural fields. The model cannot be used to simulate processes that are occurring in urban watersheds. One more disadvantage is that the model assumes that the field being modeled is homogenous and thus does not account for spatial variability (USEPA, 2006).

PESTICIDE ROOT ZONE MODEL

The Pesticide Root Zone Model (PRZM) (Carsel et al., 1984) is a field scale continuous simulation model developed by the EPA to simulate the effects of agricultural management practices on pesticide fate and transport. It is a one-dimensional, daily time scale, management model for predicting pesticide movement within entire vadose zone. In addition to its use for pesticide registration, PRZM can consider cropping practices and agricultural management practices such as tillage. The model Simulates the entire vadose zone from the soil surface to groundwater. The vadose zone can be divided into several layers with varying properties and degradation rates. Pesticide processes considered include advective and dispersive flux, sorption, degradation in the soil, and plant uptake. Pesticide applications can be partitioned between foliage and the soil surface, and surface applications can be incorporated by tillage. The model permits only one application of pesticides per year, which may not be very realistic.

The model consists of hydrology and chemical transport components. The hydrology component includes surface runoff, evapotranspiration, and perco-lation. Modified curve number method (Williams and LaSeur, 1976) and modified universal soil loss equation

(Williams and Berndt, 1977) are used to simulate surface runoff and erosion. Actual evapotranspiration is calculated from the daily pan evaporation, soil water availability, and stage of crop growth. Remaining water, after subtracting runoff, evapotranspiration, and interception losses from rainfall, infiltrates into the soil matrix. The routing of soil water within the unsaturated zone is based on storagerouting techniques ("tipping bucket" scheme) that consider the water holding capacity of the soil, such as field capacity and wilting point. The chemical transport component predicts dissolved, adsorbed, and vapor phase concentrations in the soil considering convection-dispersion transport, plant uptake, degradation, and foliar wash-off. Pesticide degradation is described using first-order kinetics and sorption is assumed as linear. Different degradation rates can be defined for each soil layer as well as for plant foliage. PRZM has been validated in several studies;however, most of these studies emphasize soil water distribution and the behavior of pesticides in soil.

ROOT ZONE WATER QUALITY MODEL

Root Zone Water Quality Model (RZWQM) is a one-dimensional, process-based, research-level simulation model to simulate hydrologic and chemical responses of agricultural management systems (Hanson et al., 1998). The model can simulate plant growth and movement of water, nutrients, and pesticides over, within, and below the crop root zone by considering physical, chemical, and biological processes. RZWQM can be used as a tool for evaluating the impact of a variety of agricultural management practices on the behavior and movement of nitrate and pesticides to surface runoff and subsurface environment. These management practices include drainage, tillage and residue practice, crop rotations, and application (method, amount, and timing) of irrigation, fertilizer, manure, and pesticide. In addition to the simulation of a tile drainage system, the model can also simulate high and fluctuating water tables. RZWQM can also be used to estimate the potential loadings of non-point source pollutant to the ground water (Cho, 2007).

RZWQM consists of six major processes: physical, plant growth, soil chemical, nutrients, pesticide, and management processes. These processes are considered at daily and hourly time scales. Hourly based processes, which are contained in physical processes, include heat movement, infiltration and runoff, actual evaporation and transpiration, snowpack dynamics, soil water redistribution, pesticide wash-off, plant nitrogen uptake, chemical transport, and reconsolidation of tilled soils. Potential evapotranspiration is estimated using a revised version of the double-layer model of Shuttleworth and Wallace (1985). Sequential partial piston displacement and mixing approach, which is simpler than the convection and dispersion equation, is used to simulate transport of chemicals in the soil matrix. Pesticide processes include the transformations and degradation of pesticides on plant surfaces, crop residue, the soil surface, and in the soil matrix. Degradation algorithms allow for a single lumped dissipation constant or two dissipation rates that represent a quick dissipation period after the time of application until the next rainfall event and a slower dissipation period after a rainfall event. Adsorption coefficients are updated daily to consider variations in organic matter decomposition and bulk density changes (Hanson et al., 1998).

CONCLUSION

The essence of a groundwater quality monitoring system is a modern, rational, effective and permanent water quality control, a way to direct all the activities in the domain of protection against degradation and pollution, to find, in incidental cases, effective and adequate remedial measures, and to monitor and control the aftermath of incidents. In this paper an attempt is made to provide a review of few models out of a lot of models that existed and are used for evaluating pesticide contamination/leaching in groundwater. This review is intended to provide a head way for researchers to apply any of these models to investigate pesticide contamination of groundwater in Nigeria. As stated earlier, the non utilization of these models in Nigeria calls for their applicability to test. It is hope that will aid further researchers into underground water quality assessment.

For further investigation, the following elements should be considered as key in establishing a sound groundwater management scheme:

- Identification and mapping of sources of pollution.
- Establishment of database and information management system.
- Development of groundwater vulnerability map.
- Assessing groundwater protection needs and priorities
- Initiation of a monitoring network.
- Integration of groundwater protection in the urban planning process, legislation and institutional coordination;
- Promotion of public awareness and participation.

The principal goal of a groundwater management strategy is to conserve the groundwater resource by preventing/reducing quality deterioration and over-exploitation. In Nigeria, groundwater occurrence and use is widespread, but highly localised. It is physically and economically unfeasible to protect all groundwater resources to the same degree. Preventing all impacts on groundwater quality, would also not allow for the much needed social and economic development. The protection of groundwater resources will have to be prioritised according to:

• The value of the resource.

- The vulnerability of the resource.
- The risk of adverse impacts on human health and ecosystems.

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