TITLE

A Review of Simulation Models for Evaluating the Effectiveness of Buffers in Reducing Pesticide Exposure

DATA REQUIREMENTS

None (Special Study)

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VOLUME 1 OF 1 OF STUDY

PAGE 1 OF 51

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Vegetated buffer areas established between agricultural fields and receiving waters have long been recommended as a best management practice (BMP) to reduce the amount of sediment, nutrients, and pesticides entering water bodies. The USDA Natural Resources Conservation Service recognizes several types of buffer areas, among them unmanaged buffers (UMBs) and intensively managed vegetated filter strips (VFSs). These practices have been documented to reduce pesticide transport from agricultural fields to receiving waters in field studies in a variety of cropping systems and hydrologic settings. Sabbagh et al. (2009) reviewed ten field studies with reported pesticide reduction efficiencies of between 11% and 100%. They reported that the factors that influence the efficiency of a buffer in reducing pesticide runoff are more complex than simply the width of the buffer. The mechanisms by which pesticide transport is reduced include particle trapping by vegetation, settling of suspended solids, infiltration of runoff, and pesticide degradation. The intensity and duration of the runoff event, the chemical properties of the pesticide, and the topographic, soil, and vegetation cover of the buffer determine the degree to which each mechanism will act to mitigate pesticide transport. While the body of data from field studies on the pesticide reduction efficiencies of buffers is a valuable source for guidance on the effectiveness of these BMPs, it is impossible to extrapolate these results to all conditions that might require investigation. For this purpose, we must turn to mathematical models to evaluate buffer effectiveness over the full range of conditions that may be required.

Five models were chosen for evaluation of their suitability and capability for simulating the effectiveness of VFSs and UMBs in reducing pesticide runoff from a treated field. These five models (APEX, PRZM, REMM, SWAT, and VFSMOD-W) were considered to have strengths in both their simulation of pesticide fate and transport and their approaches to simulating VFSs and/or UMBs. While these models share many characteristics and capabilities, they can be differentiated in several important respects, including: spatial and temporal scale, modeling approach (empirical versus physical), input requirements, types of buffers modeled (VFSs, UMBs), and the range of physical processes accounted for within each model.

This document provides important background information on APEX, PRZM, REMM, SWAT, and VFSMOD-W, as well as focused discussions on each model’s approach to simulating the reduction in pesticide transport in runoff through a buffer. To enable direct comparison of certain model characteristics, an evaluation criteria matrix was developed. This criteria matrix summarizes a broad range of model characteristics, including model scale, model use and capabilities, model input requirements, weather data requirements, hydrology simulation, sediment simulation, source field simulation, buffer simulation, pesticide fate and transport processes, pesticide entrapment in buffer, and model usability. Based upon the model descriptions and the evaluation criteria matrix, we specify key conceptual and function differences among the models and explicitly identify the most significant strengths and weaknesses associated with each model. Model performance, while an important consideration when selecting a model, is not addressed in this report. Validation of each of the models evaluated has been independently described in the literature; however a direct comparison of the models using a common dataset has yet to be conducted. Until such a comparison study is completed, inclusion of model performance as a metric in the model evaluation will yield potentially misleading conclusions. At the close of this document, the reader will have gained a thorough understanding of how each model simulates pesticide reduction through a buffer and will be able to make an informed selection of the most appropriate model for a given application. A modeling study to compare the performance of each model using a common dataset is suggested as a future project.

1.0 INTRODUCTION

The use of vegetated filter strips (VFSs) and unmanaged buffers (UMBs) as agricultural best management practices (BMPs) has gained in popularity over the past decade, in part due to the National Conservation Buffer Initiative of the US Department of Agriculture, Natural Resources Conservation Service (NRCS) (Applied Research Systems, 1999). NRCS has also promoted conservation buffers specifically to reduce off-field movement of pesticides (USDA, 2000). Increasingly, the use of VFSs and UMBs is being recommended or required on pesticide labels as a mitigation measure to reduce the risk of pesticide runoff. In order to estimate the effectiveness of buffers in reducing pesticide exposure risk, one of two approaches is generally employed. The first approach involves designing and conducting field experiments to assess the effectiveness of buffers in reducing pesticide mass transport at the field edge. Recent reviews of such studies have shown that a wide range in VFS effectiveness has been observed in the field (Reichenberger et al., 2007; Sabbagh et al., 2009), making general statements regarding their presumed effectiveness untenable. Furthermore, the characteristics of a buffer that confer its pesticide removal efficiency have been shown to be more complex than simply buffer width (Lacas et al., 2005), suggesting that predicting removal efficiency based solely on buffer width is inappropriate.

Because unanticipated weather conditions can occur and accurate measurement of flow rate and representative sampling of overland flow between the edge of field and across a buffer is difficult, field runoff studies can become costly and sometimes inconclusive. Furthermore, results from field experiments are pertinent primarily to the specific site and chemical conditions the experiments were conducted for. Performing field studies to assess buffer effectiveness for every pesticide product under every crop, buffer width and condition, weather, and soil scenario for which they are required would be impractical and cost prohibitive. A second approach is to use mathematical simulation models to estimate the effectiveness of a buffer in reducing pesticide exposure. A properly calibrated and validated mathematical model has the advantage of being able to simulate a wide range of agricultural, meteorological, and buffer area conditions for a wide range of chemicals and geographical areas. The costs of parameterizing and running these models is considerably less than conducting field studies (although the value and necessity of field studies in the calibration and validation of mathematical models should not be understated).

This document will focus on a review of five currently available mathematical modeling approaches for evaluating buffer effectiveness in reducing pesticide runoff from treated agricultural fields. The review will first discuss the rationale for selecting the models chosen for evaluation. This will be followed by a detailed description of the approach and methods used by each of the models to simulate VFSs and UMBs. The model descriptions will be followed by a short section describing the model evaluation criteria and approaches used for model comparison. This will lead to a final discussion section that highlights conceptual and functional differences among the models, and presents significant strengths and weaknesses of each approach. A matrix summarizing the relevant characteristics of each model considered in the evaluation will be presented at the conclusion of the document.

2.0 MODEL REVIEW AND SELECTION

Many publicly and privately available water quality models include components that allow for the simulation of pesticide fate and transport. Among these, some provide capabilities for simulating best management practices such as VFSs and UMBs. A 2001 survey of water quality models by the Water Environment Research Foundation (WERF, 2001) provides an extensive review of several categories of water quality models, including non-urban and urban watershed runoff models, receiving water models, and chemical fate and transport models. While this publication has become somewhat dated, it still serves as a comprehensive survey of water quality models. The category of models evaluated by WERF that is most closely relevant to the models to be evaluated in this document is the group of non-urban watershed runoff models. Table 2.2 from the WERF (2001) report, reproduced in Appendix A–Table A.1 of this document, serves as a reference for non-urban runoff models, many of which contain the pesticide and buffer modeling capabilities required of models in this evaluation. In the discussion of the non-urban watershed runoff models, the WERF report includes pesticides as one of the main water quality constituents simulated by this group of models. This group of models has evolved primarily from the agricultural research community, with the algorithms used in their development derived from processes on agricultural landscapes. Within this class of models, models with the ability to simulate pesticide transport include: AGNPS (Young et al., 1989), APEX (Williams et al., 2008), EPIC (Williams et al, 1984), GLEAMS (Leonard et al., 1987), GWLF (Haith and Shoemaker, 1987), HSPF (Bicknell et al., 1997), PRZM-3 (Suaréz, 2005), RZWQM (Ahuja et al., 2000), and SWAT (Arnold et al., 1998b). In a more recent report prepared for the US Environmental Protection Agency (EPA) on water quality models for use in TMDL (total maximum daily load) development, Shoemaker et al. (2005) provide a detailed comparison of many of the same models reviewed in the 2001 WERF study, as well as some others (e.g., REMM). Table 4.4 from the Shoemaker report, which is reproduced in Appendix A–Table A.2, provides an excellent summary of model capabilities, identifying those watershed-scale, water quality models capable of simulating pesticides and several best management practices, including “vegetative practices”.

The model reviews by WERF (2001) and Shoemaker et al. (2005) are recent examples of broad evaluations of water quality models. The purpose of this document is to focus specifically on those models most suitable for quantification of the effectiveness of VFSs and UMBs in reducing pesticide runoff from agricultural fields, both at the field and broader watershed scale. From the population of models possessing the minimum capabilities required, APEX, PRZM, REMM, SWAT, and VFSMOD-W were chosen for a detailed evaluation. Of these models, APEX, PRZM, REMM, and SWAT were previously evaluated in one or both of the WERF and Shoemaker reviews. A fifth model, VFSMOD-W (Sabbagh et al., 2009), reviewed herein, is a recently developed hybrid combining a physically-based model designed specifically for flow and sediment transport across a VFS with an empirical equation for predicting pesticide reduction. These five models were selected because of their known strengths in simulating pesticide fate, buffer systems, or both. They represent a sampling of both new and novel approaches to simulating the effectiveness of buffers in reducing pesticide movement (e.g., VFSMOD-W and SWAT 2009) and approaches which have been extensively tested and validated for pesticide fate and/or buffer system simulations (e.g., APEX, PRZM, and REMM). The models were also chosen to represent simulation capabilities across a range of scales, as the analysis of buffer effectiveness is of interest for both edge-of-field and watershed assessments. All of the models selected have an active development team and a relatively broad user base for their intended applications, ensuring that they are likely to experience continued validation and improvements in the future. Finally, four of the five models (APEX, PRZM, REMM, and VFSMOD-W) were identified as strong buffer modeling approaches by both the regulatory and industry parties involved in pesticide registration as evidenced by their inclusion in an Environmental Modeling Public Meeting hosted by the EPA Office of Pesticide Programs (EMPM, December 9, 2008). In the following sections, each of these models will be discussed, including more specific rationales for their evaluation, and their key capabilities and attributes relative to buffer and pesticide modeling.

2.1 Agricultural Policy/Environmental Extender: APEX

2.1.1 APEX Model Background

The Agricultural Policy/Environmental Extender model (APEX) was developed at the Texas Blackland Research and Extension Center (Williams et al., 2008). APEX was designed as a farm/small watershed scale model for simulating the effects of agricultural management practices on environmental quality and agricultural productivity. It is a physically-based, continuous, distributed parameter model which can be used to model up to 4,000 distinct and hydrologically connected “subareas”. The principal building blocks of APEX include the EPIC erosion and crop growth model (Williams et al., 1984) and the GLEAMS pesticide fate model (Leonard et al., 1987). The introductory section from the APEX theoretical documentation is presented in Appendix B to provide an overview of APEX and its development. APEX was selected for evaluation based on several of its core strengths, including:

- Integrated linkage of field hydrologic, agronomic, and chemical processes with buffer processes
- Strong crop growth model for simulation of both field and buffer vegetation processes
- Ability to explicitly and physically simulate buffers across many fields within a watershed
- Flexible parameterization of the erosion process, important in simulation of sediment transport to and within buffers

APEX, and its predecessor EPIC, have been applied extensively in evaluation of agricultural management on farms and small watersheds (Gassman et al., 2005). In addition, APEX has been applied in national assessments of vegetated filter strip performance (Arnold et al., 1998a) as well as in the broader BMP performance assessments conducted through the USDA’s Conservation Effects Assessment Program (Mausbach and Dedrick, 2004), for which it has been chosen as the primary model for evaluating agricultural management practices. Furthermore, APEX has been used specifically to evaluate pesticide loss from treated areas under various management practices for both forested (Wang et al., 2007,) and agricultural catchments

(Harman et al., 2004). The APEX model can be obtained via the Web at, http://www.brc.tamus.edu/simulation-models/epic-and-apex.aspx.

2.1.2 Simulation of Vegetated Filter Strips with APEX

The APEX model simulates individual fields as “subareas”. Each subarea is homogeneous in terms of soils, land cover, weather, and agricultural management practices. Subareas are connected to one another through definition of hydrologic flow paths. Once the hydrologic connectivity of subareas is defined, routing of flow, sediment, and pesticides between subareas may occur as both overland flow and concentrated channel flow. The physical characteristics of routing channels are defined individually for each subarea channel.

Modeling of buffers in APEX can be accomplished through one of two approaches. The first approach requires explicit definition of buffers and their spatial/hydrologic connectivity to fields that drain through them. The second approach creates “virtual” buffers assigned to user-specified APEX subareas (crops or fields) within a small watershed.

Explicit Buffers: Following explicit buffer approach, a modeler would define a subarea representing a field generating runoff, sediment, and pesticide, and a second subarea representing a down-slope buffer or filter strip. Crop subareas and buffer subareas can be defined for one or more field/buffer combinations within a single model simulation. In addition, multiple buffer zones in series (e.g., vegetated filter strip followed by an unmanaged riparian vegetation buffer) can be simulated by adding multiple subareas downstream of a subarea treated with pesticide. This approach offers the greatest flexibility in defining the properties of each buffer, including:

- Buffer width
- Buffer vegetation
- Soil conditions
- Topographic characteristics (slope, roughness)
- Buffer management (mowing, fertilization, irrigation)
- Fraction of concentrated flow passing through the buffer
- Growth and health of vegetation

The proportion of flow and sediment entering the downstream buffer as overland sheet flow versus concentrated channel flow is controlled by one of two methods. The first method employs a user-defined parameter that defines the fraction of flow entering the buffer subarea as overland sheet flow (FFPQ). As FFPQ approaches 1, sheet flow increasingly dominates transport processes. A high FFPQ value would be appropriate where the buffer subarea has a very uniform slope surface. Lower FFPQ values should represent less uniform surface topography within the buffer subarea, resulting in greater amounts of concentrated (channel) flow. The second method used to partition flow and entrained material between sheet flow and concentrated flow uses the dimensions of a channel flowing through a buffer to calculate when the capacity of the channel has been exceeded, resulting in the excess flow routing through the buffer as overland flow. In the first option, the partitioning of flow entering a buffer between channel and overland flow is constant, while in the second option, it is variable. This is shown schematically in Figure 2.1. If the constant FFPQ method is employed, the runoff carrying sediment and pesticide is partitioned into channel and overland flow as follows:

$$Q_{vfs\text{-}ch} = (1\text{-}FFPQ) * Q_{field} \qquad (1)$$
$$Q_{vfs\text{-}buf} = FFPQ * Q_{field} \qquad (2)$$

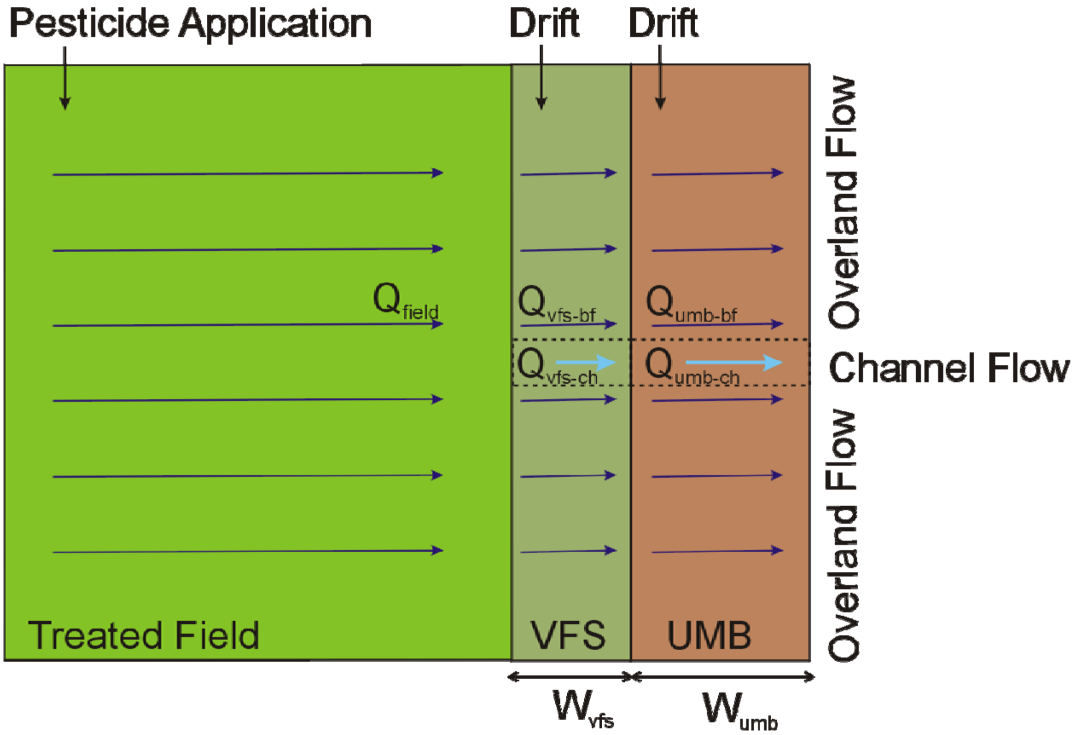
If the method based on channel capacity is employed, the runoff carrying sediment and pesticide is partitioned into channel and overland flow as follows:

$$\text{If } Q_{field} > Q_{ch\text{-}capacity},\ Q_{vfs\text{-}buf} = Q_{field} - Q_{ch\text{-}capacity} \qquad (3)$$
$$\text{If } Q_{field} <= Q_{ch\text{-}capacity},\ Q_{vfs\text{-}buf} = 0 \qquad (4)$$
$$Q_{vfs\text{-}ch} = Q_{field} - Q_{vfs\text{-}buf} \qquad (5)$$

Where, Q_{field} = Runoff carrying sediment and pesticide from main field into buffer
$FFPQ$ = Fraction of flow from upstream subarea entering buffer as sheet flow
$Q_{vfs\text{-}ch}$ = Runoff carrying sediment and pesticide as concentrated flow into buffer
$Q_{ch\text{-}capacity}$ = Channel flow capacity through buffer
$Q_{vfs\text{-}buf}$ = Runoff carrying sediment and pesticide as sheet flow into buffer

The partitioning of the runoff entering a second buffer zone, as illustrated in Figure 2.1, follows the same methodology described by equations 1 – 5 above; however, independent FFPQ and channel flow dimensions may be defined for each buffer subarea.

Figure 2.1.: Conceptualization of APEX buffer simulation.



Infiltration in both the source field and buffer subareas can be calculated using either the Green and Ampt method, or one of several curve number techniques. When Green and Ampt is used, hourly time step rainfall input is required. The time-step for routing of flow and sediment from the source field through the buffer can either be daily or sub-daily. The sub-daily option uses the Variable Storage Coefficient method (VSC) developed by Williams (1975). Within the buffer, overland flow infiltrates the buffer, infiltrating soluble pesticide as well. The amount of infiltration that occurs is a function of the travel time of overland sheet flow through the buffer and the soil infiltration rate. The travel time is calculated according to Manning's equation for overland flow, using the buffer width and slope defined by the modeler. The infiltration rate in the buffer is assumed to equal the saturated hydraulic conductivity of the buffer's second soil layer. Soluble pesticide is assumed to be conserved during routing of flow through the buffer; infiltration is the only removal mechanism simulated. Chemical adsorption and degradation in surface runoff are not simulated.

In both channel and overland flow, sediment deposition and re-entrainment can occur. Sediment routing through the channel and overland flow sections are calculated independently, and in both cases, a variation of Bagnold's sediment transport equation (Bagnold, 1977), which estimates transport capacity as a function of flow velocity, is applied. As sediment is routed through the buffer, the particle size distribution of the suspended sediment is calculated in the flow entering and leaving a buffer. The pesticide transported with sediment is calculated using an enrichment ratio approach, in which the concentration of sorbed pesticide is calculated as a function of the mean sediment particle sizes in the buffer inflow and the outflow.

Virtual Buffers: The "virtual" buffer approach allows users to assign generic vegetated buffers to control specified APEX subareas (crops or fields) within a small watershed. The virtual buffer approach is attractive for watershed-scale assessments where the modeler may be interested in an assessment of buffer effectiveness at reducing pesticide exposure in water bodies draining multiple fields and non-agricultural areas. Currently, the physical characteristics of the buffer (e.g., soils, vegetation, slope) are not controlled by the modeler. Instead, default values for slope and soil type for the buffer are assigned to be the same as for the field subarea which drains through it, and the buffer vegetation is assumed to be perennial Bermuda grass (approximating a managed VFS). The virtual buffer approach allows the following parameterization options:

- Specification of which subareas (fields) will have VFSs
- The fraction of the subarea (field) controlled by the VFS
- The width of the VFS

In the case of virtual buffers, the physical infiltration and flow and sediment routing processes are simulated using the same methods as the explicitly defined buffer case.

Both approaches to defining buffers in APEX (explicit and virtual definition) can be implemented through a GIS-integrated graphical user interface. A summary of APEX model characteristics relevant to its use as a tool for evaluating buffer effectiveness are provided in Table 4.2 of this document.

2.2 Pesticide Root Zone Buffer Model: PRZM-BUFF

2.2.1 PRZM Model Background

PRZM is a dynamic, compartmental model for use in simulating water and chemical movement in unsaturated soil systems within and below the plant root zone (Suaréz, 2005). The model simulates time-varying hydrologic behavior on a daily time step, including physical processes of runoff, infiltration, erosion, and evapotranspiration. The chemical transport component of PRZM calculates pesticide uptake by plants, surface runoff, erosion, decay, vertical movement, foliar loss, dispersion, and retardation. PRZM includes the ability to simulate metabolites, irrigation, and hydraulic transport below the root zone. PRZM-BUFF was included as a tool for VFS assessment based on its ability to account for pertinent environmental processes at an appropriate scale and time step, its rigorous treatment of chemical transformation and decay processes, and because of PRZM's use by EPA's Office of Pesticide Programs in regulatory assessments. PRZM also has been widely used internationally over the past ten years as part of the European Union's FOCUS groundwater and surface water modeling systems.

2.2.2 Simulation of Vegetated Filter Strips with PRZM-BUFF

PRZM-BUFF is a modified version of PRZM developed by Waterborne Environmental, Inc. (WEI, Leesburg, VA) to enable the evaluation of the effectiveness of VFSs and UMBs in reducing pesticide runoff flux, pesticide erosion flux, and pesticide spray drift to downstream areas. The approach is based on the premise that runoff follows topography as concentrated flow (e.g., within swales and other drainage paths). As a result, only certain sections of the buffer are effective in reducing pesticide runoff, but the entire buffer is effective in reducing drift. In PRZM-BUFF, pesticide transport across the effective area of the buffer is a function of the width of the buffer, vegetation cover (e.g., untreated crop, trees with underbrush, or grasses), slope, and storm intensity. The condition of the buffer (as it relates to sediment trapping and infiltration) changes as a function of vegetation growth stage and antecedent weather condition (precipitation and evapotranspiration) within the buffer. PRZM-BUFF currently uses a daily time step infiltration model (curve number), making it most appropriate for simulating storm events of 1 day duration or longer. There are plans to incorporate a storm duration factor into the PRZM-BUFF model to better account for sub-daily duration storms (M. Cheplick, WEI, personal communication 2009).

PRZM-BUFF, is configured as a run-off / run-on model with main field water and chemical mass from runoff and erosion input as boundary condition inflows into adjacent untreated areas. In addition to runoff and erosion, drift can be applied to the buffer and subsequently added to runoff water either as eroded mass or plant washoff/soil runoff. The following schematic (Figure 2.2) illustrates water, sediment, and chemical movement from the main field through the buffer to the EPA standard 1 ha, 2 m deep pond. Since it is generally acknowledged that concentrated flow/preferential paths typically occur in practice (i.e., at low points or due to short circuiting of the buffer caused by sediment deposition or wheel tracks), PRZM-BUFF allows the buffer to be divided into effective segments (where sheet flow would occur) and ineffective segments. In the schematic, water and chemical flux are shown moving from the treated field through an effective portion of the buffer, which for illustration purposes comprises 30% of the buffer area. The effective portion of the buffer can range from 1 to 100% of the total buffer area, with 100% representing a perfect buffer with uniform runoff depth and velocities.

In PRZM-BUFF, a sequence of five PRZM simulations are required to represent the interaction of pesticide losses from the treated field in runoff water, eroded sediment, and spray drift over the effective and ineffective runoff areas of the buffer.

- Simulation 1 is the treated field. Runoff water (Q), dissolved-phase pesticide in runoff (R), and eroded sediment (E) are predicted by a PRZM run, and then become external loadings to the effective runoff area of the buffer.
- Simulation 2 (buffer runoff – BR) calculates the transport of dissolved-phase pesticide in runoff (R) from the treated field onto/through the buffer to the water body. The pesticide mass from runoff retained in the buffer is equal to the inflow mass multiplied by the ratio of infiltrated water divided by runoff water. The captured mass is distributed in the buffer (CAM=2[1]) and the remainder passes through the buffer.
- Simulation 3 (buffer erosion – BE) calculates the transport of sorbed-phase residues (E) from the treated field onto/through the buffer to the water body. Pesticide deposition in the buffer is based on runoff depth, flow velocity, settling velocities, and travel time. Settling velocities can be calibrated or obtained from literature. For most applications of the model, settling velocities appropriate for organic matter and fine-grained particles should be used. The remainder of the erosion mass remains suspended and passes through the buffer.
- Simulation 4 (buffer drift – BD) calculates the transport of drift loads from the target field to the effective portion of the runoff buffer. Pesticide residues entering the buffer from drift are handled in the same manner as foliar applications (CAM=2) and may be subjected to runoff and erosion during future storm events.
- Simulation 5 (buffer drift – CD) calculates the transport of drift loads from the target field to the ineffective runoff buffer. Residues entering the buffer from drift are handled in the same manner as foliar applications (CAM=2) and may be subjected to runoff and erosion during future storm events.

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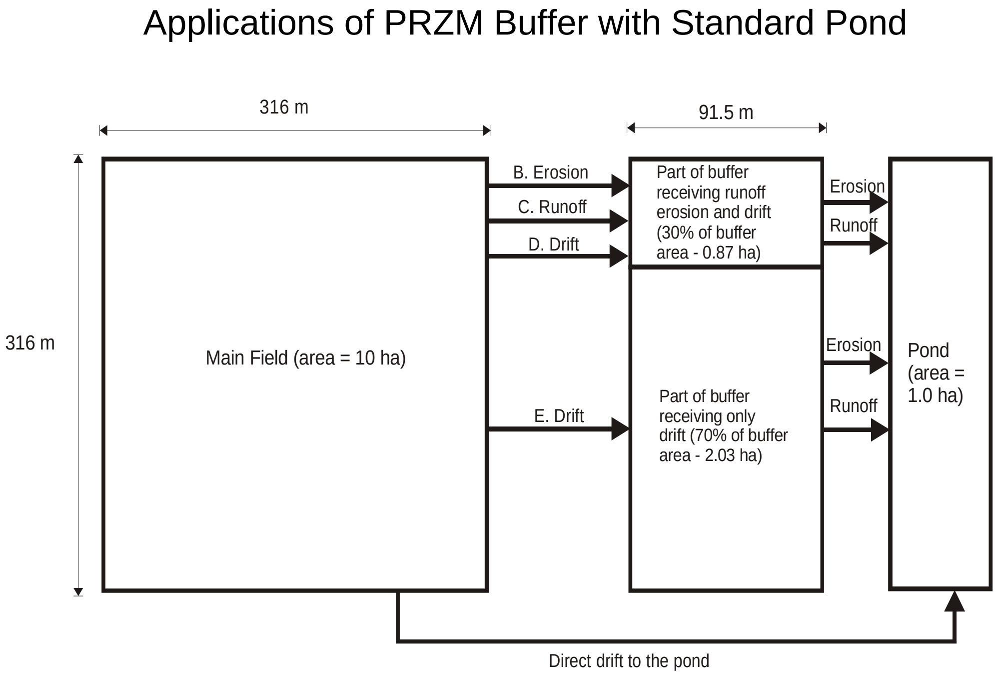
[1] CAM 2 (Chemical Application Method 2) simulates interception based on crop canopy, as a straight-line function of crop development; chemical reaching the soil surface is incorporated to 4 cm

Figure 2.2.: Conceptualization of PRZM VFS approach.



Runoff and erosion losses from Simulation 1 are driven by rainfall and irrigation. Runoff and erosion losses from Simulations 2, 3, and 4 are driven by rainfall onto the buffer and runoff water (Q) predicted by Simulation 1. Runoff and erosion losses from Simulation 5 are driven by rainfall. Finally, runoff and erosion losses from Simulations 2, 3, 4, and 5 are combined in a post-processor to provide loadings into the EXAMS model. It is important to note that this is a continuous simulation. Residues trapped in the buffer from previous events are subjected to future infiltration, runoff, and erosion.

In order to facilitate creation of the necessary PRZM input files and to run the five PRZM simulations, modifications were made to Waterborne Environmental's EXPRESS shell. This modified EXPRESS shell (Buffer-EXPRESS) currently contains the EPA standard PRZM soil/drop/meteorology scenarios coupled with two EXAMS water bodies (Standard Pond and Index Reservoir). The Buffer-EXPRESS shell currently allows for three buffer scenarios: grassed, herbaceous, and cropped. Additional buffer environments can be simulated outside the shell. By selecting the buffer option, all the necessary files are created automatically and the simulations are run. The Buffer-EXPRESS shell is not publicly available at the time of this report's submittal; the latest projected release date is June of 2009. Inquiries on availability may be made by visiting Waterborne Environmental on the Web at, http://www.waterborne-env.com/ or contacting Mark Cheplick at cheplickm@waterborne-env.com.

Two papers, Ramanarayanan et al. (2002) and Giddings et al. (2005) detail previous applications, including validation of the PRZM-BUFF methodologies. However, some modifications to the PRZM-BUFF code have been made since their publication. A summary of PRZM-BUFF model characteristics relevant to its use as a tool for evaluating buffer effectiveness is provided in Table 4.2 of this document.

2.3 Riparian Ecosystem Management Model: REMM

2.3.1 REMM Model Background

The Riparian Ecosystem Management Model (REMM) was developed at the USDA-ARS Southeast Watershed Research Laboratory in Tifton, GA (Lowrance et al., 2002). REMM was designed as a tool for estimating the non-point source pollution control by field-scale riparian ecosystems. Originally based on buffer system specifications recommended by the USDA Forest Service and the NRCS, REMM is a process-based digital simulation model for use in modeling water quality, nutrient cycling, vegetation dynamics, hydrology, pesticide, and soil movement within, between, and out of riparian zones adjacent to agricultural fields.

In REMM, hydrologic behavior varies over time on a daily time step basis. Water movement and storage are characterized by a combination of interception by vegetation (canopy and litter layer), evapotranspiration, vertical drainage, surface runoff, subsurface lateral flow, upward flux from the water table, and deep seepage. Water movement through each REMM riparian buffer zone is controlled by a combination of mass balances and transport rates. Erosion is simulated using the Universal Soil Loss Equation (USLE) method in conjunction with separation of the buffer into rill and interrill areas. The pesticide transport component of REMM includes plant uptake, vertical movement in the soil profile within a buffer, lateral movement via runoff and erosion across a buffer, linear and non-linear adsorption/desorption, and degradation.

REMM was selected for evaluation based on several of its core strengths, including:

- Specifically designed to simulate vegetative buffers adjacent to agricultural fields with published validation of hydrologic processes
- Strong vegetative growth model for simulation of buffer vegetation processes
- Ability to explicitly and physically simulate filter strip behavior including thatch or leaf litter interactions with off-field runoff and sediment
- Flexible parameterization of the erosion process including channeling, which is important in simulation of sediment trapment by the filter strip
- Ability to simulate complex riparian buffer systems including combinations of managed and unmanaged buffer zones

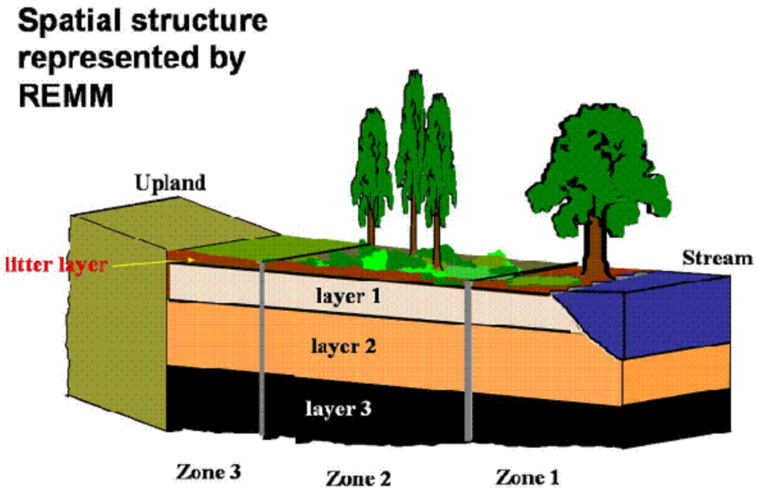
REMM was created over 15 years ago and has been used extensively to simulate nutrient trapment by buffer strips adjacent to agricultural fields as well as by more complicated systems of managed buffer systems next to unmanaged buffer systems. The REMM 2008 model version has the added ability to simulate pesticide behavior within and out of a user-specified buffer system based on user-supplied pesticide loadings from an adjacent field and the physical/chemical properties of the pesticide. Up to three different pesticides can be simulated at a time through a system of three adjacent buffer zones between the agricultural field and a water body, allowing for simulation of changes in vegetative and environmental conditions as one moves further away from an agricultural field.

It has been demonstrated that REMM can be used to simulate trends in litter production, nutrients in the litter, and nitrogen concentrations in streamflow due to fresh litter fall (Bhat, et al, 2007). Using REMM to predict the most effective buffer system based on vegetation type, slope, surface soil conditions, and overland flow parameters was investigated by Graff et al. (2005). REMM is a field-scale model and requires inputs from upland areas. To expand existing watershed-scale models to include representation of buffers and to expand REMM to the watershed-scale, REMM has been integrated with SWAT (Singh et al., 2007) and AnnAGNPS (Yuan et al., 2007). REMM 2008 is nearing completion of beta testing and may be obtained by contacting Randy Williams of the USDA-ARS at randy.williams@ars.usda.gov.

2.3.2 Simulation of Vegetated Filter Strips with REMM

REMM (2008) is designed to evaluate the effectiveness of multiple zone buffers in reducing pesticide runoff and pesticide erosion to downstream areas. In REMM, the riparian system is considered to consist of three zones between the field and the water body. Each zone includes litter and three soil layers that terminate at the bottom of the plant root system and a plant community that can include up to six different plant types in two canopy levels. The spatial structure in REMM is depicted in Figure 2.3. The model begins with the user entering daily runoff, erosion, and pesticide off-field loadings which “drain” into a VFS (designated as Zone 3) adjacent to the agricultural field. Daily weather input accompanies the daily loadings, which allows for simultaneous rainfall and weather conditions on both the field and the adjacent VFS. Output pesticide residues in surface runoff, surface seepage, subsurface seepage, and erosion out of Zone 3 can be used to evaluate VFS effectiveness in trapping pesticides.

Figure 2.3.: REMM conceptual model of upland and buffer zones.



REMM input requirements include upland inputs (off-field runoff loadings, off-field erosion loadings, and off-field pesticide loadings in runoff and eroded sediment), daily weather data, site description, soil characteristics, erosion factors, vegetation characteristics, and pesticide properties. Infiltration within the buffer is simulated using a modified Green-Ampt equation. For storm events where runoff into the buffer exceeds soil infiltration, excess water is added to surface runoff. Subsurface lateral movement of water over an impeding soil horizon is calculated using Darcy’s Equation. Preferential flow is not calculated. Excess subsurface flow is released to the surface as surface seepage.

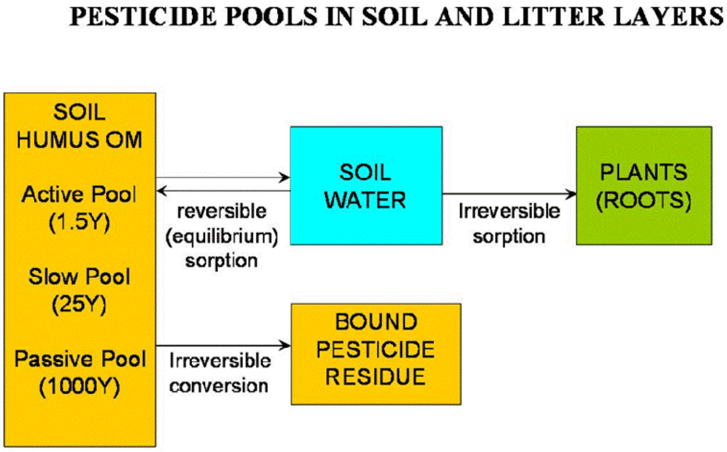
Currently, REMM simulates three subsurface soil layers that are individually parameterized by the user. A litter (or thatch in the case of grass) layer is included at the surface. Research has shown the importance of a litter layer in trapping runoff and eroded sediment, and thus trapping pesticide residues in off-field loadings (Vought et al., 1994).

Erosion is simulated in REMM using the USLE. The fraction of sand, silt, clay, small aggregate, and large aggregate particle size classes at the point of detachment are determined using the Foster approach. The buffer zones are separated into rill and interrill areas. Channels through a buffer run parallel to the buffer slope and have uniform, triangular, cross-sections with interrill areas sloping toward the channels. The channel length and slope are assumed to be identical to user-specified buffer zone length and slope. REMM allows the user to specify buffer zone width and the number of channels and channel widths within the buffer, allowing for flexibility in simulating a range of erosion conditions within a buffer**.**

REMM does not currently simulate drift across a buffer. Drift can only be simulated as additional user-input edge-of-field loadings into the buffer on the date of pesticide application. Future enhancements to REMM may include development of a drift module which allows for varying drift deposition as a function of distance from the treated field.

In REMM, pesticide transport across the buffer is a function of soil deposition, transport in runoff and infiltration, adsorption to organic matter in litter and soil, width of the buffer relative to the width of the draining field, vegetation cover of the buffer, slope relative to the draining field, and storm intensity. REMM requires user-supplied physical and chemical properties to simulate pesticide behavior in the buffer. The model simulates degradation in the soil (including temperature-dependent degradation), plant pesticide uptake, and a flexible approach to simulating adsorption/desorption. Adsorption and desorption can be simulated as either a linear or non-linear function of soil or litter organic matter. Figure 2.4 is a schematic of how REMM simulates adsorption and desorption.

Figure 2.4.: Conceptual model of pesticide adsorption/desorption in REMM.



In REMM, pesticides are simulated as two pools in equilibrium (water phase and soil phase). Adsorption/desorption is based on the pesticide K_{OC}. The water phase pool can adsorb to the soil phase if equilibrium is disturbed, be taken up into plant roots with water uptake, or degrade. Degradation is simulated as a function of a first-order reaction constant and soil water concentration. Binding is calculated using a first-order rate constant and soil phase concentration. Plant uptake of pesticide is calculated using the Briggs “translocation stream concentration factor” which is a function of K_{OW}. It should be noted that binding, plant uptake, and degradation are all loss functions within REMM.

A summary of REMM model characteristic relevant to its use as a tool for evaluating buffer effectiveness is provided in Table 4.2 of this document.

2.4 Soil and Water Assessment Tool: SWAT

2.4.1 SWAT Model Background

The Soil and Water Assessment Tool (SWAT) was developed at the USDA-ARS Grassland, Soil and Water Research Laboratory (Neitsch et al., 2005). SWAT is a watershed-scale, continuous, physically-based, semi-distributed model designed for the simulation of flow and sediment, nutrient, and pesticide transport in ungaged watersheds. SWAT is the result of an evolution of Agricultural Research Service field and watershed-scale models, including CREAMS (Knisel, 1980), GLEAMS (Leonard et al., 1987), EPIC (Williams et al., 1984), and SWRBB (Arnold et al., 1990). SWAT is under continual development, with official updates released every 3 to 4 years. A significant update to SWAT will occur in the summer of 2009, which includes a considerable improvement to how VFSs are modeled (White and Arnold, 2009). Since this version will be released within months of this document’s completion, it was chosen for evaluation in the interest of keeping this review current and relevant. An excerpt from the introduction of the SWAT 2005 Theoretical Documentation (Neitsch et al., 2005) is presented in Appendix B in order to provide a fuller description of its development and theoretical basis. SWAT was selected as one of the models for evaluation based on several of its core strengths, including:

- Suitability for assessment of the impacts of VFSs at the larger watershed scale
- Integrates simulation of loadings from agricultural fields to VFSs and into receiving waters within a single model
- Strong crop growth model and agricultural management components
- A new and improved empirical model for VFSs which accounts for non-uniform flow

SWAT has been widely used internationally over the past ten years as a tool for evaluating the impacts of land use, management, and climate change of water resources and water quality. A literature review of the SWAT model (Gassman et al., 2007) provides an extensive survey of the widely varying applications of SWAT, including five references which evaluated pesticides and eleven which studied the effects of BMPs on pollutant losses. A additional study by Holvoet et al. (2007) evaluated SWAT and the use of filter strips as a BMP for reducing pesticides in runoff; however, this study used a customized filter strip simulation algorithm not in the standard SWAT model. The current version of SWAT can be obtained via the Web at, http://www.brc.tamus.edu/swat/. The SWAT 2009 version reviewed in this document is scheduled for public release by August of 2009. The model's beta version may be obtained by contacting Nancy Sammons of the USDA-ARS at Nancy.Sammons@ARS.USDA.GOV.

2.4.2 Simulation of Vegetated Filter Strips with SWAT

SWAT divides watersheds into subbasins and hydrologic response units (HRUs). An HRU represents an area of homogeneous land use, soils, weather inputs, and agricultural management practices. An HRU can be defined to represent a single field or an aggregation of multiple fields within a watershed. At a daily timestep, SWAT simulates the flow, sediment, and pesticide leaving an HRU. The fluxes leaving an HRU are input to subbasin tributaries which are in turn routed to a main subbasin channel. Outputs of flow, sediment, and pesticide are added and routed from individual subbasins downstream. All outputs (flow, sediment, and pesticide) may be tracked at the HRU, subbasin, and watershed level.

VFSs can be assigned to any HRUs chosen by the modeler. Earlier versions of SWAT (SWAT version 2005 and earlier) simulated the reduction in pesticide mass leaving an HRU using a non-linear regression equation that is a function of buffer width. This regression equation calculates a trapping efficiency which is then applied to both soluble pesticide in surface runoff and to pesticide sorbed to sediment entering the VFS.

In SWAT version 2009, a new approach to modeling VFSs has been developed (White, 2009). The approach contains empirical models for runoff and sediment reduction across a filter strip at the plot scale and accounts for the field-scale processes that typically result in trapping efficiencies lower than those observed at the plot scale. These plot-scale empirical models were developed from both field study data and simulations made using a process-based vegetated filter strip model, VFSMOD (Muñoz-Carpena et al, 1999), which is reviewed in the next section. The VFSMOD simulations were used exclusively in the development of the runoff reduction model component, while primarily field data were used to develop the sediment reduction model component. The independent variables in the runoff reduction model are saturated hydraulic conductivity and runoff loading to the buffer. The form of the runoff reduction model is shown in Equation 6 below, where R_R equals the runoff reduction in the buffer, R_L equals the runoff loading to the buffer, and K_{SAT} equals the surface saturated hydraulic conductivity in the buffer.

$$R_R = 75.8 - 10.8 \ln(R_L) + 25.9 \ln(K_{SAT}) \qquad (6)$$

The independent variables in the sediment reduction model are the runoff reduction fraction and the sediment load to the buffer. The form of the sediment reduction model is shown in Equation 7 below, where S_R equals the sediment reduction in the buffer, S_L equals the sediment load to the buffer, and R_R equals the runoff reduction in the buffer.

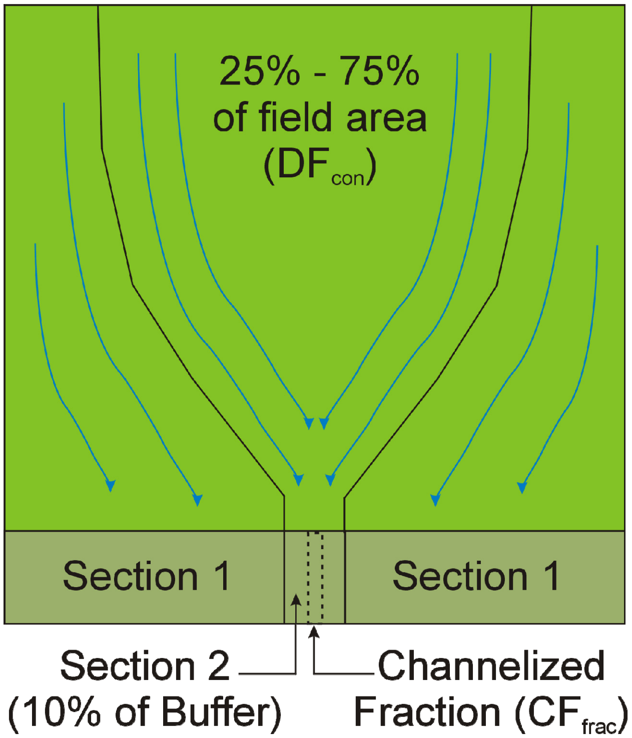
$$S_R\ (\%) = 79.0 - 1.04\ S_L + 0.213\ R_R \qquad (7)$$

The method as applied to pesticides includes the assumption that the reduction of soluble pesticide is proportional to the reduction in runoff and that the reduction in sorbed pesticide is proportional to the reduction in sediment across the buffer.

Many physically-based models of VFSs assume uniform flow across the filter strip. Plot-scale field experiments typically seek to achieve uniform flow to assess the effectiveness of VFSs, which, as reported by some researchers (e.g., Abu-Zreig et al., 2001), can be difficult to achieve. At the field scale, concentrated flow will certainly occur and the effectiveness of VFSs will be reduced. The SWAT approach acknowledges this tendency towards flow concentration by accounting for areas of non-uniform and concentrated flow from a field across a VFS. Based upon a review of published literature and high-resolution digital elevation model simulations of overland flow accumulation, it was estimated that 10% of a VFS will receive flow from 25% - 75% of a field. The remainder of the field passes less concentrated flow through 90% of the VFS. In addition, a fraction of the buffer receiving the heaviest loading may experience concentrated flow, rendering that segment of the buffer ineffective. This conceptual model of a buffer and its source field is shown in Figure 2.5. The parameters required to describe non-uniform flow through a buffer are:

- Drainage area to VFS area ratio ($DAFS_{ratio}$)
- Fraction of field drained by the most heavily loaded 10% of the VFS (DF_{con})
- Fraction of flow passing through the most heavily loaded 10% of the VFS which is fully channelized (CF_{frac})

Figure 2.5.: Conceptual model of source field and buffer in SWAT.



The $DAFS_{ratio}$ parameter is calculated as the ratio of drainage area to buffer area, the DF_{con} can be estimated based upon topographic analysis of the field, while CF_{frac} is somewhat more difficult to determine (it will typically be set to a value of zero) (M. White, personal communication 2009). Validation of the new approach to simulating VFS effectiveness at the field and small watershed scale was not performed because datasets required for such a validation were unavailable. Finally, it should be noted that the new approach to buffer simulation in SWAT 2009 is meant to represent the behavior of a managed VFS as opposed to an unmanaged buffer (UMB).

The development and parameterization of a SWAT model simulation, including definition of VFSs, is performed through a GIS-based graphical user interface (Winchell et al., 2008). A summary of SWAT model characteristics relevant to its use as a tool for evaluating buffer effectiveness is provided in Table 4.2 of this document.

2.5 Vegetated Filter Strip Model: VFSMOD-W

2.5.1 VFSMOD-W Model Background

VFSMOD (the Vegetative Filter Strip MODeling System) is a model used to study hydrology, sediment, and chemical transport through vegetative filter strips. The model includes a field component to simulate transport from the field to the VFS and a component to estimate the efficiency of the VFS in reducing runoff and in trapping sediment and pesticides. The VFS component combines the strength of a numerical submodel to describe overland flow and infiltration and an algorithm for the filtration of suspended solids by grass. The model handles complex sets of inputs similar to those found in natural events—it includes descriptions of flow through the filter; changes in flow resulting from sediment deposition; physically-based, time-dependent soil water infiltration; handling of complex storm pattern and intensity; and varying surface conditions (slope and vegetation) along the filter. The VFS component can be used in conjunction with the field component or it can be interfaced with other field hydrologic/water quality models such as PRZM, CREAMS, APEX, and EPIC.

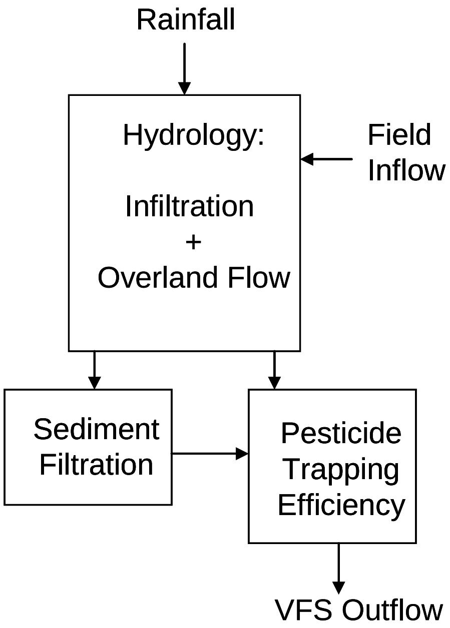
VFSMOD has been used by state regulators and city engineers for design and evaluation of buffer strips. Other applications of VFSMOD included integrating the model with PRZM within the FOCUS surface water exposure modeling system (Roepke et al., 2009), and incorporation of the model into a web-based Google Maps tool linked to SSURGO soils data (http://www.envsys.co.kr/~vfsmod/). The VFSMOD-W software, together with manuals and publications on the performance of the model, can be found on the Web at http://carpena.ifas.ufl.edu/VFSMOD/.

2.5.2 Simulation of Vegetated Filter Strips with VFSMOD-W

VFSMOD-W is a field-scale, mechanistic, storm-based model designed to route the incoming hydrograph and sedimentograph from an adjacent field through a vegetative filter strip (VFS) and to calculate the outflow, infiltration, and sediment trapping efficiency. The model handles time-dependent hyetographs, space-distributed filter parameters (vegetation roughness or density, slope, infiltration characteristics), and different particle size of the incoming sediment. Any combination of unsteady storm and incoming hydrograph types can be used to match the characteristics of natural storm events.

VFSMOD-W consists of a series of modules integrated under a flexible MS-Windows graphical user interface (GUI) that simulate the behavior of water, sediment, and pesticide in the surface of the VFS (Figure 2.6).

Figure 2.6.: Flowchart for VFSMOD-W Filter Strip Module.



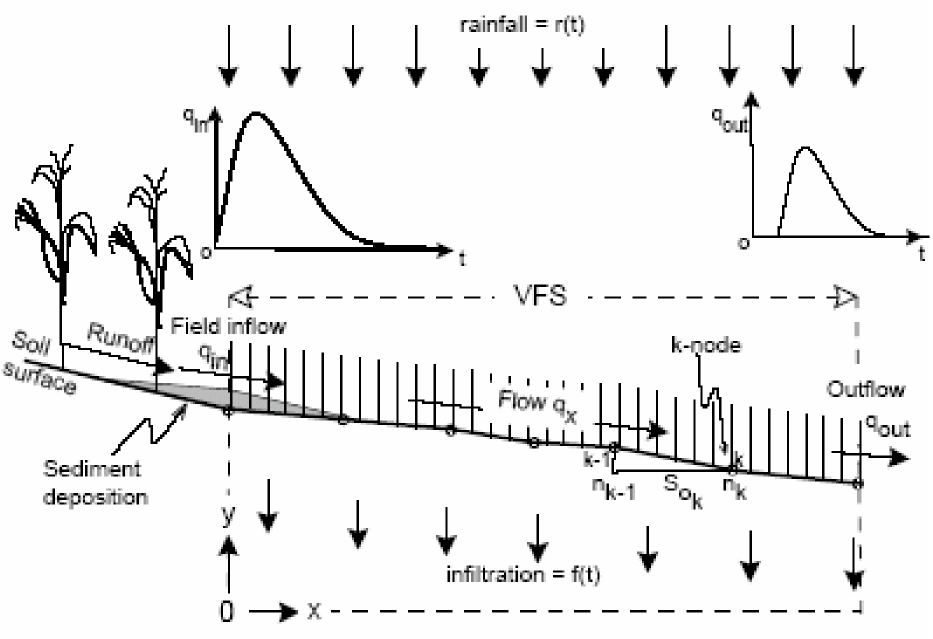
VFSMOD-W is a 1-D model for the description of water flow transport, sediment deposition, and pollutant transport along the VFS. The model can also be used to describe transport at the field scale (or field edge) if flow and transport is mainly in the form of sheet flow (Hortonian) and the 1-D path represents average conditions (field effective values) across the VFS. The VFSMOD-W model uses an advanced Petrov-Galenkin finite element solution with a variable time step, chosen to limit mass balance errors induced by solving the overland water flow equation (Muñoz-Carpena et al., 1993a). The time step for the simulation is selected by the kinematic wave model to satisfy convergence and computational criteria of the finite element method based on model inputs (Muñoz-Carpena et al., 1993a,b). The model inputs are specified on a storm basis. State variables are integrated after each event to yield storm outputs.

The windows based VFSMOD-W interface was developed as a tool to aide in the optimal design of buffers to meet target pollutant reductions (Muñoz-Carpena and Parsons, 2004). The interface includes sensitivity analysis, calibration, and uncertainty analysis algorithms which help users to identify critical model parameters, identify their most appropriate values, and understand the confidence levels in the model predictions (Shirmohammadi et al., 2006; Muñoz-Carpena et al., 2007).

2.5.2.1 Hydrology

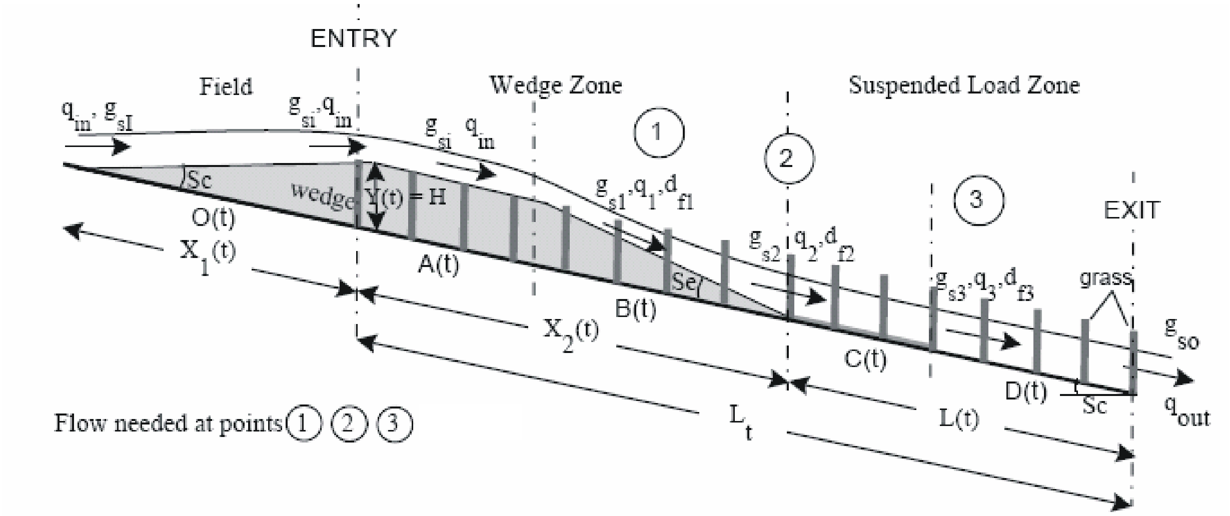
The hydrology component solves the kinetic wave approximation of the Saint-Vennant's (1881) equations for overland flow (KW) for the 1-D case as presented by Lighthill and Whitham (1955). The runoff is calculated from the hyetograph and a modification to the Green-Ampt infiltration method at every time step (Muñoz-Carpena et al., 1993b). The overland flow model (Figure 2.7) was coupled, for each time step, with an infiltration submodel based on a modification of the Green-Ampt equation for unsteady rainfall (Chu, 1978; Mein and Larson 1971, 1973; Skaggs and Khaheel, 1982; Muñoz-Carpena et al., 1993b).

Figure 2.7.: VFSMOD-W domain discretization for the finite element overland flow submodel.



The hydrology model is linked to a model for filtration of suspended solids by artificial grass media, developed and later tested for field conditions (Barfield et al., 1978, 1979; Hayes et al., 1979, 1984; Tollner et al., 1976, 1977; Wilson et al., 1981). The sediment transport model is based on the hydraulics of flow, transport, and deposition profiles of sediment under laboratory conditions. The model presents the advantage of being developed specifically for the filtration of suspended solids by grass. This is shown schematically in Figure 2.8.

Figure 2.8.: Filter description for the sediment transport algorithm in VFSMOD-W.



The original sediment model, which was developed at the University of Kentucky, uses a simple approach to calculate flow conditions at specific points of the filter and does not consider the complex effects of rainfall, infiltration, and flow delay caused by the buffer. VFSMOD-W provides a more accurate description of the flow conditions from the hydrology submodel, whereas changes in surface conditions (topography, roughness) due to sediment deposition during the event are obtained from the sediment filtration submodel.

2.5.2.3 Pesticide Reduction

The reduction in total pesticide mass (soluble and sorbed phase) is calculated with the empirical pesticide trapping efficiency equation proposed by Sabbagh et al. (2009) and tested by Poletika et al. (2009), which is shown in Equation 8.

$$\Delta P = 24.8 + 0.5(\Delta Q) + 0.5(\Delta E) - 2.4\ln(F_{ph} + 1) - 0.9(\%C) \qquad (8)$$

where ΔP is the pesticide removal efficiency (%), ΔQ is the infiltration (%) defined as the difference between flow entering the VFS (i.e., inflow run-on plus precipitation) minus the runoff from the VFS, ΔE is the sediment reduction (%), F_{ph} is a phase distribution factor (i.e., ratio between the mass of pesticide in the dissolved phase relative to the mass of the pesticide sorbed to sediment), and %C is the clay content of the sediment entering the VFS. The use of the F_{ph} factor in accounting for the phase partitioning of pesticides, as well as nutrient forms, is supported by previous research (e.g., Dosskey et al., 2008). Due to the sign on the coefficients of this regression equation, it can be noted that ΔQ and ΔE have a positive effect on trapping efficiency (i.e., the greater the ΔQ and ΔE, the greater the trapping efficiency). The F_{ph} function and the %C of the sediment entering the buffer have a negative effect on trapping efficiency.

A summary of VFSMOD-W model characteristics relevant to its use as a tool for evaluating buffer effectiveness is provided in Table 4.2 of this document.

3.0 Model Evaluation Methodology

The five models considered were evaluated using two complementary approaches. The first approach was to develop a matrix of model characteristics that are easily quantified and objective. Use of a criteria or attribute matrix is a common approach for comparing models (WERF, 2001 Shoemaker et al., 2005), allowing for an objective evaluation of critical characteristics. The model characteristics chosen were designed to reflect both model usability and capability for use in evaluating buffers. The categories of model characteristics chosen were as follows:

- Model Background: This attribute group was included to document important metadata for each model.
- Model Scale: This attribute group was included to indicate primary and secondary scales for which each model is applied.
- Model Use and Capabilities: This attribute group was included to provide an indication of the intended use(s) of each model.
- Model Input Requirements: This attribute group was included to provide an understanding of the variability in required and optional inputs for each model.

- Weather Data Requirements: This attribute group, while a component of input requirements, was separated out to better understand the details of the weather data requirements.
- Hydrology: This attribute group was included to enable comparison of the critical hydrologic cycle components of each model.
- Sediment: As sediment transport is a key process in buffers, this group of attributes was included to allow comparison of methods used in each model.
- Source Field Simulation: Some models reviewed contained the ability to simulate the source field as part of the buffer simulation. This group of attributes was included to provide an understanding of the important source field simulation capabilities of these models.
- Buffer Simulation: This attribute group was included to understand the key differences in how processes critical to buffer behavior are simulated among models. This includes the simulation of processes that impact buffer quality, such as vegetation growth and buffer management such as fertilization and irrigation.
- Pesticide Fate and Transport: This attribute group was included to provide information regarding how the primary pesticide fate and transport processes are simulated.
- Pesticide Entrapment in Buffer: This attribute group focuses on the pesticide processes modeled within the buffer. It is designed to provide some specifics of the algorithms used to represent various processes.
- Model Usability: This attribute group was included to represent a range of model characteristics that determine model usability.

The second evaluation approach was to assess each of the models' Strengths, Weaknesses, Opportunities, and Threats (SWOT). In the context of comparison of simulation models, the SWOT analysis was intended to consider each of the candidate models relative to the objective of quantifying the effectiveness of buffers at reducing pesticide transport to a receiving water body. The strengths and weaknesses were evaluated independently for each model and are related to the internal design and capabilities of the modeling approach. The opportunities and threats were assessed for the modeling approaches in general and reflect the external factors that may influence the success of applying simulation models to evaluate buffer effectiveness and in turn design best management practices. To minimize bias in this somewhat subjective exercise, each model was limited to the four most significant strengths and weaknesses.

4.0 Discussion

The important characteristics and capabilities of each model which are relevant to the simulation of VFS and UMB effectiveness at reducing pesticides entering water bodies are summarized in Table 4.2 at the conclusion of this section. All five modeling approaches meet the minimum requirements; however, there are significant differences among the models, both in terms of the conceptual approach and the mathematical methods employed to simulate the relevant physical processes. This document has sought to highlight these differences in both the discussion of the models in Section 2 and in the model comparison matrix provided in Table 4.2. The reader is encouraged to study this matrix to help further their understanding of each model. The remainder of this discussion will focus on broader conclusions derived from the model comparisons.

The question of which model performs the best is not straightforward to answer, nor can it even be addressed without a direct comparison of the models' simulation results based upon several datasets. Conclusions can be drawn regarding the conceptual and functional differences among the models and their most significant strengths and weaknesses.

4.1 Conceptual and Functional Differences

The following are important conceptual and functional differences among the models that are relevant when selecting an appropriate buffer effectiveness model for a given application:

- Model Spatial Scale: All of the models are capable of simulating the effects of buffers at the field scale. APEX and SWAT are also capable of simulating the effects of buffers at the watershed scale.
- Model Temporal Scale: VFSMOD-W is a storm event based model. The other models are continuous models.
- Storm Duration: APEX, REMM, and VFSMOD-W use a sub-daily time step infiltration model. PRZM-BUFF and SWAT use a daily time step infiltration model. A sub-daily infiltration model may have advantages in capturing the dynamics of short-duration, high-intensity rainfall events which are significant runoff and sediment load producers.
- Model Conceptual Approach: APEX, PRZM-BUFF, and REMM utilize physically based methods to predict pesticide reduction in buffers. Physically-methods have the strength of basing their predictions upon equations derived from governing physical theories and observations of relevant environmental parameters. The weakness of physically-based methods is that because of simplifications in the natural processes and the uncertainty in observed parameters, calibration is often required. SWAT and VFSMOD-W utilize empirical equations to predict pesticide reduction within buffers. Empirically derived methods have the strength of being based upon observed data. The weakness of empirical methods is that their applicability is constrained by the observations from which they were derived.
- Buffer Conditions: APEX, PRZM-BUFF and REMM simulate long term (days to years) changes in buffer soil moisture and surface conditions by modeling evapotranspiration and vegetation dynamics. SWAT and VFSMOD-W do not simulate these long term changes in buffer conditions with time. When evaluating the variability in buffer effectiveness throughout multiple growing seasons, the change in the antecedent soil moisture should be considered along with any significant changes in vegetation.
- Buffer Vegetation: APEX, PRZM-BUFF, and REMM can simulate any type vegetation within the buffer. The plant growth models in APEX and REMM are more sophisticated and have a more significant effect on the buffer conditions than the PRZM-BUFF plant growth model. VFSMOD-W was designed specifically for grass filter strips, however its use has been extended to other types of vegetation (Munoz-Carpena et al., 1999). SWAT assumes that the buffer is a grass filter strip.
- Buffer Zones: APEX can simulate multiple buffer zones in sequence. REMM can simulate up to three buffer zones in a sequence. VFSMOD-W, by breaking up a buffer into segments, can also simulate multiple buffer zones. In the current PRZM-BUFF model, a single buffer zone is simulated. SWAT simulates a single buffer zone.

- Ineffective Buffer Areas: APEX, PRZM-BUFF, REMM, and SWAT account for regions of a buffer that are ineffective at reducing pesticide runoff. VFSMOD-W assumes that all regions along the length of a buffer are effective.
- Overland Flow and Deposition Dynamics: VFSMOD-W allows for variable sediment deposition rates within multiple buffer segments. This results in time-varying overland flow conditions and changes in sediment deposition rates and capacity within different segments of the buffer. The other models do not have the capability of simulating spatially varying conditions impacting flow and sediment transport within a buffer.
- Buffer Litter Layer Simulation: REMM simulates pesticide adsorption/desorption on organic matter in a litter layer. The empirical models SWAT and VFSMOD-W indirectly account for this process in a lumped fashion. APEX accounts for residue on the surface of a buffer; however, pesticide chemical interactions with the residue are not simulated. PRZM-BUFF does not simulate a litter layer. Sorption and degradation of pesticides in the litter layer may be an important process in reducing pesticide concentrations in runoff (Vought et al., 1994).
- Pesticide Drift: APEX and PRZM-BUFF allow pesticide input from drift to be added to the surface of the buffer vegetation. For REMM, SWAT, and VFSMOD-W, there is not a mechanism for drift inputs onto the buffer.
- Pesticide Loading to Buffer: APEX, PRZM-BUFF, and SWAT generate their own flow, sediment, and pesticide loadings to a buffer internally. REMM and VFSMOD-W require inputs of flow, sediment, and pesticide loads from an independent source (this would typically be another model or observed loads from field data).
- Pesticide Metabolite Simulation: PRZM-BUFF simultaneously simulates the transformation of a parent pesticide and metabolites as a function of time. The other models do not.

4.2 Model Strengths and Weaknesses

The four most significant strengths and weaknesses for each of the modeling approaches are summarized in Table 4.1 below. The constraint of four strengths and weaknesses was followed to provide a more even assessment. Some of the strengths and weaknesses listed stem from the conceptual and functional differences listed above but have been re-interpreted to represent a strength or weakness in the approach.

Table 4.1: SWOT table for runoff buffer model comparison.

Model	Strengths	Weaknesses
APEX	Well suited for both small watershed and field-scale assessments	Less sophisticated treatment of dynamic hydraulic and sediment deposition processes within a buffer than VFSMOD-W
	Allows simulation of effective and ineffective (channelized) zones through a buffer	No simulation of plant uptake of pesticide
	Will allow for simulation of buffers with multiple zones in sequence (i.e., managed turf, shrub, riparian)	No pesticide sorption to organic matter in litter layer
	Simulates changes in buffer vegetation and condition as a function of time	
PRZM-BUFF	Accounts for both effective and ineffective buffer areas	Daily timestep may not capture the dynamics of a runoff event passing through a buffer

Model	Strengths	Weaknesses
	Explicitly includes drift as component of pesticide load to a buffer	Simplification of the overland flow routing of flow through buffer
	The EXPRESS-BUFF shell allows direct integration with standard scenarios and EXAMS	Standard shell does not allow for simulation of multiple buffer zones in sequence (i.e., managed turf, shrub, riparian)
	Basic model already supported by EPA as a regulatory model for pesticide exposure assessments	More simplistic simulation of plant growth and condition of buffer as a function of time compared to APEX or REMM
REMM	Designed specifically to simulate multiple zone riparian buffers next to agricultural fields	Complex treatment of buffer processes requires more data input requirements than some models (including daily storm duration and humus organic matter pool partitioning)
	Based on well tested nutrient, water, sediment, and litter behavior within vegetative buffers	Needs easier-to-use model interfaces to generate input files
	Great flexibility to consider a variety of pesticide transport processes and descriptions of chemical behavior	Requires a separate model or observations to provide loadings to buffer
	Simulates reduction in pesticide through a buffer resulting from subsurface lateral flow	Drift handled only as additional edge-of-field pesticide loading
SWAT	Well suited for watershed-scale assessments	Does not simulate changing conditions in a buffer as a function of time
	Empirical buffer effectiveness approach based on physical model and observed data	Unable to parameterize specific buffer characteristics (model assumes a grass filter strip)
	Accounts for ineffective VFS area and non-uniform flow through a buffer	Does not allow for simulation of multiple buffer zones in sequence (i.e., managed turf, shrub, riparian)
	Integrated with well-tested field model to simulate inputs of flow sediment and pesticide to the buffer	The empirical pesticide reduction model may not provide accurate predictions when used in situations outside the range of the test data
VFSMOD-W	Specifically developed for simulating runoff and sediment trapping in grass filter strips	Being event based, it does not allow for long term simulation of buffer effectiveness
	Rigorous handling of sediment deposition dynamics within a buffer	Not designed for simulation of unmanaged buffer vegetation (e.g., riparian areas)
	The empirical pesticide reduction model was developed via regression against pesticide specific buffer effectiveness field data	Subsurface lateral flow and associated pesticide reduction is not simulated.
	Variable, sub-daily time step overland flow and infiltration model captures dynamics of infiltration-based pesticide reduction for short duration storm events	The empirical pesticide reduction model may not provide accurate predictions when used in situations outside the range of the test data

4.3 Opportunities and Threats

The use of simulation models to estimate the effectiveness of VFSs and UMBs at reducing pesticide exposure risk provides several opportunities. When compared to field studies, modeling is a cost-effective alternative for understanding how buffers can act to reduce off-site movement of pesticides. In addition, application of the models described in this document will result in more realistic risk assessments by including the effect of mitigation measures. Finally, the use of these models will increase our understanding of the benefits of buffers as a mitigation practice and potentially encourage their implementation, leading to reduced off-site transport of all pesticides (including those for which a buffer strip is not required by its label).

In order for the opportunities offered by the use of buffer simulation models to be realized, a few potential threats will need to be addressed. First, the application of models used to predict the efficiency of pesticide reductions by buffers needs to be conducted using tools, data, and assumptions appropriate for the situation. This document should provide valuable guidance in the selection of an appropriate tool. Furthermore, the success of buffers as a mitigation practice, particularly for managed VFSs, is contingent upon proper implementation and maintenance of the buffer strips by growers. This issue can be addressed by proper training and stewardship on the part of farm advisors and the agro-chemical industry.

4.4 Conclusions

The detailed listing of model characteristics in Table 4.2, the summarization of model conceptual and functional differences, and the SWOT table (Table 4.1) presented in this section will allow informed decisions to be made when choosing a model to evaluate buffer effectiveness. As has been shown, all of the models evaluated have strong credentials for use in buffer effectiveness applications for pesticides. The choice of appropriate model will depend upon the temporal and spatial scale of the assessment, data availability, and the characteristics of the buffer which needs to be modeled.

The question of model performance is important. Each of the models reviewed has been validated over a range of conditions and applications; however, a comprehensive comparison using common datasets has yet to be conducted. Such a comparison study would need to be conducted running the models in both an uncalibrated and a calibrated mode (note that uncalibrated versus calibrated simulations are only relevant to the three physically based models, APEX, PRZM, and REMM). Evaluation of the performance of the uncalibrated models is important because a common implementation of the models would be in the absence of observed data for calibration. With proper calibration, it is likely that all physically based models would be able to adequately simulate pesticide runoff reduction across a buffer; however, some models could offer advantages in both performance and ease of calibration.

Table 4.2: Runoff buffer model evaluation criteria summary matrix.

	APEX	**PRZM-BUFF**	**REMM**	**SWAT**	**VFSMOD-W**
Model Background					
Model sponsor/developer	TX Blackland Research and Extension Center	Waterborne Env.	USDA/ARS	USDA/ARS	Univ. of Florida
Model availability/cost	Public	Public	Public	Public	Public
Model version evaluated	APEX 0604	WINPRZM 3.24[1]	REMM2008	SWAT 2009	VFSMOD-W 5.1.6
Model year	2008	2009	2008	2009	2009
Model Scale					
Primary spatial scale	Farm/Small watershed	Field	Field	Watershed	Buffer
Secondary spatial scale	Field	Farm/Small watershed	Farm/Small watershed	Field	Field
Time scale	Continuous	Continuous	Continuous	Continuous	Event
Output time step	Daily	Daily	Daily	Daily	Break Point
Model Use and Capabilities					
Primary use	Agricultural non-point source	Agricultural non-point source	Nutrient trapping by managed and unmanaged riparian buffers adjacent to agricultural fields	Non-point source / Water quality	Non-point source / Water quality/buffer design optimization
Used for pesticide simulation in peer-reviewed literature	Yes	Yes	No	Yes	Yes
Used for vegetated buffer effectiveness in peer-reviewed literature	Yes	Yes	Yes	Yes	Yes
Model Input Requirements					
Flow loadings to buffer	Generated within model	Generated within model	Input or generated by other models	Generated within model	Input or generated by other models

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[1] This represents the PRZM version upon which PRZM-BUFF was based.

Table 4.2-cont: Runoff buffer model evaluation criteria summary matrix.

	APEX	**PRZM-BUFF**	**REMM**	**SWAT**	**VFSMOD-W**
Sediment loadings to buffer	Generated within model	Generated within model	Input or generated by other models	Generated within model	Input or generated by other models
Pesticide loadings to buffer	Generated within model	Generated within model	Input or generated by other models	Generated within model	Input or generated by other models
Field topographic characteristics	Yes	Yes	N/A	Yes	N/A
Buffer topographic characteristics	Optional	Yes	Yes	No	Yes; Simulates multiple segments within the buffer
Land cover/crop growth characteristics	Yes	Yes	Yes	Yes	Yes; Simulates multiple segments within the buffer
Soils	Yes	Yes	Yes	Yes	Yes
Field management operations	Yes	Yes	N/A	Yes	N/A
Weather Data Requirements					
Daily precipitation	Optional	Yes	Yes	Optional	Optional
Hourly precipitation	No	No	No	Optional	Optional
Daily temperature	Optional	Yes	Yes	Optional	Not Needed
Daily relative humidity	Optional	No	Yes	Optional	No
Daily wind	Optional	Yes	Yes	Optional	No
Daily solar radiation	Optional	Yes	Yes	Optional	No
Rainfall intensity distribution	Optional	No	Yes	No	Yes
Weather generator capabilities	Yes	No	No	Yes	No
Hydrology Simulation					
Potential evapotranspiration calculation methods available[2]	PT, PM, HG, BR	PE, HM	PM	PT, PM, HG, UD	Not needed for event based model

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[2] PT = Priestley-Taylor, PM = Penman/Monteith, HG = Hargreaves, BR = Baier-Robertson, UD = User-defined, PE = Pan Evaporation, HM = Harmon's

Table 4.2-cont: Runoff buffer model evaluation criteria summary matrix.

	APEX	**PRZM-BUFF**	**REMM**	**SWAT**	**VFSMOD-W**
Infiltration/runoff methods available[3]	CN, GA	CN	GA	CN, GA	Extended GA (Chu, 1978; Skaggs, 1982)
Daily curve number variation methods[4]	SM, SMDW, ST, ET	SM	N/A	SM, ET	N/A
Subsurface lateral flow calculation method	Partitioning of excess soil layer water between quick return flow to channel and subsurface lateral flow downstream, pipe flow	User defined partitioning of excess soil layer water at selected depth	Darcy's Equation	Kinematic storage	None
Saturated subsurface flow calculation method	Unsteady as a function of groundwater storage	External to shell	None. Deep seepage is a loss function	Unsteady as a function of groundwater storage	None. Deep seepage is a loss function
Subsurface drainage simulated	Yes	External to shell	No	Yes	No
Sediment Simulation					
Erosion calculation from buffer/field method[5]	MUST, AOF, USLE, MUSS, MUSLE, MUSI, RUSLE, RUSLE2	MUST, MUSS, MUSLE, (RUSLE)	USLE	MUSLE	MUSLE or generated by other models
Sediment deposition in buffer simulated	Yes	Yes	Yes	Yes (empirical)	Yes
Sediment resuspension in buffer simulated	Yes	Yes	Yes	No	Yes
Pesticide transport with sediment approach[6]	ER	ER	ER	ER	Regression
Source Field Simulation					

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[3] CN = Curve number, GA = Green & Ampt

[4] SM = Soil moisture storage, SMDW = Soil moisture depth weighting, ET = evapotranspiration / Soil moisture index, ST = Stochastic

[5] MUSLE = Modified Universal Soil Loss Equation, AOF = Onstad-Foster, USLE = Universal Soil Loss Equation, MUSS = Small Watershed MUSLE, MUSI = Modified MUSLE with input parameters, RUSLE = Revised Universal Soil Loss Equation, RUSLE2 = Modified RUSLE

[6] ER = enrichment ratio

Table 4.2-cont: Runoff buffer model evaluation criteria summary matrix.

	APEX	**PRZM-BUFF**	**REMM**	**SWAT**	**VFSMOD-W**
Crop growth model	Yes	Yes	Yes	Yes	No
Management operations simulated[7]	PL, HV, IR, FT, TL, PT, GR, MW	PL, HV, IR, TL, PT	PL,HV, FT	PL, HV, IR, FT, TL, PT, GR	No
Other in-field erosion control practices simulated[8]	PF, FD	PF	PF	PF	PF
User-defined pesticide application dates	Yes	Yes	N/A-pesticide load is an input	Yes	N/A-pesticide load is an input
Multiple pesticide application dates possible	Yes	Yes	N/A-pesticide load is an input	Yes	N/A-pesticide load is an input
Pesticide application incorporation into soil	Yes	Yes	N/A-pesticide load is an input	Yes	N/A-pesticide load is an input
Foliar pesticide interception / degradation / wash-off	Yes	Yes	N/A-pesticide load is an input	Yes	N/A-pesticide load is an input
Buffer Simulation					
Crop growth model	Yes	Yes	Yes	Yes	No
Management operations simulated	Yes	Yes	Yes	Yes	Yes
Simulation of ineffective buffer areas	Yes	Yes	Yes	Yes	Yes
Simulation of channel flow through buffer	Yes	No	Yes	Yes	Yes
Simulation of surface organic matter/litter	No (surface roughness only)	No	Yes	No	No (surface roughness only)
Pesticide Fate and Transport					
Volatilization	Yes	Yes	Yes	Yes	No
Adsorption/desorption	Yes	Yes	Yes	Yes	Yes
Soil degradation	Yes	Yes	Yes	Yes	No

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[7] PL = Planting, HV = Harvest, IR = Irrigation, FT = Fertilization, TL = Tillage, PT = Pesticide application, GR = Grazing , MW = Mowing

[8] PF = Cropping practices (e.g., strip cropping, contouring terracing) via USL P-Factor, FD = Furrow diking

Table 4.2-cont: Runoff buffer model evaluation criteria summary matrix.

	APEX	PRZM-BUFF	REMM	SWAT	VFSMOD-W
Transport in surface runoff	Yes	Yes	Yes	Yes	Yes, reduction
Transport on sediment	Yes	Yes	Yes	Yes	Yes, reduction
Transport in lateral flow	Yes	Yes	Yes	Yes	No
Transport in saturated subsurface flow	Yes	Yes	Yes	Yes	No
Uptake by plants	No	Yes	Yes	No	No
Simulation of pesticide metabolites	No	Yes	No	No	No
Pesticide Entrapment in Buffer					
Physically based or empirical	Physical	Both	Physical	Empirical	Empirical
Reduction of soluble pesticide in surface runoff simulated	Yes	Yes	Yes	Yes	Yes
Mechanism(s) for soluble pesticide reduction in surface runoff	Infiltration, degradation, sorption	Infiltration, degradation, sorption	Infiltration, degradation, sorption	Infiltration	Infiltration, degradation, sorption (empirical)
Reduction of sorbed pesticide in sediment simulated	Yes	Yes	Yes	Yes	Yes
Mechanism(s) for sorbed pesticide reduction in sediment	Deposition, sorption, degradation	Deposition, sorption, degradation	Deposition, sorption, degradation	Deposition	Deposition, sorption, degradation (empirical)
Reduction of pesticide in lateral flow simulated	Yes	Yes	Yes	No	No
Mechanism(s) for reduction in lateral flow pesticide	Degradation, sorption	Deposition, sorption, degradation	Degradation, sorption, plant uptake	N/A	No
Reduction of pesticide in subsurface flow simulated	Yes	Yes	Yes	No	No
Mechanism(s) for reduction in subsurface flow pesticide	Degradation, sorption, deep seepage	Degradation, sorption, deep seepage (external)	Degradation, sorption, deep seepage	N/A	No

Table 4.2-cont: Runoff buffer model evaluation criteria summary matrix.

	APEX	**PRZM-BUFF**	**REMM**	**SWAT**	**VFSMOD-W**
Model Usability					
Data requirements[9]	Medium	Low*	Medium	Medium	Medium
Complexity of parameterization[9]	Medium	Medium	Medium	Medium	Medium
Level of modeler expertise required[9]	Medium	Low*	Medium	Medium	Medium
Model interface ease of use[10]	Easy	Easy	Medium	Easy	Easy
Ease of model output interpretation[10]	Moderate	Easy	Easy	Moderate	Easy
Level of interface integration with GIS[11]	Good	None	None	Good	None for stand alone version, Moderate for the version of the model that is interfaced with Google-Maps
Level of interface integration with supporting database[11]	Good	Good	Poor	Good	None
Model documentation[11]	Good	(in development)	Good	Good	Good
Level of user support available[11]	Moderate/Good	Moderate	Moderate	Moderate/Good	Moderate/Good

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[9] Low, medium, high

[*] Using EXPRESS shell defaults, otherwise medium

[10] Easy, moderate, difficult

[11] Poor, moderate, good

5.0 References

Abu-Zreig M., R. P. Rudra, and H. R. Whiteley. 2001. Validation of a vegetated filter strip model (VFSMOD). Hydrological Processes 15(5): 729-742.

Ahuja, L. R., K. W. Rojas, J. D. Hanson, M. J. Shaffer, and L. Ma (eds). 2000. The Root Zone Water Quality Model. Water Resources Publications LLC. Highlands Ranch, CO. 372pp.

Applied Research Systems, Inc. 1999. The national conservation buffer initiative: a qualitative evaluation. Report prepared for the Natural Resources Conservation Service. 52 p.

Arnold, J.G., J. D. Atwood, V. W. Benson, R. Srinnivasan, and J. R. Williams. 1998a. Potential Environmental and Economic Impacts of Implementing National Conservation Buffer Initiative Sedimentation Control Measures. USDA, NRCS Staff paper.

Arnold, J. G., R. Srinivasan, R. S. Muttiah, and J. R. Williams. 1998b. Large area hydrologic modeling and assessment: Part I. Model development. J. American Water Resour. Assoc. 34(1): 73-89.

Arnold, J. G., J. R. Williams, A. D. Nicks, and N. B. Sammons. 1990. SWRRB: A basin scale simulation model for soil and water resources management. Texas A&M Univ. Press, College Station, TX.

Arnold, J .G., J. R. Williams and D. R. Maidment. 1995. Continuous-time water and sediment-routing model for large basins. Journal of Hydraulic Engineering 121(2):171-183.

Bagnold, R. A., 1977. Bed-load transport by natural rivers. Water Resources Research, 13(2): 303-312.

Barfield, B. J., E. W. Tollner, and J. C. Hayes. 1978. The use of grass filters for sediment control in strip mining drainage. Vol. I: Theoretical studies on artificial media. Pub. no. 35-RRR2-78. Institute for Mining and Minerals Research, University of Kentucky, Lexington.

Barfield, B. J., E. W. Tollner, and J. C. Hayes. 1979. Filtration of sediment by simulated vegetation I. Steady-state flow with homogeneous sediment. Transactions of ASAE. 22(5):540-545.

Bhat, S., K. Hatfield, J. Jacobs, R. R. Lowrance, and R. G. Williams. 2007. Surface runoff contribution of nitrogen during storm events in a forested watershed: Application of the Riparian Ecosystem Management Model (REMM). Biogeochemistry. 85(3):253-262.

Bicknell, B. R., J. C. Imhoff, J. L. Kittle Jr., A. S. Donigian Jr., and R. C. Johanson. 1997. Hydrological Simulation Program--Fortran, User's manual for version 11: U.S. Environmental Protection Agency. National Exposure Research Laboratory, Athens, Ga., EPA/600/R-97/080. 755 p.

Chu, S. T. 1978. Infiltration during unsteady rain. Water Resour. Res. 14(3):461-466.
Dosskey, M. G., M. J. Helmers, and D. E. Eisenhauer. 2008. A design aid for determining width of filter strips. Journal of Soil and Water Conservation 63(4): 232-241.

Flowers, J. D., J. R. Williams, and L.M. Hauck. 1996. "NPP integrated modeling system: calibration of the APEX model for dairy waste application fields in Erath County, Texas." Project Report PR 96-07.
Texas Institute for Applied Environmental Research, Tarleton State University.

Gassman, P. W., M. R. Reyes, C. H. Green, and J. G. Arnold. 2007. The soil and water assessment tool: historical development, applications, and future directions. Transactions of ASABE 50(4): 1211-1250.

Gassman, P. W., J. R. Williams, V. W. Benson, R. C. Izaurralde, L. M. Hauck, C. A. Jones, J. D. Atwood, J. R. Kiniry, and J. D. Flowers. 2005. Historical development and applications of the EPIC and APEX models. Working Paper 05-WP 397, Center for Agricultural and Rural Development, Iowa State University. 43 p.

Giddings, J.M., T.A. Anderson, L.W. Hall Jr., A.J. Hosmer, R.J. Kendall, R.P. Richards, K.R. Solomon, and W.M. Williams, 2005. Appendix D: Runoff buffer model methodology and validation. In: Atrazine in North American Surface Waters: A Probabilistic Aquatic Ecological Risk Assessment. Pensacola, FL. Society of Environmental Toxicology and Chemistry (SETAC). p 313-332.

Graff, C. D., A. M. Sadeghi, R. R. Lowrance, and R. G. Williams. 2005. Quantifying the sensitivity of the riparian ecosystem management model (REMM) to changes in climate and buffer characteristics common to conservation practices. Transactions of the ASAE. 48(4):1377-1387.

Haith, D. A. and L.L. Shoemaker. 1987. Generalized watershed loading functions for stream flow nutrients. Water Resources Bulletin. 23(3):471-478.

Harman, W. L., E. Wang, and J. R. Williams. 2004. Reducing Atrazine Losses: Water Quality Implications of Alternative Runoff Control Practices. J. Environ. Qual. 33:7–12.

Hayes, J. C., B. J. Barfield, and R. I. Barnhisel. 1979. Filtration of sediment by simulated vegetation II. Unsteady flow with non-homogeneous sediment. Transactions of ASAE. 22(5):1063-1967.

Hayes, J. C., B. J. Barfield, and R. I. Barnhisel. 1984. Performance of grass filters under laboratory and field conditions. Transactions of ASAE. 27(5):1321-1331.

Holvoet, K., V. Gevaert, A. Van Griensven, P. Seuntjens, and P. A. Vanrolleghem. 2007. Modeling the effectiveness of agricultural measures to reduce the amount of pesticide entering surface waters. Water Resources Management 21:2027–2035.

Knisel, W.G. 1980. CREAMS, a field scale model for chemicals, runoff and erosion from agricultural management systems. USDA Conservation Research Rept. No. 26.

Lacas, J. G., M. Voltz, V. Gouy, N. Carluer, and J. J. Gril. 2005. Using grassed strips to limit pesticide transfer to surface water: a review. Agron. Sustain. Dev. 25: 253–266.

Leonard, R. A., W. G. Knisel, and D. A. Still. 1987. GLEAMS: Groundwater loading effects on agricultural management systems. Trans. ASAE 30(5):1403-1428.

Lighthill, M. J. and C. B. Whitham. 1955. On kinematic waves: flood movement in long rivers. Proc. R. Soc. London Ser. A. 22:281-316.

Lowrance, R. R., L. S. Altier, R. G. Williams, S. P. Inamdar, D. D. Bosch, J. M. Sheridan, D. L. Thomas, and R. K. Hubbard. 2002. The Riparian Ecosystem Management Model: simulator for ecological processes in riparian zones. USDA-ARS Conservation Research Report 46.

Mausbach, M. J., and A. R. Dedrick. 2004. The length we go: Measuring environmental benefits of conservation practices. J. Soil and Water Cons. 59(5): 96−103.

Mein, R. G. and C. L. Larson. 1971. Modeling the infiltration component of the rainfall runoff process, Bulletin 43, University of Minnesota, MN, Water Resources Research Center.

Mein, R. G., and C. L. Larson. 1973. Modeling Infiltration during a Steady Rain, Water Resour. Res., 9(2), 384–394.

Muñoz-Carpena, R., C. T. Miller and J. E. Parsons. 1993a. A quadratic Petrov-Galerkin solution for kinematic wave overland flow. Water Resour. Res. 29(8):2615-2627.

Muñoz-Carpena, R., J. E. Parsons and J. W. Gilliam. 1993b. Numerical approach to the overland flow process in vegetative filter strips. Transactions of ASAE. 36(3):761-770.

Muñoz-Carpena, R., J. E. Parsons, and G. J. Wendell. 1999. Modeling hydrology and sediment transport in vegetative filter strips. Journal of Hydrology 214(1999): 111-129.

Muñoz-Carpena, R . and J. E. Parsons. 2004. A design procedure for vegetative filter strips using VFSMOD-W. Trans. of ASAE 47(5):1933-1941

Muñoz-Carpena, R., Z. Zajac and Y.-M. Kuo. 2007. Evaluation of water quality models through global sensitivity and uncertainty analyses techniques: application to the vegetative filter strip model VFSMOD-W. Trans. of ASABE 50(5):1719-1732.

Neitsch, S. L., J. G. Arnold, J. R. Kiniry, and J. R. Williams. 2005. Soil and Water Assessment Tool theoretical documentation, Version 2005. Temple, Tex.: USDA ARS Grassland, Soil and Water Research Laboratory. 476 p.

Poletika, N. N., P. N. Coody, G. A. Fox, G. J. Sabbagh, S. C. Dolder, and J. White. 2009 Chlorpyrifos and atrazine removal from runoff by vegetated filter strips: experiments and predictive modeling. Journal of Environmental Quality 38(3): 1042-1052.

Putman, J., J. Williams, and D. Sawyer. 1988. Using the erosion productivity calculator (EPIC) model to estimate the impact of soil erosion for the 1985 RCA appraisal. J. Soil Water Conserv. 43(4):321-326.

Ramanarayanan, T. S., J. M. Cheplick, R. Allen, R. F. Pugsley, M. G. Dobbs, and W. M. Williams. 2002. Probabilistic assessment of runoff exposure to non-target plants from a herbicide applied to adjacent corn fields. Presented at 2002 ASAE Annual International Meeting / CIGR XV World Congress, Chicago, USA. ASAE Meeting Paper Number: 02-2011.

Reichenberger, S., M. Bach, A. Skitschak, and H.-G. Frede. 2007. Mitigation strategies to reduce pesticide inputs into ground- and surface water and their effectiveness: a review. Sci. Total Environ. 384: 1-35.

Roepke, B., H. Meyer, G. J. Sabbagh, A. Horn, N. Mackay and R. Munoz-Carpena. 2009. “Modelling runoff mitigation capability of vegetated filter strips”. Poster presentation at the Pesticide Behaviour in Soils, Water and Air Symposium; 14-16 September; York, UK.

Sabbagh, G. J., G. A. Fox, A. Kamanzi, B. Roepke, and J. Z. Tang. 2009. “Effectiveness of vegetative filter strips in reducing pesticide loading: Quantifying pesticide trapping efficiency”. Journal of Environmental Quality 38(2):762-771.

Sharpley, A. N. and J.R. Williams, eds. 1990. EPIC--erosion/productivity impact calculator: 1. model documentation. U.S. Dept. Agric. Tech. Bull. No. 1768.

Shirmohammadi, A., I. Chaubey, R. D. Harmel, D. D. Bosch, R. Muñoz-Carpena, C. Dharmasri, A. Sexton, M. Arabi, M. L. Wolfe, J. Frankenberger, C. Graff, and T. M. Sohrabi. 2006. Uncertainty in TMDL models. Trans. of ASABE 49(4):1033-1049.

Shoemaker, L., T. Dai, and J. Koenig. 2005. TMLD model evaluation and research needs. EPA Report: EPA/600/R-05/149. 403p.

Singh, A., R. Rudra, W. Yang, B. Gharabaghi, R. R. Lowrance, and M. Diluzio. 2007. Swat-remm interface for modeling effects of riparian buffer system on sub-basin hydrology. Transactions of the ASABE.

Skaggs, R. W. and R. Khaheel. 1982. Chapter 4: Infiltration. In Hydrologic modeling of small watersheds. Ed. by C. T. Haan, H. P. Johnson and D. L. Brakensiek, ASAE Monograph No. 5, American Society of Agricultural Engineers, St. Joseph, MI, pp. 121-168.

Suaréz, L. A. 2005. PRZM-3, A model for predicting pesticide and nitrogen fate in crop root and unsaturated zones: Users manual for release 3.12.3. Nation Exposure Research Laboratory. 426 p.

Tollner, E. W., B. J. Barfield, C. T. Haan and T. Y. Kao. 1976. Suspended sediment filtration capacity of simulated vegetation. Transactions of ASAE 19(4):678-682.

Tollner, E. W., B. J. Barfield, C. Vachirakornwatana and C. T. Haan. 1977. Sediment deposition patterns in simulated grass filters. Transactions of ASAE. 20(5):940-944.

United States Department of Agriculture (USDA). 2000. Conservation buffers to reduce pesticide losses. USDA Natural Resources Conservation Service. 21 p.

Vought, L. B., M. J. Dahl, C. L. Pedersen, and J.O. Lacoursiere. 1994. Nutrient retention in riparian ecotones. Ambio 23:342-348.

Wang, X., A. Saleh, M. W. McBroom, J. R. Williams, and L. Yin. 2007. Test of APEX for nine forested watersheds in east Texas. J. Environ. Qual. 36:983–995.

WERF. 2001. Water quality models: a survey and assessment. Water Environment Research Foundation Project 99-WSM-5. 102 p.

White, M. J., J. G. Arnold. 2009. Development of a simplistic vegetative filter strip model for sediment and nutrient retention at the field scale. Hydrologic Processes. In Press.

Williams, J. R. 1975. HYMO flood routing, J. Hydrology, 26, 17-27.

Williams, J.R. 1995. The EPIC model: In V. P. Singh, Computer models of watershed hydrology. Water Resources Publications, Highlands Ranch, CO. p 909-1000.

Williams, J. R., C. A. Jones and P. T. Dyke. 1984. A modeling approach to determining the relationship between erosion and soil productivity. Trans. ASAE 27(1):129-144.

Williams, J. R., R. C. Izaurralde, and E. M. Steglich. 2008. Agricultural policy/environmental extender model theoretical documentation. BREC Report #2008-17. Blackland Research and Extension Center. 130 p.

Williams, J. R., A. D. Nicks, and J. G. Arnold. 1985. SWRRB, a simulator for water resources in rural basins. ASCE Hydr. J., 111(6): 970-986.

Wilson, B. N., B. J. Barfield, and I. D. Moore. 1981. A hydrology and sedimentology watershed model, part I: modeling techniques. Technical Report. Department of Agricultural Engineering. University of Kentucky. Lexington.

Winchell, M.F., R. Srinivasan, M. Di Luzio, and J. Arnold. 2008. ArcSWAT 2.1 interface for SWAT 2005 user's guide. Blackland Research Center, Texas Agricultural Experiment Station. 453 p.

Young, R. A., C. A. Onstad, D. D. Bosch, and W. P. Anderson. 1989. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. J. Soil & Water Conserv. 44(2):168-173.

Yuan, Y., R. L. Bingner, R. G. Williams, R. R. Lowrance, D. D. Bosch, and J. M. Sheridan. 2007. Integration of AnnAGNPS and REMM for watershed riparian buffer system assessment. International Journal of Sediment Research, 22(1): 60-69.

APPENDIX A – EXAMPLE MODEL EVALUATION MATRICES

Table A.1: Rural watershed model criteria matrix, from WERF, 2001.

Table 2-2. Model Selection Criteria Matrix for Rural Watershed Models

	Model Type		Space-scale					Time-scale			Pollutants			Level of Analysis		Source Release				Processes	
	Urban	Point Sources	Field	Small Watershed	Large Watershed	Lumped	Distributed	Event	Continuous	Annual	Sediment	Nutrients	Chemicals	Screening	Detailed/Planning	Constant	Time-varying	Single	Multiple	Transport	Trans-formations
AGNPS-98		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ANSWERS			X	X	X		X	X	X	X	X	X		X	X	X	X	X		X	
APEX			X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
BASINS (HSPF)	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
BASINS (SWAT)		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
CREAMS			X			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
DR3M-QUAL	X		X	X		X		X	X	X	X	X	X	X	X	X	X	X		X	
EPIC			X			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
ETD			X	X		X		X	X	X			X	X		X	X	X		X	X
FHWA	X		X	X		X		X		X		X	X	X		X		X			
GISPLM	X	X	X	X	X	X		X	X	X		X		X	X	X	X	X	X	X	
GLEAMS			X			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
GWLF	X	X	X	X	X	X		X	X	X	X	X		X		X	X	X	X	X	
HSPF	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
HUMUS		X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
ILWAS			X	X	X	X		X	X	X		X	X	X	X	X	X	X		X	X
KINEROS	X	X	X	X			X	X	X	X	X			X	X	X	X	X	X	X	
LWWM	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
MAGIC			X	X		X			X	X			X	X		X	X	X		X	X
MIKE SHE	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
NAPRA			X			X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
NLEAP			X			X		X	X	X		X		X	X	X	X	X		X	X
Opus			X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
OWLS			X	X			X	X	X	X				X							
PRMS	X		X	X	X	X		X	X	X	X			X	X	X	X	X	X	X	
PRZM-3		X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
SHE/SHESED	X	X	X	X	X		X	X	X	X	X			X	X	X	X	X	X	X	
SITEMAP	X			X		X		X	X	X		X		X		X	X	X	X	X	
SLAMM	X	X	X	X		X		X	X	X	X	X	X	X	X	X	X	X	X	X	
SLOSS-PHOSPH			X	X		X		X		X	X	X		X		X		X		X	
SLURP	X		X	X	X		X	X	X	X				X							
SPUR-91			X	X		X		X	X	X	X	X		X	X	X	X	X		X	X
SSARR			X	X	X	X		X	X	X				X	X						
STORM	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X	X		
SWAT		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
SWMM	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X	
SWRRBWQ		X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	
USGSREGR	X		X	X		X		X		X	X	X	X	X		X		X			
UTM-TOX-WHTM		X	X	X	X	X		X	X	X	X	X	X	X	X	X		X	X	X	
WARMF	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
WATERSHED	X	X	X	X		X		X		X	X	X		X		X		X	X	X	
WEPP			X	X		X		X	X	X	X			X	X	X		X	X	X	
WMM	X	X	X	X	X	X				X		X	X	X		X		X	X	X	X
WMS (HSPF)	X	X	X	X	X	X		X	X	X	X	X	X	X	X	X	X	X	X	X	X
WSTT	X	X	X	X	X	X		X	X	X	X	X	X	X		X	X	X	X	X	

Table A.1-cont.: Rural watershed model criteria matrix, from WERF, 2001.

Table 2-2. Model Selection Criteria Matrix for Rural Watershed Models (cont.)

	Input Aids		Output Aids		BMP Evaluation		Level of Effort			Data Requirements			Modeler Expertise			Documentation		Other Support		Model Availability	
	GUIs	Linkage to GIS	GUIs	Linkage to GIS	Simple	Detailed	Low	Medium	High	Low	Medium	High	Low	Medium	High	Weak	Strong	Sponsor Support	Workshops	Public Domain	Proprietary
AGNPS-98	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X	X	
ANSWERS					X	X		X	X		X	X		X	X	X	X	X		X	
APEX	X	X	X	X	X	X		X			X			X		X		X	X	X	
BASINS (HSPF)	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X	X	
BASINS (SWAT)	X	X	X	X	X	X		X			X			X		X	X	X	X	X	
CREAMS					X	X		X	X		X	X		X	X	X	X	X	X	X	
DR3M-QUAL								X			X			X		X	X	X	X	X	
EPIC	X	X	X	X	X	X		X			X			X		X	X	X	X	X	
ETD					X		X	X		X			X	X		X				X	
FHWA							X			X			X			X	X			X	
GISPLM	X	X	X	X	X	X		X			X			X		X		X		X	
GLEAMS		X		X	X	X		X	X		X	X		X	X	X	X	X	X	X	
GWLF					X		X			X				X		X	X	X		X	
HSPF	X		X		X	X		X	X		X	X		X	X	X	X	X	X	X	
HUMUS	X	X	X	X	X	X		X			X			X		X	X	X	X	X	
ILWAS					X	X			X			X			X	X	X	X			X
KINEROS			X		X	X		X	X		X	X		X	X	X	X	X		X	
LWWM	X	X	X	X	X	X			X			X			X	X	X	X		X	
MAGIC					X		X	X		X	X		X	X		X	X	X		X	
MIKE SHE	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X		X
NAPRA	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X	X	
NLEAP	X	X	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	
Opus	X	X	X	X	X	X			X			X			X	X	X	X		X	
OWLS	X	X	X	X	X			X			X			X		X					X
PRMS	X	X	X	X	X	X		X	X		X	X		X		X	X	X	X	X	
PRZM-3					X	X		X			X			X		X	X	X	X	X	
SHE/SHESED		X		X	X	X			X		X	X		X	X	X	X	X			X
SITEMAP	X		X		X			X			X			X		X	X	X			X
SLAMM		X		z	X	X		X			X			X		X		X	X	X	
SLOSS-PHOSPH							X			X				X		X	X			X	
SLURP	X	X	X	X				X			X			X		X	X	X		X	
SPUR-91		X		X	X	X		X	X		X	X		X	X	X		X		X	
SSARR	X		X		X	X		X			X			X		X	X	X		X	
STORM					X			X	X		X	X		X	X	X	X			X	
SWAT	X	X	X	X	X	X		X			X			X		X	X	X	X	X	
SWMM	X	X	X	X	X	X			X			X			X	X	X	X	X	X	X
SWRRBWQ	X		X		X	X		X	X		X	X		X	X	X		X		X	
USGSREGR							X			X			X			X		X		X	
UTM-TOX-WHTM									X			X			X	X				X	
WARMF	X	X	X	X	X			X				X		X		X	X	X	X		X
WATERSHED					X			X			X			X		X	X			X	
WEPP	X	X	X	X	X	X		X				X		X		X	X	X	X	X	
WMM					X		X			X				X		X					X
WMS (HSPF)	X	X	X	X	X	X		X	X		X	X		X	X	X	X	X	X		X
WSTT	X	X	X	X	X		X			X			X			X		X		X	

Table A.2: Model management practices summary matrix, from Shoemaker et al., 2005.

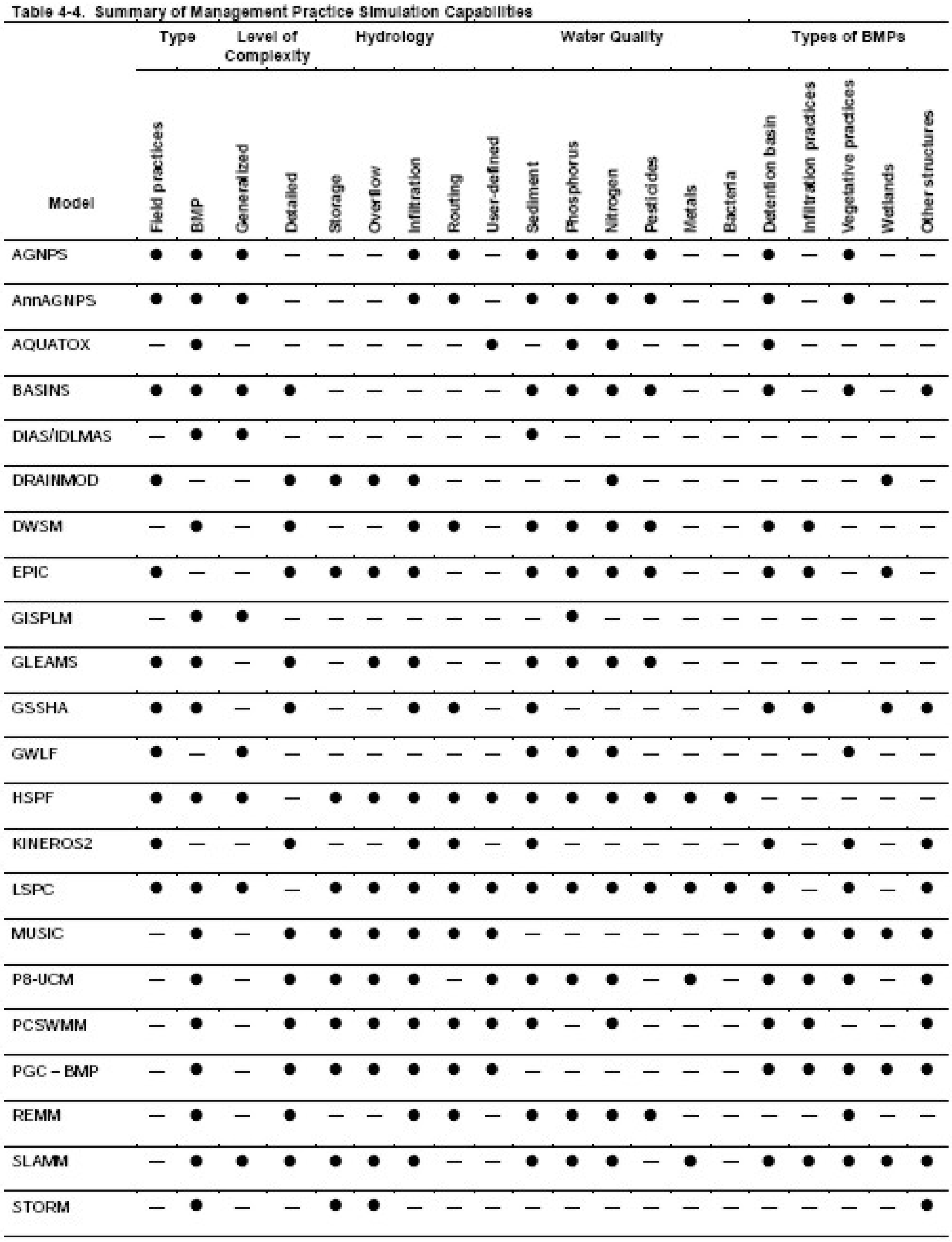
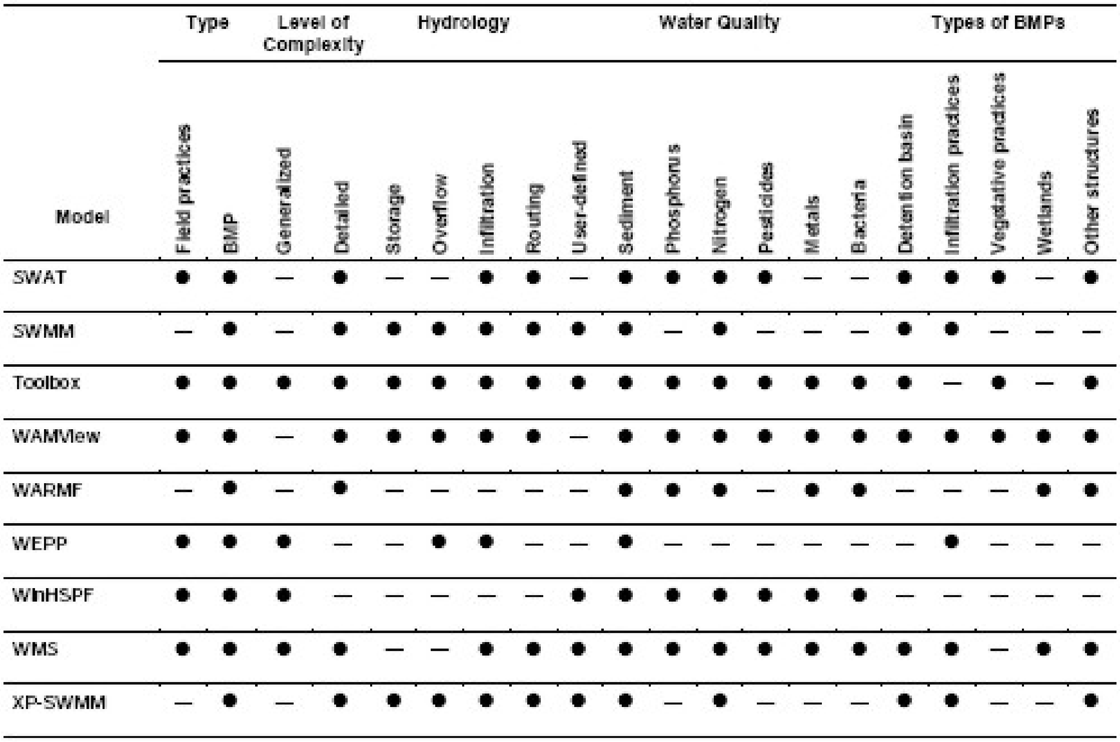


Table 4-4. Summary of Management Practice Simulation Capabilities

Model	Type		Level of Complexity		Hydrology					Water Quality						Types of BMPs				
	Field practices	BMP	Generalized	Detailed	Storage	Overflow	Infiltration	Routing	User-defined	Sediment	Phosphorus	Nitrogen	Pesticides	Metals	Bacteria	Detention basin	Infiltration practices	Vegetative practices	Wetlands	Other structures
AGNPS	●	●	●	—	—	—	●	●	—	●	●	●	●	—	—	●	—	●	—	—
AnnAGNPS	●	●	●	—	—	—	●	●	—	●	●	●	●	—	—	●	—	●	—	—
AQUATOX	—	●	—	—	—	—	—	—	●	—	●	●	—	—	—	●	—	—	—	—
BASINS	●	●	●	●	—	—	—	—	—	●	●	●	●	—	—	●	—	●	—	●
DIAS/IDLMAS	—	●	●	—	—	—	—	—	—	●	—	—	—	—	—	—	—	—	—	—
DRAINMOD	●	—	—	●	●	●	●	—	—	—	—	●	—	—	—	—	—	—	●	—
DWSM	—	●	—	●	—	—	●	●	—	●	●	●	●	—	—	●	●	—	—	—
EPIC	●	—	—	●	●	●	●	—	—	●	●	●	●	—	—	●	●	—	●	—
GISPLM	—	●	●	—	—	—	—	—	—	—	●	—	—	—	—	—	—	—	—	—
GLEAMS	●	●	—	●	—	●	●	—	—	●	●	●	●	—	—	—	—	—	—	—
GSSHA	●	●	—	●	—	—	●	●	—	●	—	—	—	—	—	●	●		●	●
GWLF	●	—	●	—	—	—	—	—	—	●	●	●	—	—	—	—	—	●	—	—
HSPF	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●	—	—	—	—	—
KINEROS2	●	—	—	●	—	—	●	●	—	●	—	—	—	—	—	●	—	●	—	●
LSPC	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	●
MUSIC	—	●	—	●	●	●	●	●	●	—	—	—	—	—	—	●	●	●	●	●
P8-UCM	—	●	—	●	●	●	●	—	●	●	●	●	—	●	—	●	●	●	—	●
PCSWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	●
PGC – BMP	—	●	—	●	●	●	●	●	●	—	—	—	—	—	—	●	●	●	●	●
REMM	—	●	—	●	—	—	●	●	—	●	●	●	●	—	—	—	—	●	—	—
SLAMM	—	●	●	●	●	●	●	—	—	●	●	●	—	●	—	●	●	●	●	●
STORM	—	●	—	—	●	●	—	—	—	—	—	—	—	—	—	—	—	—	—	●

Table A.2-cont.: Model management practices summary matrix, from Shoemaker et al., 2005.



	Type		Level of Complexity		Hydrology					Water Quality						Types of BMPs				
Model	Field practices	BMP	Generalized	Detailed	Storage	Overflow	Infiltration	Routing	User-defined	Sediment	Phosphorus	Nitrogen	Pesticides	Metals	Bacteria	Detention basin	Infiltration practices	Vegetative practices	Wetlands	Other structures
SWAT	●	●	—	●	—	—	●	●	—	●	●	●	●	—	—	●	●	●	—	●
SWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	—
Toolbox	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	—	●	—	●
WAMView	●	●	—	●	●	●	●	●	—	●	●	●	●	●	●	●	●	●	●	●
WARMF	—	●	—	●	—	—	—	—	—	●	●	●	—	●	●	—	—	—	●	●
WEPP	●	●	●	—	—	●	●	—	—	●	—	—	—	—	—	—	●	—	—	—
WinHSPF	●	●	●	—	—	—	—	—	●	●	●	●	●	●	●	—	—	—	—	—
WMS	●	●	●	●	—	—	●	●	●	●	●	●	●	●	●	●	●	—	●	●
XP-SWMM	—	●	—	●	●	●	●	●	●	●	—	●	—	—	—	●	●	—	—	●

APPENDIX B – MODEL DOCUMENTATION

APEX Model Documentation (from Williams et al., 2008)

The Agricultural Policy/Environmental eXtender (APEX) model was developed for use in whole farm/small watershed management. The model was constructed to evaluate various land management strategies considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, plant competition, weather and pests. Management capabilities include irrigation, drainage, furrow diking, buffer strips, terraces, waterways, fertilization, manure management, lagoons, reservoirs, crop rotation and selection, pesticide application, grazing, and tillage. Besides these farm management functions, APEX can be used in evaluating the effects of global climate/CO2 changes; designing environmentally safe, economic landfill sites; designing biomass production systems for energy; and other spin off applications. The model operates on a daily time step (some processes are simulated with hourly or less time steps) and is capable of simulating hundreds of years if necessary. Farms may be subdivided into fields, soil types, landscape positions, or any other desirable configuration.

The individual field simulation component of APEX is taken from the Environmental Policy Integrated Climate (EPIC) model, which was developed in the early 1980's to assess the effect of erosion on productivity (Williams, et al., 1984). Various components from CREAMS (Knisel, 1980) and SWRRB (Williams, et al., 1985) were used in developing EPIC and the GLEAMS (Leonard, et al., 1987) pesticide component was added later. Since the 1985 National RCA application (Putman,et al., 1988), the model has been expanded and refined to allow simulation of many processes important in agricultural management (Sharpley and Williams, 1990; Williams, 1995). The drainage area considered by EPIC is generally a field-size area, up to about 100 ha, where weather, soils, and management systems are assumed to be homogeneous. The major components in EPIC are weather simulation, hydrology, erosion-sedimentation, nutrient cycling, pesticide fate, crop growth, soil temperature, tillage, economics, and plant environment control. Although EPIC operates on a daily time step, the optional Green and Ampt infiltration equation simulates rainfall excess rates at shorter time intervals (0.1 h). The model offers options for simulating several other processes—five PET equations, six erosion/sediment yield equations, two peak runoff rate equations, etc. EPIC can be used to compare management systems and their effects on nitrogen, phosphorus, carbon, pesticides and sediment. The management components that can be changed are crop rotations, tillage operations, irrigation scheduling, drainage, furrow diking, liming, grazing, tree pruning, thinning, and harvest, manure handling, and nutrient and pesticide application rates and timing.

The APEX model was developed to extend the EPIC model capabilities to whole farms and small watersheds. In addition to the EPIC functions, APEX has components for routing water, sediment, nutrients, and pesticides across complex landscapes and channel systems to the watershed outlet. APEX also has groundwater and reservoir components. A watershed can be subdivided as much as necessary to assure that each subarea is relatively homogeneous in terms of soil, land use, management, and weather. The routing mechanisms provide for evaluation of interactions among subareas involving surface runoff, return flow, sediment deposition and degradation, nutrient transport, and groundwater flow. Water quality in terms of nitrogen (ammonium, nitrate, and organic), phosphorus (soluble and adsorbed/mineral and organic), and pesticide concentrations may be estimated for each subarea and at the watershed outlet. Commercial fertilizer or manure may be applied at any rate and depth on specified dates or automatically. The GLEAMS pesticide model is used to estimate pesticide fate considering runoff, leaching, sediment transport, and decay. Because of routing and subdividing, there is no limit on watershed size. The major uses of APEX have been dairy manure management to maintain water quality in Erath and Hopkins Counties, TX, (Flowers, et al., 1996) and a national study to assess the effectiveness of filter strips in controlling sediment and other pollutants (Arnold, et al.,1998a). APEX has its own databases for weather simulation, soils, crops, tillage, fertilizer, and pesticides. Convenient interfaces are supplied for assembling inputs and interpreting outputs.

SWAT Model Documentation (from Neitsch et al., 2005)

SWAT is the acronym for Soil and Water Assessment Tool, a river basin, or watershed, scale model developed by Dr. Jeff Arnold for the USDA Agricultural Research Service (ARS). SWAT was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods of time. To satisfy this objective, the model

♦ is physically based. Rather than incorporating regression equations to describe the relationship between input and output variables, SWAT requires specific information about weather, soil properties, topography, vegetation, and land management practices occurring in the watershed. The physical processes associated with water movement, sediment movement, crop growth, nutrient cycling, etc. are directly modeled by SWAT using this input data.

♦ uses readily available inputs. While SWAT can be used to study more specialized processes such as bacteria transport, the minimum data required to make a run are commonly available from government agencies.

♦ is computationally efficient. Simulation of very large basins or a variety of management strategies can be performed without excessive investment of time or money.

♦ enables users to study long-term impacts. Many of the problems currently addressed by users involve the gradual buildup of pollutants and the impact on downstream water bodies. To study these types of problems, results are needed from runs with output spanning several decades.

SWAT is a continuous time model, i.e. a long-term yield model. The model is not designed to simulate detailed, single-event flood routing.

SWAT incorporates features of several ARS models and is a direct outgrowth of the SWRRB1 model (Simulator for Water Resources in Rural Basins) (Williams et al., 1985; Arnold et al., 1990). Specific models that contributed significantly to the development of

SWAT were CREAMS2 (Chemicals, Runoff, and Erosion from Agricultural Management Systems) (Knisel, 1980), GLEAMS3 (Groundwater Loading Effects on Agricultural Management Systems) (Leonard et al., 1987), and EPIC4 (Erosion-Productivity Impact Calculator) (Williams et al., 1984).

Development of SWRRB began with modification of the daily rainfall hydrology model from CREAMS. The major changes made to the CREAMS hydrology model were: a) the model was expanded to allow simultaneous computations on several subbasins to predict basin water yield; b) a groundwater or return flow component was added; c) a reservoir storage component was added to calculate the effect of farm ponds and reservoirs on water and sediment yield; d) a weather simulation model incorporating data for rainfall, solar radiation, and temperature was added to facilitate long-term simulations and provide temporally and spatially representative weather; e) the method for predicting the peak runoff rates was improved; f) the EPIC crop growth model was added to account for annual variation in growth; g) a simple flood routing component was added; h) sediment transport components were added to simulate sediment movement through ponds, reservoirs, streams and valleys; and i) calculation of transmission losses was incorporated.

The primary focus of model use in the late 1980s was water quality assessment and development of SWRRB reflected this emphasis. Notable modifications of SWRRB at this time included incorporation of: a) the GLEAMS pesticide fate component; b) optional SCS technology for estimating peak runoff rates; and c) newly developed sediment yield equations. These modifications extended the model's capability to deal with a wide variety of watershed management problems.

In the late 1980s, the Bureau of Indian Affairs needed a model to estimate the downstream impact of water management within Indian reservation lands in Arizona and New Mexico. While SWRRB was easily utilized for watersheds up to a few hundred square kilometers in size, the Bureau also wanted to simulate stream flow for basins extending over several thousand square kilometers. For an area this extensive, the watershed under study needed to be divided into several hundred subbasins. Watershed division in SWRRB was limited to ten subbasins and the model routed water and sediment transported out of the subbasins directly to the watershed outlet. These limitations led to the development of a model called ROTO (Routing Outputs to Outlet) (Arnold et al., 1995), which took output from multiple SWRRB runs and routed the flows through channels and reservoirs. ROTO provided a reach routing approach and overcame the SWRRB subbasin limitation by "linking" multiple SWRRB runs together. Although this approach was effective, the input and output of multiple SWRRB files was cumbersome and required considerable computer storage. In addition, all SWRRB runs had to be made independently and then input to ROTO for the channel and reservoir routing. To overcome the awkwardness of this arrangement, SWRRB and ROTO were merged into a single model, SWAT. While allowing simulations of very extensive areas, SWAT retained all the features which made SWRRB such a valuable simulation model.

SWAT allows a number of different physical processes to be simulated in a watershed. These processes will be briefly summarized in this section. For more detailed discussions of the various procedures, please consult the chapter devoted to the topic of interest.

For modeling purposes, a watershed may be partitioned into a number of subwatersheds or subbasins. The use of subbasins in a simulation is particularly beneficial when different areas of the watershed are dominated by land uses or soils dissimilar enough in properties to impact hydrology. By partitioning the watershed into subbasins, the user is able to reference different areas of the watershed to one another spatially.

Input information for each subbasin is grouped or organized into the following categories: climate; hydrologic response units or HRUs; ponds/wetlands; groundwater; and the main channel, or reach, draining the subbasin. Hydrologic response units are lumped land areas within the subbasin that are comprised of unique land cover, soil, and management combinations.

No matter what type of problem studied with SWAT, water balance is the driving force behind everything that happens in the watershed. To accurately predict the movement of pesticides, sediments or nutrients, the hydrologic cycle as simulated by the model must conform to what is happening in the watershed. Simulation of the hydrology of a watershed can be separated into two major divisions. The first division is the land phase of the hydrologic cycle. The land phase of the hydrologic cycle controls the amount of water, sediment, nutrient and pesticide loadings to the main channel in each subbasin. The second division is the water or routing phase of the hydrologic cycle which can be defined as the movement of water, sediments, etc. through the channel network of the watershed to the outlet.