Prediction of NO_3-N Losses in Surface Runoff from a Field with Seepage Zones Using GLEAMS and RZWQM

A. Chinkuyu, T. Meixner, T. Gish, A. P. Nejadhashemi

Abstract. *Seepage zones have been shown to be of critical importance in controlling contaminant export from agricultural watersheds. However, their impacts on water quality have not been effectively modeled. The Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) model and the Root Zone Water Quality Model (RZWQM) were used to predict daily and monthly nitrate−nitrogen (NO_3−N) concentration and loss in surface runoff from an agricultural field with seepage zones. The results of the study show that calibrated GLEAMS and RZWQM predicted daily NO_3−N concentration [index of agreement (D) > 0.57] in surface runoff from the field with seepage zones. Based on the different model evaluation techniques used in this study, both GLEAMS and RZWQM performed fairly well in assessing the effects of seepage zones on daily NO_3−N losses in surface runoff. However, GLEAMS (D = 0.93) performed relatively better than RZWQM (D = 0.45) in predicting NO_3−N loss in surface runoff on a monthly basis, while both GLEAMS and RZWQM performed equally well in predicting NO_3−N loss in surface runoff on a daily basis. Both models performed poorly in predicting NO_3−N concentration in surface runoff on a monthly basis (D < 0.44). Additionally, since neither model adequately simulated monthly NO_3−N concentration in surface runoff from the field with seepage zones, their ability in water quality modeling for such fields will be compromised, and further model evaluation and development is justified.*

Keywords. *Model, NO_3−N, OPE^3, Runoff, Watershed.*

Although surface runoff processes have been studied extensively, our understanding of the impact that subsurface stratigraphy has on watershed-scale runoff quantity and quality is lacking. To date, no protocol exists for determining the location or size of subsurface stratigraphy and the impact of subsurface hydrology on surface runoff. With the advent of various geophysical instruments like ground-penetrating radar (GPR), global positioning systems (GPS), digital elevation maps (DEM), and geographic information systems (GIS), detailed analysis of the subsurface soil structure can be obtained, which will enhance our knowledge of subsurface hydrology and its potential impact on surface hydrologic processes.

Although variable source area processes, such as seepage zones, have been well studied in forested and range land systems (Grayson and Blöschl, 2001; Walter et al., 2000), the impacts of these processes on agricultural processes have only recently been closely investigated and only in a limited number of settings (Gburek and Sharpley, 1998; Daughtry et al., 2001; Gish et al., 2004). Seepage zones occur when subsurface flow pathways emerge on the surface and are common to agricultural lands bordering riparian wetlands and surface streams; however, their impacts on agricultural water quality have not been effectively modeled because of limited data (Engman and Rogowski, 1974; Gburek, 1978; Gburek et al., 2002; Gish et al., 2001).

Seepage zones are dynamic, often responding to a single precipitation event, mixing water of differing ages. Depending on the soil moisture status of the soil profile as well as rainfall intensity and duration, the ratio of surface runoff to seepage water can change substantially. In addition to climate, seepage zones are associated with low or decreased downslope water table gradients or decreased permeability, e.g., down-gradient shifts from coarser- to finer-textured soils (Pionke and Urban, 1985).

Seepage zones can strongly influence surface runoff and chemical fluxes from agricultural fields. Previous studies have shown that watersheds with seepage zones generated more surface runoff and lost more nitrate-nitrogen (NO_3−N), phosphorus, and pesticides than watersheds without seepage zones (Gburek and Sharpley, 1998; Chinkuyu et al., 2005). Some subsurface flow pathways come close to the soil surface (but do not emerge on the surface) and increase soil moisture content in the topsoil layers. The increased soil moisture contents in the top layers have been found to impact chemical loss and crop yield (Gish et al., 2005). These seepage zone studies demonstrate the dramatic impact that subsurface stratigraphy can have on surface runoff-chemical fluxes, even when soil properties, yield distributions, and climate are similar.

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The authors are **Adion Chinkuyu, ASABE Member Engineer,** Environmental Engineer, District of Columbia, Department of the Environment, Washington, D.C.; **Tom Meixner,** Assistant Professor, Department of Hydrology and Water Resources, University of Arizona, Tucson, Arizona; **Timothy Gish,** Soil Scientist, USDA-ARS Hydrology and Remote Sensing Laboratory, Beltsville, Maryland; and **Amir P. Nejadhashemi, ASABE Student Member,** Watershed Modeling Specialist, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, Kansas. **Corresponding author:** Amir P. Nejadhashemi, Department of Biological and Agricultural Engineering, Kansas State University, Manhattan, KS 66506; phone: 785-532-2923; fax: 785-532-5825; e-mail: pouyan@ksu.edu.

Computational agricultural water quality models provide an opportunity to evaluate the response of soil and water resources to different farming practices, climatic conditions, soil, and topographic properties in an efficient and cost-effective way. However, the reliability of these models depends on how well each process is represented and on the accuracy of the model parameters used. To determine if the model adequately simulates the real conditions and to gauge model usefulness, an assessment of its performance for a variety of soils, crop, management practices, hydrologic, and climatic conditions is needed.

Correlation and correlation-based measures (e.g., R^2) have been widely used to evaluate model performance by measuring the "goodness-of-fit" of hydrologic and water quality models. However, correlation-based measures are oversensitive to extreme values (outliers) (Legates and McCabe, 1999; Ott, 1993). In general, a single evaluation measure can indicate that a model is a good predictor, when in reality it is not. Because of these limitations, additional evaluation criteria, e.g., relative percent error (%E), modeling efficiency (E), index of agreement (D), and root mean square error (RMSE), have been proposed by different researchers to assess model performance (Buchleiter et al., 1995; Haan et al., 1993; Legates and McCabe, 1999; Chinkuyu et al., 2004).

In this study, two well-known and comprehensive models, the Groundwater Loading Effects of Agricultural Management Systems (GLEAMS) v. 3.0.1, and the Root Zone Water Quality Model (RZWQM), were calibrated and evaluated using data from an agricultural field (field C) with seepage zones and treated with composted dairy cow liquid manure at the USDA Beltsville Agricultural Research Center in Beltsville, Maryland. Although GLEAMS and RZWQM do not explicitly have seepage zone processes incorporated into them, these models were chosen for this study because: (1) they have not been evaluated on agricultural fields with seepage zones due to limited data, (2) no agricultural water quality models have saturated and seepage zone processes incorporated into them, (3) these models are widely used to evaluate agricultural management practices under different soil, climatic, and hydrologic conditions, and (4) the hydrologic and chemical concepts of these models are passed on to other larger-scale models such as the Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998). Few scientists have the equipment to identify, define, and study subsurface flow pathways and seepage zones in agricultural lands, and thus there is little data to develop or test models for seepage zones. To our knowledge, no agricultural nonpoint-source pollution model represents saturation and seepage zone processes in addition to the important biological and chemical controls on agricultural water quality (e.g., nutrient dynamics and pesticide processes).

The main objective of this study was to determine whether GLEAMS and RZWQM can adequately model NO_3–N concentration and loss in surface runoff from agricultural fields with seepage zones on a daily, monthly, and annual bases.

Background on the GLEAMS Model

The GLEAMS model was developed to simulate edge-of-field and bottom-of-root-zone loadings of water, sediment, pesticides, and plant nutrients from complex climate-soil-management interactions (Knisel, 1993). As a field-scale water quality model, GLEAMS has been evaluated for nutrient and pesticide losses under different conditions and management practices with varied successful results (Chinkuyu et al., 2005; Chinkuyu and Kanwar, 2001; Bakhsh et al., 2000). The ability of GLEAMS to represent variable source area processes (seepage zones) is limited to generating compensating hydrologic parameter values to represent these processes in a limited manner. Thus, there is no direct representation of water and chemical losses through seepage zones in GLEAMS.

Although GLEAMS has different components, only the nutrient component is of interest to this study. For detailed description of the other components, such as hydrology, pesticides, sediments, and erosion, refer to Knisel (1993). The nutrient subcomponent considers both nitrogen (N) and phosphorus (P) cycles. The N component includes processes such as nitrification, mineralization, ammonification, immobilization, volatilization, denitrification, plant uptake, fixation by legumes, and N losses through runoff, erosion, and percolation below the root zone. The P component includes mineralization, crop uptake, immobilization, loss to sediment, surface runoff, and leaching. The nutrient component also includes fertilizer and animal waste application.

Background on the RZWQM Model

The USDA-ARS Root Zone Water Quality Model (RZWQM) is a physically based simulation model designed to predict hydrologic and chemical responses, including potential groundwater contamination from agricultural management systems (Ahuja et al., 2000; USDA-ARS, 1995). RZWQM is sufficiently comprehensive to predict the relative response of plants and interactions among system processes to changes in water balance, temperature, nutrient cycling, plant growth, soil chemistry, and management practices. Management practices include tillage and application of manure, pesticides, and crop residues. Specific details of RZWQM components are given in the model documentation (Ahuja et al., 2000). Similar to GLEAMS, seepage zone processes are not explicitly represented in RZWQM model and must be represented by calibrating the effective hydrologic and chemical parameters of the model (within the defined parameter ranges).

Chemical transport within the soil matrix is calculated using a sequential partial displacement and mixing approach in 1 cm increments during water infiltration. The nutrient sub-model, organic matter/nitrogen cycling (OMNI), of RZWQM is a state-of-the-art model for carbon and nitrogen cycling in the soil system. A detailed description of the nutrient model is given in the technical documentation of RZWQM (Ahuja et al., 2000). Organic matter is distributed over five computational pools and is decomposed by three microbial biomass populations. These pools are fast and slow incorporated soil residue pools, and fast, medium and slow soil humus pools. OMNI simulates all the major nitrogen pathways including mineralization-immobilization of crop residues, manure, and other organic wastes; mineralization of the soil humus fractions; inter-pool transfers of carbon and nitrogen; denitrification, gaseous loss of ammonia, and nitrification of ammonium to produce NO_3–N; production and consumption of methane gas and carbon dioxide; and microbial biomass growth and death.

RZWQM has been evaluated for chemical losses under different conditions with different results. Ahuja et al. (1996)

and Azevedo et al. (1997) found that individual soil concentration predictions (depth and time) were generally within an order of magnitude of those observed. Jaynes and Miller (1999) observed that RZWQM did not adequately predict soil nutrient distribution because observed peak concentrations were at the soil surface (0 to 7.5 cm), but the predicted peak concentrations were at 15 cm (using the equilibrium-only model). Most assessments found that RZWQM simulated soil-water content adequately, but restricting layers in the soil profile were sometimes blamed for less accurate simulations because they are not adequately parameterized and represented in the model (Cameira et al., 1998; Wu et al., 1999). Cracks specified in RZWQM cannot be changed (as a function of soil moisture) during the simulation period. This limitation produces poor surface runoff and chemical concentrations in runoff from clay soils where there is cracking (during dry periods) and no cracking (during wet periods) (Ghidey et al., 1999). Malone et al. (2004) reviewed RZWQM validation studies and found that accurate parameterization of restricting soil layers (low permeability horizons) improved simulated soil-water content.

Materials and Methods

Description of the Experimental Site

Five years of data (1999 to 2003) for calibration and evaluation of GLEAMS and RZWQM were obtained from a field (field C) that is part of a 21 ha agricultural research site located at the USDA Beltsville Agricultural Research Center in Beltsville, Maryland (39° 01′ 00″ N, 76° 52′ 00″ W). Field C is part of the Optimizing Production inputs for Economic and Environmental Enhancement (OPE^3) research site. The OPE^3 study seeks to compare agricultural production systems at a scale large enough to capture the spatial variability of crop and soil parameters, yet small enough for fields to be in similar climatic and geologic settings. The site has a weather station that measures several weather parameters at different time intervals, such as soil and air temperature, relative humidity, wind speed, rainfall, solar radiation, and evapotranspiration. The five-year average annual precipitation measured at the research site is about 99 cm. Annual total precipitation values in 1999, 2000, 2001, 2002, and 2003 were approximately 95, 91, 87, 89, and 135 cm, respectively. In 1999, no significant amount of rain fell until September, when major storms, including Hurricane Floyd, generated significant surface runoff. During the other years, precipitation was uniformly distributed during the growing season (between April to mid-November), which resulted in some surface runoff throughout the season.

Table 1. Selected physical soil properties measured at the study site and used as inputs in the models (Daughtry et al., 2001).

Soil Depth (cm)	Clay (%)	Silt (%)	Sand (%)	Organic Matter (%)
0 - 15	5	15	80	3.5
15 - 30	11	18	71	3.2
30 - 75	7	10	83	3.0
75 - 90	6	16	78	2.0
90 - 120	10	25	65	2.0

Field C drains into a riparian wetland forest, which contains a first-order stream. About 88% of the field has <2% slope, and only 12% of the field has >3% slope. The soils are sandy textured with buried clay lens (coarse-loamy, siliceous, semiactive, mesic, Typic Hapludult). Soil cores (12.6 cm^2 by 1 m long) and auger samples as deep as 2.5 m were collected in the field to provide soil property data (Gish et al., 2002). The samples were analyzed for pH, texture, organic matter content, and major ions (K, Ca, and Mg). The soil profile predominantly consists of a sandy loam Ap horizon for the top 0.30 m, followed by a loam Bt horizon that continues down to 0.80 m, a loamy sand C horizon from 0.80 to 1.20 m, and fine textured clay loam lens from about 1.20 to 2.50 m (Gish et al., 2002). Selected physical soil properties measured in the research field are presented in table 1 (Daughtry et al., 2001).

Field C has large natural seepage zones. Seepage zones are common to agricultural lands bordering streams and occur when subsurface flow emerges on the surface. Subsurface flow pathways were identified and delineated in the field using ground-penetrating radar (GPR) data and digital elevation maps (DEM). At the research site, seepage zones occurred when subsurface flow channels were primarily within 1.5 m of the soil surface and drained >1.5 ha of arable land. For a detailed description of the delineation of subsurface flow pathways at the site, refer to Gish et al. (2002). Water from seepage zones mixes with surface runoff before leaving the field. These seepage zones result in higher amounts of surface runoff, nutrient, and pesticide losses from the field (Daughtry et al., 2001).

The field was tilled in early spring using a chisel plow. Composted dairy cow liquid manure was applied from 1999 to 2003. Immediately after application of the manure, the soil was disked to incorporate the manure and minimize nitrogen loss through volatilization. After disking, corn (*Zea mays* L.) was planted each year. Additional urea ammonium nitrate (UAN) fertilizer was side-dressed according to the Pre-Side dress Nitrate Test (PSNT) (Meisinger et al., 1992). Application rates of manure and fertilizers and dates of management activities are given in table 2.

Table 2. Dates of farm operations at the study site from 1999 to 2003.

	Year and Date				
Farm Operation	1999	2000	2001	2002	2003
Primary tillage	8 May	17 May	12 May	20 May	10 May
Applying/incorporating manure	15 May	2 June	25 May	10 June	30 May
Planting corn	28 May	9 June	29 May	12 June	4 June
Applying starter fertilizer	28 May	9 June	29 May	12 June	4 June
Applying herbicides	5 June	13 June	10 June	24 June	18 June
Applying UAN fertilizer	26 June	13 July	28 June	15 July	18 July
Harvesting corn	7 Nov.	5 Nov.	1 Nov.	10 Nov.	9 Nov.

Surface runoff water (including runoff from seepage zones) from the field was measured at the outlet with a 45.7 cm H-flume equipped with a flowmeter and a water sampler (ISCO, Lincoln, Neb.). The amount of surface runoff was measured automatically and continuously recorded whenever there was a runoff event. Surface runoff water samples were collected after every 5000 L passed through the flume. Surface runoff water samples were collected and analyzed for NO_3−N concentrations among other chemicals. Although field observations and other seepage zone studies (Daughtry et al., 2001; Gburek and Sharpley, 1998; Gish et al., 2005) show that water still flows several hours after a major storm has ended, surface runoff data in this study was not separated into seepage zone and direct runoff.

GLEAMS and RZWQM Data Input

Climatic data measured at the research site and used as input to both GLEAMS and RZWQM included daily minimum, maximum, and mean air temperatures; daily and breakpoint precipitation; mean monthly maximum and minimum temperatures; solar radiation; wind speed; and relative humidity. Data on clay, silt, sand, and organic matter contents were measured at the site and used as inputs to the models (table 1). Soil porosity, field capacity, wilting point, and hydraulic conductivity were obtained from the GLEAMS and RZWQM databases (default values) and used as inputs to the respective models. Details of the default hydrologic parameters are given in Chinkuyu et al. (2004). In both GLEAMS and RZWQM, an effective maximum rooting depth of 120 cm was used and divided into five layers based on soil texture of the site. All management (tillage, planting, harvesting) information was collected each year at the site and used as input to both models. Other crop characteristic data, such as leaf area index, crop height, dry matter ratio, and C:N ratio, were taken from the models' respective databases.

Sensitivity Analysis

Default input parameters were obtained from the GLEAMS databases (Knisel, 1993) and RZWQM databases (Ahuja et al., 2000) based on local site information from the Prince George's County, Maryland, soil survey and from laboratory and field measurements made at this research site. Model parameters were then tested for sensitivity based on the model users' manuals (Knisel, 1993; Ahuja et al., 2000). Sensitive input parameters for GLEAMS and RZWQM were identified using on-site field-measured data on surface runoff, and NO_3−N concentration and loss in surface runoff, for 1999 and 2000. The test ranges for each sensitive parameter are given in table 3. These test ranges were based on data from the literature and the models' respective databases. Sensitive model parameters were identified by observing the change in model output as a result of a change in a parameter value. Twenty thousand simulations (changes) were conducted, and surface runoff, NO_3−N concentration, and NO_3−N loss were recorded as model outputs. These simulations were conducted using the Monte Carlo simulation technique. A normalized sensitivity coefficient between standard deviations of the parameter and model outputs was computed (Ma et al., 2000). The normalized sensitivity coefficient can be defined as:

$$\beta_i = \frac{b_i S_{Xi}}{S_{Yi}} \tag{1}$$

where S_{Xi} and S_{Yi} are the standard deviations of the ith model parameter (X_i) (e.g., curve number) and the ith model output (Y_i) (e.g., surface runoff), respectively, and b_i is the corresponding coefficient. A sensitivity coefficient of 1.0 means that one standard deviation change in the model parameter will lead to one standard deviation change in the model output. Only parameters that resulted in a sensitivity coefficient greater than ± 0.5 were considered sensitive. The 20,000 simulations were also used to identify the best values for the sensitive parameters for each model. Thus, the best parameter values identified gave the best match (relative percent error of $\pm 20\%$) between measured and predicted surface runoff, and NO_3−N concentration and loss in surface runoff, from field C.

GLEAMS and RZWQM Model Calibration

In water quality modeling, the hydrology component (e.g., surface runoff, percolation, evapotranspiration) is calibrated first before the chemical component because hydrology determines water quality. Surface runoff and percolation water move chemicals on the soil surface as well as through the soil profile. In this study, brief discussions of the calibration and results of the hydrology component (surface runoff) are given to explain the relevance of the results for NO_3−N concentration and loss in surface runoff. For a detailed presentation of sensitive parameters, calibration, and results of the hydrology component (surface runoff and soil moisture content), refer to Chinkuyu et al. (2004).

Sensitive parameters were calibrated for each model. Calibration of GLEAMS hydrologic parameters included the Natural Resources Conservation Service (NRCS) curve number for soil moisture condition II (CN2), field capacity, permanent wilting point, and effective maximum rooting depth (RD). Saturated hydraulic conductivity, field capacity, and rooting depth were calibrated for surface runoff, evapotranspiration, and soil moisture content in RZWQM. After calibration of the hydrology components of both GLEAMS and RZWQM, parameters affecting NO_3−N concentration and loss in surface runoff were calibrated next. Crop residue, total soil N, soil NO_3−N concentration, and potentially mineralizable N content in the soil profile were used as sensitive parameters in controlling N losses in surface runoff from GLEAMS (table 4). In RZWQM, initialization

Table 3. Chemical content and application rates of animal manure and chemical fertilizer during the study period.

Component	Year				
	1999	2000	2001	2002	2003
Manure application rate (L/ha)	37400	95000	95000	95000	95000
Nitrogen application rate (kg/ha)	61	192	166	180	175
Phosphorus (as P_2O_5) application rate (kg/ha)	25	73	56	68	61
Starter fertilizer rate (kg−N/ha)	75	75	75	75	75
Side dressing fertilizer rate (kg−N/ha)	106	106	106	106	106

Table 4. Test range, default (from model database), and calibrated nutrient and plant growth parameters used in GLEAMS.

Parameter	Test Range	Default Estimate	Calibrated[a]
Crop residue (kg/ha)	500 - 100000	500	7000
Total N content (%) at depth:			
15 cm	0 - 10	0.10	0.40
30 cm	0 - 10	0.10	0.40
45 cm	0 - 10	0.10	0.40
95 cm	0 - 10	0.10	0.20
120 cm	0 - 10	0.10	0.20
Soil NO_3−N concentration (mg/L) at depth:			
15 cm	0 - 1000	10.0	5.0
30 cm	0 - 1000	10.0	5.0
45 cm	0 - 1000	10.0	5.0
95 cm	0 - 1000	10.0	3.5
120 cm	0 - 1000	10.0	3.5
Mineralizable N (kg/ha) at depth:			
15 cm	0 - 1000	300	150
30 cm	0 - 1000	300	150
45 cm	0 - 1000	300	100
95 cm	0 - 1000	300	100
120 cm	0 - 1000	300	100

[a] "Calibrated" means final initial conditions after calibration. Calibrated values were used to simulate 2001, 2002, and 2003.

Table 5. Test range, default, and calibrated nutrient and plant growth parameters used in RZWQM.

Parameter	Test Range	Default Estimate	Cali-brated[a]
Max. N uptake rate (g/plant/day)	0 - 50	5.5	5.00
Propagule age effect	0 - 1	0.12	0.11
Photosynthate to respire (/day)	0 - 1	0.60	0.70
Seed age effect	0 - 1	0.45	0.80
Soil NO_3−N conc. (μg−N/g) at depth:			
15 cm	0 - 1000	19.86	6.35
30 cm	0 - 1000	1.71	7.67
45 cm	0 - 1000	2.02	4.65
90 cm	0 - 1000	1.21	5.52
120 cm	0 - 1000	1.07	4.50
Slow residue concentration (μg−C/g) at depth:			
15 cm	0 - 10000	99.0	140.4
30 cm	0 - 10000	85.0	9.6
45 cm	0 - 10000	60.0	7.5
90 cm	0 - 10000	25.0	10.7
120 cm	0 - 10000	10.0	3.9
Transition humus concentration (μg−C/g) at depth:			
15 cm	0 - 10000	863.6	630.7
30 cm	0 - 10000	633.5	549.0
45 cm	0 - 10000	668.4	395.4
90 cm	0 - 10000	653.3	550.1
120 cm	0 - 10000	625.4	438.8
Stable humus concentration (μg−C/g) at depth:			
15 cm	0 - 10000	8470.5	9291.6
30 cm	0 - 10000	4941.8	4178.7
45 cm	0 - 10000	2999.2	3018.7
90 cm	0 - 10000	3349.2	1638.3
120 cm	0 - 10000	3098.9	1260.4

[a] "Calibrated" means final initial conditions after calibration. Calibrated values were used to simulate 2001, 2002, and 2003.

of various residue, humus, and microorganism pools was made following the guidelines given in the user's manual. Measured values of soil organic matter in the field were used to initialize and distribute its contents among fast, medium, and slow humus pools and three microorganism pools. Slow residue concentrations, transition and stable humus in the profile, soil NO_3−N concentration, maximum N uptake rate, photosynthate to respire, propagule age effect, and seed age effect were calibrated as sensitive parameters in RZWQM (table 5).

Data measured and predicted in 1999 and 2000 were used for calibration. If average daily and monthly predicted surface runoff, and NO_3−N concentration and loss in surface runoff, did not match the daily observed values (within a relative percent error range of ±20%), then the sensitive parameters were calibrated repeatedly until suitable model responses (surface runoff, NO_3−N concentration, and NO_3−N loss) were obtained. Thus, the models were considered calibrated when the overall relative percent errors between predicted and measured values (on daily and monthly bases) were between −20% and 20% for both 1999 and 2000 data (Hanson et al., 1999; Bakhsh et al., 2000; Chinkuyu et al., 2004). Note that only data collected in 1999 and 2000 were used for model calibration, and data collected in 2001, 2002, and 2003 were used for model validation. Initial and final calibrated nutrient parameter values are given in tables 4 and 5 for GLEAMS and RZWQM, respectively.

Model Evaluation and Data Analysis

Site-calibrated GLEAMS and RZWQM models were evaluated using daily and monthly measured data from the field over a three-year evaluation period (2001 to 2003). Objective and subjective approaches were used to test the performance of the models (Bakhsh et al., 2000; Chinkuyu and Kanwar, 2001; Chinkuyu et al., 2004, 2005). Subjective criteria included graphical display of simulated and measured NO_3−N concentration and loss in surface runoff. The subjective criteria were used to locate anomalies in model predictions and to provide an insight into temporal response of the models for the entire simulation period. The objective/statistical techniques, relative percent error (%E), coefficient of determination (R^2), and index of agreement (D), were used to evaluate these models. These statistical criteria account for differences over the whole simulation period, ignoring differences between simulations and observations over time. The three statistics were defined as follows:

Relative percent error:

$$\%\text{E} = \frac{\sum_{i=1}^{N}(P_i - O_i)*100}{N*|\overline{O}|} \tag{2}$$

Coefficient of determination:

$$R^2 = \left\{ \frac{\sum_{i=1}^{N}(O_i - \overline{O})(P_i - \overline{P})}{\left[\sum_{i=1}^{N}(O_i - \overline{O})^2\right]^{0.5}\left[\sum_{i=1}^{N}(P_i - \overline{P})^2\right]^{0.5}} \right\}^2 \tag{3}$$

Index of agreement:

$$D = 1.0 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}(|P_i - \overline{O}| + |O_i - \overline{O}|)^2} \qquad (4)$$

where %E is relative percent error, R^2 is coefficient of determination, D is index of agreement, P_i is the predicted value, $\overline{P}$ is the mean of predicted values, O_i is the observed value, $\overline{O}$ is the mean of the observed values, and N is the total number of values.

A model was considered to have performed well when relative percent error was between −20% and +20%, the coefficient of determination was equal to or greater than 0.5, and the index of agreement was greater than zero (0). These benchmark values were chosen based on other studies that gave similar "acceptable" values showing good model performance (Bakhsh et al., 2000; Hanson et al., 1999; Ma et al., 2000; Leavesley et al., 1983; Ott, 1993; Wilcox et al., 1990; Chinkuyu et al., 2005). By using graphical comparison and several statistical tests, we hoped to get a more robust picture of model performance than if we had just used graphical comparison and a single statistical test, as is often done for most water quality modeling studies.

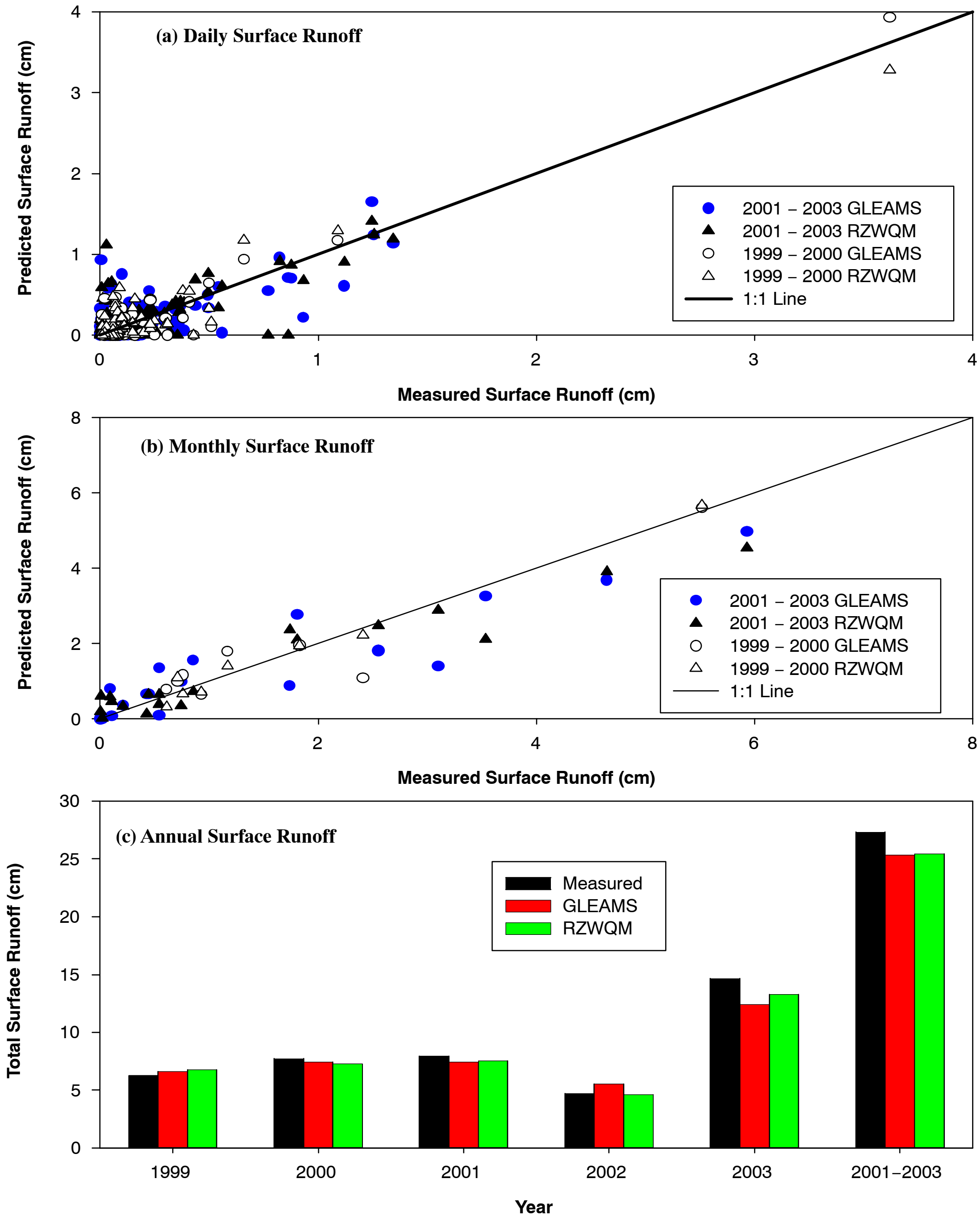

Figure 1. Comparison of daily, monthly, and total growing-season measured and simulated surface runoff from the field from 1999 to 2003. Note that 1999 and 2000 data were used for model calibration, and 2001, 2002, and 2003 data were used for model evaluation.

Table 6. Comparison of daily and monthly measured and simulated surface runoff from 1999 to 2003.

Year[a]	Measured Total	Predicted Daily Surface Runoff (cm)[b] Total	%E	R^2	D	Predicted Monthly Surface Runoff (cm)[b] Mean	%E	R^2	D
GLEAMS									
1999	6.23	6.46	3.6	0.95	0.99	3.23	3.6	0.99	0.99
2000	7.71	7.41	−3.9	0.53	0.84	1.23	−3.9	0.15	0.62
2001	7.94	7.42	−6.5	0.19	0.66	1.06	−6.5	0.48	0.74
2002	4.70	5.54	17.8	0.48	0.83	0.79	17.8	0.95	0.98
2003	14.67	12.39	−15.5	0.29	0.70	2.48	−15.5	0.87	0.95
2001−2003	27.31	25.35	−7.2	0.29	0.72	1.33	−7.2	0.85	0.95
RZWQM									
1999	6.23	6.48	4.0	0.91	0.98	3.24	4.0	0.99	0.99
2000	7.71	7.25	−5.9	0.65	0.89	1.21	−5.9	0.93	0.98
2001	7.94	7.52	−5.3	0.91	0.97	1.07	−5.3	0.98	0.99
2002	4.70	4.64	−1.4	0.01	0.22	0.66	−1.4	0.89	0.87
2003	14.67	13.29	−9.4	0.76	0.93	2.66	−9.4	0.93	0.95
2001−2003	27.31	25.44	−6.8	0.57	0.87	1.34	−6.8	0.92	0.96

[a] Note that 1999 and 2000 data were used for model calibration. The 2001, 2002, and 2003 data were used for model evaluation.
[b] %E = relative percent error (%, R^2 = coefficient of determination, and D = index of agreement.

Results and Discussion

Note that data and predictions for 1999 and 2000 were used to calibrate model parameters so that model outputs would match the observations. Data for 2001, 2002, and 2003 were used for model validation.

Surface Runoff

The data presented in figure 1 show that the amount of daily, monthly, and annual surface runoff predicted by GLEAMS and RZWQM followed the pattern of measured surface runoff from field C. GLEAMS predicted surface runoff from field C with an average index of agreement of 0.72 and relative percent error of −7%, (table 6). Predicted daily surface runoff by RZWQM was also similar to the measured surface runoff from field C (fig. 1). The results in table 6 show that daily RZWQM-predicted and measured surface runoff amounts from field C were in fair agreement, showing an index of agreement of 0.87. The relative percent error (−7%) and coefficient of determination (0.57) indicate that RZWQM predicted daily surface runoff from field C. However, in 2002, RZWQM performed poorly (R^2 = 0.01 and D = 0.22). These results show that RZWQM barely predicted the low surface runoff produced in field C.

The results presented in figure 1 and table 6 also show that both GLEAMS and RZWQM predicted monthly and annual surface runoff from field C. Overall statistical results in table 6 show that GLEAMS and RZWQM monthly performance improved relative to daily performances. In addition, the index of agreement (>0.95) indicates that both models predicted monthly surface runoff from the field. These results indicate that both calibrated GLEAMS and RZWQM were capable of adequately predicting surface runoff from a field with seepage zones. These data also suggest that RZWQM performed better than GLEAMS on daily basis due to the representation of the infiltration process using the Green-Ampt infiltration equation, which incorporates initial soil moisture content for each rainfall event and is thus able to separate infiltration and runoff components slightly better than the NRCS curve number method in GLEAMS. Due to averaging and summation of the data, both models performed well in predicting surface runoff from field C on monthly and annual bases.

NO_3-N Concentration

The results presented in figure 2 and table 7 show that GLEAMS predicted relatively lower daily NO_3−N concentration than measured NO_3−N concentration in surface runoff from field C, showing a coefficient of determination of 0.37, relative percent error of 5%, and index of agreement of 0.63. RZWQM predicted slightly lower daily NO_3−N concentration than measured NO_3−N concentration in surface runoff from field C, with a coefficient of determination of 0.11, relative percent error of −35%, and index of agreement of 0.57 (table 7). The different evaluation techniques used in this study show that both models were not capable of adequately predicting daily NO_3−N concentration in surface runoff from field C (table 7).

The monthly results presented in figure 2 and table 7 show that both GLEAMS and RZWQM underpredicted NO_3−N concentration in surface runoff, with an index of agreement of <0.44 and coefficient of determination of <0.02. However, the relative percent error (−12%) shows that over the three-year period, RZWQM predicted monthly NO_3−N concentration in surface runoff from field C. The monthly NO_3−N concentration results were better than the daily results, probably because of averaging and/or summing values over the month, which smoothed out the effects of daily variation.

NO_3-N Loss

For the evaluation period 2001-2003, the results presented in figure 3 and table 8 show that calibrated GLEAMS performed fairly well in predicting daily NO_3−N loss in surface runoff from field C, showing a relative percent error of −28% and index of agreement of 0.78. However, the coefficient of determination (0.39) for the same period shows that calibrated GLEAMS did not predict daily NO_3−N loss in surface runoff from field C. The coefficient of determination (0.80) and index of agreement (0.93) show that GLEAMS predicted monthly NO_3−N loss in surface runoff. The relative percent error (−23%) and index of agreement (0.79) show that calibrated RZWQM predicted daily NO_3−N loss in surface runoff from field C (table 8). However, the coefficient of determination (0.06), index of agreement (0.45), and relative percent error (−31) show that calibrated RZWQM underpre−

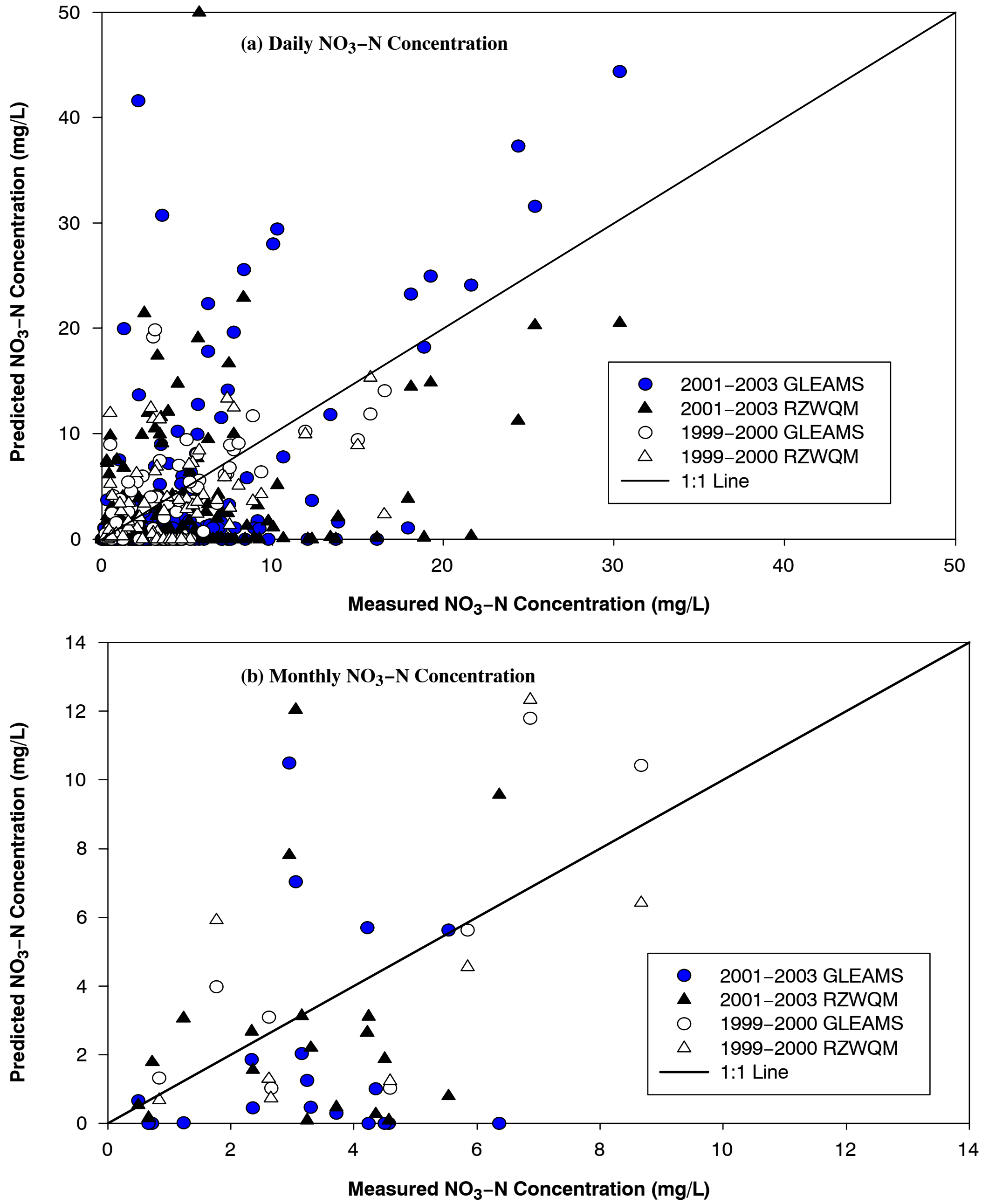

Figure 2. Comparison of daily and monthly measured and simulated NO_3−N concentration in surface runoff from the field from 1999 to 2003. Note that 1999 and 2000 data were used for model calibration, and 2001, 2002, and 2003 data were used for model evaluation.

dicted monthly NO_3−N loss in surface runoff from field C (table 8). The results show that GLEAMS performed better in predicting monthly NO_3−N loss than daily measured NO_3−N loss. The results also show that RZWQM predicted both daily and monthly NO_3−N losses. Although the annual measured NO_3−N losses were slightly higher than the predicted NO_3−N losses from both models, the yield data show that both models adequately predicted corn grain yield, which is also used as an indicator of plant N uptake. However, it is difficult to conclude that the models were adequate because not all N sinks (fates) were measured to quantify N mass balance.

Both calibrated GLEAMS and RZWQM were barely adequate in predicting NO_3−N loss in surface runoff from field C. Therefore, data from several sites should be used to further evaluate these models before model developers consider incorporating upward movement of N in the soil profile through seepage zones and redistribution of N among surface runoff, percolation, and seepage zones. These improvements should focus on the simplest representation needed to simulate observed nutrient concentrations, since our results also show that the added complexity of models like RZWQM does not necessarily payoff in better simulations of NO_3−N concentration and loss as compared to simpler models like GLEAMS.

Corn Grain Yields

Both models performed well in predicting corn grain yield during all the years, except in 1999 when the models overpredicted yields by over 200% (table 9). This was

Table 7. Comparison of daily and monthly measured and simulated NO_3–N concentration in surface runoff from 1999 to 2003.

Year[a]	Daily NO_3–N Concentration (mg/L)[b] Measured	Predicted	%E	R^2	D	Monthly NO_3–N Concentration (mg/L)[b] Measured	Predicted	%E	R^2	D
GLEAMS										
1999	5.09	4.92	−3	0.09	0.47	6.47	6.59	2	0.99	0.58
2000	4.63	5.02	8	0.13	0.34	3.25	4.08	25	0.97	0.85
2001	3.67	2.94	−20	0.02	0.36	2.68	2.07	−23	0.01	0.33
2002	4.50	4.34	−4	0.23	0.39	4.04	1.52	−62	0.30	0.16
2003	3.46	4.61	33	0.80	0.86	2.80	2.36	−16	0.88	0.92
2001−2003	3.83	4.02	5	0.37	0.63	3.21	1.94	−39	0.02	0.43
RZWQM										
1999	5.09	4.08	−20	0.87	0.94	6.47	4.06	−37	0.99	0.54
2000	4.63	3.77	−19	0.29	0.72	3.25	3.30	1	0.92	0.98
2001	3.67	2.68	−27	0.01	0.37	2.68	2.19	−18	0.01	0.33
2002	4.50	2.78	−38	0.02	0.35	4.04	4.33	7	0.08	0.37
2003	3.46	2.16	−38	0.35	0.75	2.80	1.64	−41	0.01	0.46
2001−2003	3.83	2.50	−35	0.11	0.57	3.21	2.83	−12	0.05	0.44

[a] Note that 1999 and 2000 data were used for model calibration. The 2001, 2002, and 2003 data were used for model evaluation.
[b] %E = relative percent error (%), R^2 = coefficient of determination, and D = index of agreement.

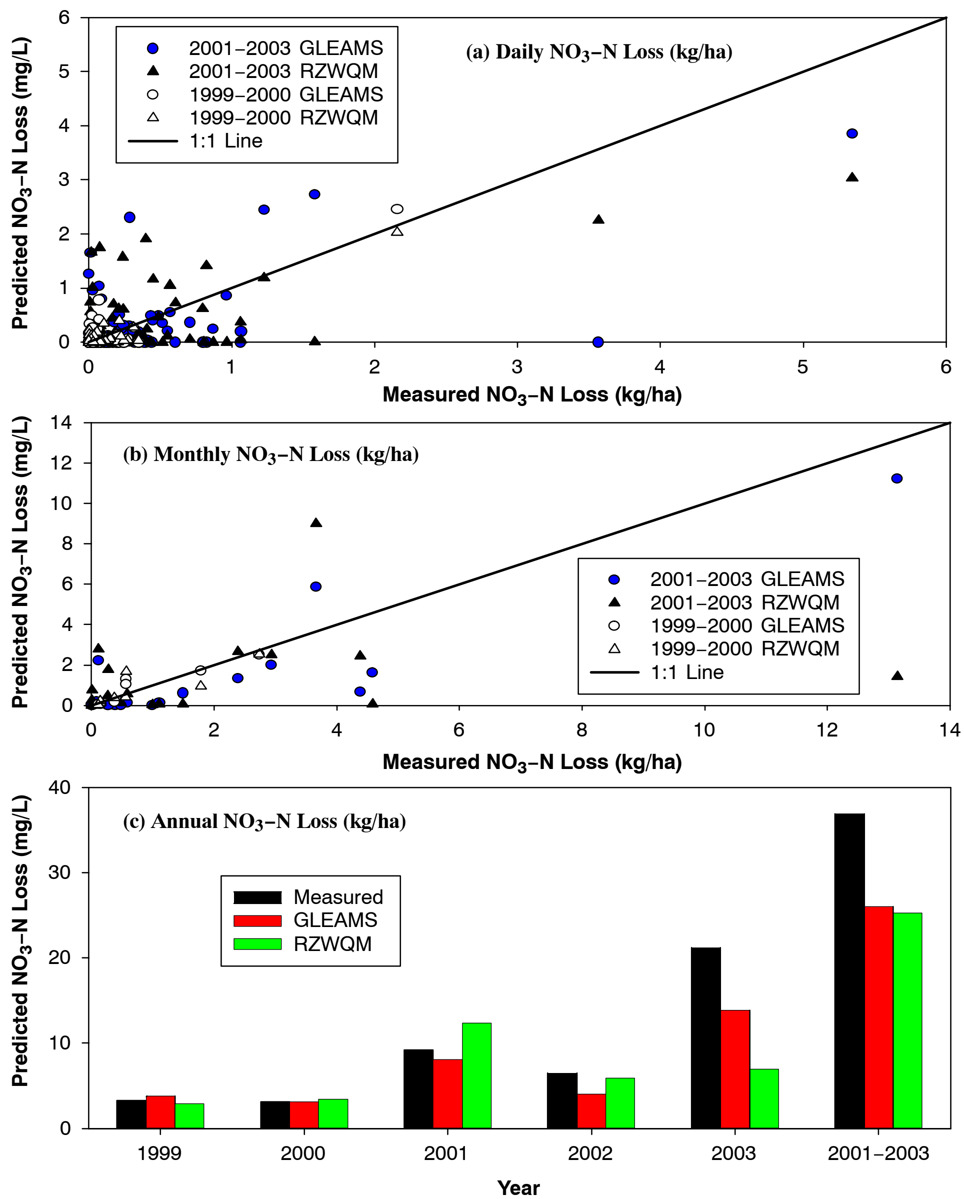

Figure 3. Comparison of daily, monthly, and total growing-season measured and simulated NO_3–N loss in surface runoff from the field from 1999 to 2003. Note that 1999 and 2000 data were used for model calibration, and 2001, 2002, and 2003 data were used for model evaluation.

Table 8. Comparison of daily and monthly measured and simulated NO_3–N loss with surface runoff from 1999 to 2003.

Year[a]	Measured Total	Predicted Daily NO_3–N (kg)[b] Total	%E	R^2	D	Predicted Monthly NO_3–N (kg)[b] Total	%E	R^2	D
GLEAMS									
1999	13.44	10.61	−21	0.78	0.89	3.69	−45	0.99	0.69
2000	13.17	12.25	−7	0.01	0.27	2.04	−7	0.86	0.96
2001	9.20	8.11	−12	0.03	0.37	1.16	−12	0.78	0.88
2002	6.47	5.03	−25	0.15	0.59	0.72	−22	0.44	0.79
2003	21.21	13.88	−35	0.53	0.84	2.78	−35	0.93	0.95
2001–2003	36.88	26.71	−28	0.39	0.78	1.37	−29	0.80	0.93
RZWQM									
1999	13.44	11.54	−14	0.96	0.96	4.92	−27	0.99	0.91
2000	13.17	12.56	−5	0.20	0.63	2.09	−5	0.96	0.99
2001	9.20	12.36	34	0.23	0.59	1.77	34	0.79	0.75
2002	6.47	5.94	−8	0.01	0.20	0.85	−8	0.16	0.13
2003	21.21	9.98	−53	0.83	0.88	1.40	−67	0.11	0.48
2001–2003	36.88	28.28	−23	0.43	0.79	1.33	−31	0.06	0.45

[a] Note that 1999 and 2000 data were used for model calibration. The 2001, 2002, and 2003 data were used for model evaluation.
[b] %E = relative percent error (%), R^2 = coefficient of determination, and D = index of agreement.

probably due to the drought that occurred at the beginning of the growing season and a hurricane towards the end of the season (in September). These results show that the models failed to account for the drought conditions at the beginning of the season. However, more data would be needed to evaluate the performance of these models under drought or relatively dry conditions. This kind of analysis would help in the development and revision of these models with respect to mass balance or redistribution of NO_3–N loss among the many processes such as crop uptake, seepage zones, runoff, and percolation.

Implications of Modeling Results

The main objective of this study was to use different evaluation techniques to determine whether GLEAMS and RZWQM can adequately model daily, monthly, and annual NO_3–N concentration and loss in surface runoff from agricultural fields with seepage zones. The various evaluation methods used in this study show that calibrated GLEAMS and RZWQM predicted NO_3–N concentration and loss in surface runoff from the fields with seepage zones with various capabilities. For example, GLEAMS performed better than RZWQM in predicting daily NO_3–N concentration in surface runoff from the field, with an index of agreement of 0.63 and relative percent error of 5% (table 7). Both RZWQM and GLEAMS performed well in predicting daily NO_3–N loss in surface runoff, with an index of agreement of 0.79 and 0.78, respectively (table 8).

Although both calibrated GLEAMS and RZWQM predicted NO_3–N concentration and loss in surface runoff from field C, the results show that the models were not adequate because some of the evaluation standards were barely met. On the other hand, the models did not perform as well in field C because they do not have seepage zone processes incorporated into them. These models do not integrate all aspects of hydrologic controls from the runoff flow perspective (variable sources), much less from interactions between surface runoff and water quality from different sources (Grayson and Blöschl, 2001). Because seepage zone processes are not represented in GLEAMS and RZWQM, several calibration trials were conducted for sensitive hydrologic and nutrient parameters. Extensive calibrations were conducted to match predicted and measured nutrient losses from field C (table 2). Based on the results of this and previous (Chinkuyu et al., 2004, 2005) studies, sensitive hydrologic parameters (e.g., curve number, field capacity, effective rooting depth) and chemical parameters (e.g., partitioning coefficient, water solubility, soil half-life) must be calibrated extensively for GLEAMS and RZWQM to be able to predict high surface runoff, pesticide, and nutrient losses from fields with seepage zones.

Based on the fact that GLEAMS and RZWQM were not adequate in this study, more data from different sites are needed to evaluate these models and assess whether there is a need for model developers to consider incorporating upward movement of water and chemicals in the soil profile and redistribution of the chemicals among surface runoff, percolation, and seepage zones. The data being collected at OPE^3 is a good starting point for long-term data that can be used to evaluate and possibly incorporate seepage zone processes in the GLEAMS and RZWQM models. Data from other research sites are also needed to evaluate GLEAMS and RZWQM before incorporation of seepage zone processes into these models.

Table 9. Comparison of measured and predicted corn yields from 1999 to 2003.

Year	Measured (kg/ha)	GLEAMS (kg/ha)	RZWQM (kg/ha)
1999	1543	7000	5007
2000	7855	6651	7252
2001	6704	6707	7862
2002	5143	7000	7294
2003	No data	6562	7249
Mean	5311	6784	6933

Summary and Conclusions

The GLEAMS and RZWQM models were used to predict daily, monthly, and annual NO_3–N concentration and loss in surface runoff from an agricultural field with seepage zones. The results of this study have particular importance in using these two models to assess the impacts of various management practices on agricultural fields that have seepage zones.

Based on the evaluation techniques used in this study, calibrated GLEAMS and RZWQM predicted daily NO_3−N concentration and loss in surface runoff from field C (index of agreement >0.57). RZWQM performed well on both daily and monthly bases in predicting NO_3−N loss in surface runoff.

Based on the fact that GLEAMS and RZWQM were not adequate in this study, there is a need for the models to be tested with long-term data from several sites before incorporating upward movement of water and chemicals in the soil profile and redistribution of chemicals among surface runoff, percolation, and seepage zones. When more sites are identified that have seepage zones and OPE^3 collects more data, then these models can be revised to incorporate seepage zones and chemical redistribution. Therefore, the data being collected at OPE^3 sites are a good starting point for modeling studies to investigate the problem of seepage zones in agricultural systems.

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