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Repository Citation

Srivastava, Puneet; Costello, Thomas A.; Edwards, Dwayne R.; and Ferguson, James A., "Validating a Vegetative Filter Strip Performance Model" (1998). *Biosystems and Agricultural Engineering Faculty Publications*. 59.
https://uknowledge.uky.edu/bae_facpub/59

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Notes/Citation Information
Published in *Transactions of the ASAE*, v. 41, issue 1, p. 89-95.

Digital Object Identifier (DOI)
https://doi.org/10.13031/2013.17161

VALIDATING A VEGETATIVE FILTER STRIP PERFORMANCE MODEL

P. Srivastava, T. A. Costello, D. R. Edwards, J. A. Ferguson

ABSTRACT. *Vegetative filter strips (VFS) reduce losses of nutrients, solids, and other materials from land area treated with fertilizers and manures. A number of models are available that simulate nutrient and sediment transport in VFS. While VFS effectiveness is considered to depend on lengths of pollutant source area and VFS areas, few published studies have tried to validate these models using variable pollutant source area and VFS area. The objective of this study was to validate an event-based nutrient transport model (Chaubey et al., 1995) that simulates soluble nutrient transport in VFS. This model links three sub-models: modified Green-Ampt infiltration, non-linear kinematic wave overland flow routing, and a nutrient transport component. The nutrient transport component considers infiltration as the only mechanism of pollutant removal from runoff. Data from a field plot experiment were used to validate the model. The model was executed using an uncalibrated runoff component, a calibrated runoff component, and measured runoff. The concentrations of parameters entering the VFS from three different poultry litter application lengths (6.1, 12.2, and 18.3 m) were not significantly different. However, predicted concentrations at subsequent lengths were different for all the three poultry litter application lengths. This finding was consistent with the observed data. Model execution with the uncalibrated runoff component, calibrated runoff component, and measured runoff underpredicted concentrations and mass transport at various locations along the length of the VFS. Underprediction of concentration was judged to be the reason for underprediction of mass transport. The agreement between the observed and predicted concentrations and mass transport, however, improved when runoff predictions from the calibrated runoff component and measured runoff were used. This suggests that accurate prediction of infiltration and runoff is critical for accurate prediction of concentration mass transport. Furthermore, since concentration was underpredicted even when measured runoff was used, this study suggests that the nutrient transport component might be improved, possibly by including nutrient removal mechanisms other than infiltration.* ***Keywords.*** *Vegetative filter strips, Infiltration, Runoff, Simulation model.*

Applying manure on the soil surfaces increases the fertility of the receiving soil but has been shown by several researchers (e.g., Westerman et al., 1983, 1985, 1987; Edwards and Daniel, 1993a) to cause potential water quality problems because of transport of manure constituents such as carbon (C), nitrogen (N), and phosphorus (P) in storm runoff. Losses of these pollutants should be controlled at or near the source to most practically meet national water quality objectives.

Vegetative filter strips (VFS) have been studied and proposed as a method of controlling pollutants near their respective sources. Vegetative filter strips (grassed areas installed down-slope of pollutant source areas) improve quality of incoming runoff by changing the flow hydraulics, which increases the opportunity for infiltration of surface runoff and pollutants into the soil profile, deposition of suspended solids, filtration of suspended sediment by vegetation, adsorption on soil and plant surfaces and absorption of soluble pollutants by plants. Among these mechanisms, infiltration has been suggested as the most significant removal mechanism affecting VFS performance (Dillaha et al., 1989). Infiltration moves the incoming rainfall and overland flow into the soil, thus reducing the mass of pollutants transported off the site (Dickey and Vanderholm, 1981; Edwards et al., 1971; Asmussen et al., 1977; Skaggs et al., 1969).

Simulation models are often used as a cost effective means of predicting pollutant loadings and to evaluate the effectiveness of Best Management Practices (BMPs) such as VFS. A group of researchers at University of Kentucky have used models to simulate transport of sediment in VFS (Barfield et al., 1977, 1979; Tollner et al., 1976, 1977; Hayes and Hairston, 1983; Hayes et al., 1979, 1984). More recently, several researchers (Delgado et al., 1992; Chaubey et al., 1995) have attempted to simulate nutrient transport through VFS. Delgado et al. (1992) proposed a continuous simulation computer model, GRAPHN, to simulate nitrogen transport in grass filter strips. Chaubey et al. (1995) also developed an event-based model to simulate nutrient transport (originating from pasture areas treated with animal manure) in vegetative filter strips. A modified Green-Ampt infiltration algorithm, non-linear kinematic wave overland flow routing algorithm, and a nutrient transport component were linked. A model developed by Overcash et al. (1981) was used as the

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Article has been reviewed and approved for publication by the Soil & Water Div. of ASAE.

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Transactions of the ASAE

VOL. 41(1):89-95

nutrient transport component. The nutrient transport model of Overcash et al. (1981) assumes infiltration, dilution, and the pollutant potential of the source area as the major factors influencing filter strip performance. This model also assumes steady-state rainfall and infiltration as well as complete mixing of nutrients in runoff and infiltrating water. In their model, Overcash et al. (1981) assumed infiltration as the only pollutant removal mechanism. Chaubey et al. (1995) concluded that the ability of Overcash's model to accurately predict concentrations and mass transport of poultry litter constituents depended on the accurate prediction of runoff and infiltration. The runoff component underpredicted runoff values at various VFS lengths; hence, mass transport at these VFS lengths were also underpredicted. However, when they used observed runoff values, the predicted mass transport and concentration values were found to be very similar to observed values. From this, it was concluded that accurate prediction of runoff is critical in assessing VFS performance through a modeling approach.

The objective of this study was to validate the combined model developed by Chaubey et al. (1995) to predict performance of grassed VFS installed below land areas of varying length having poultry litter applied. The data set used for validating the model is taken from the experiment conducted by Srivastava et al. (1994). This study investigated three different source area lengths (6.1, 12.2, and 18.3 m) receiving poultry litter with corresponding VFS lengths of up to 18.3, 12.2, and 6.1 m as opposed to only one litter application length (3.1 m) examined by Chaubey et al. (1995). Hence, the dataset used for validation is more comprehensive and better represents practical situations. Since rainfall, runoff, incoming pollutant concentration, and background pollutant concentration are the only data used by the model, this model enables prediction of VFS effectiveness with minimal hydrologic data.

Model Description

The model to be validated in this study was described in detail by Chaubey et al. (1995). The model was written to predict VFS performance using equations developed by Overcash et al. (1981) when runoff is not known. This model consists of infiltration and overland flow routing components in addition to Overcash's pollutant transport equations and is functional for a more general class of data availability than Overcash's model. The infiltration component used in this model was based on the modified Green-Ampt equation which accommodates unsteady rainfall (Green and Ampt, 1911; Chu, 1978), and the overland flow routing component is based on nonlinear kinematic wave approximation (Li et al., 1975; Lighthill and Whitham, 1955; Muñoz-Carpena et al., 1992). Figure 1 represents the components and structure of the model.

In this model, it is assumed that pollutants move only with water; therefore, loss of pollutants is only through infiltration. Nevertheless, pollutant concentration is affected by both infiltration and dilution by rainfall. The processes of rainfall and infiltration are assumed to be at steady-state. It is also assumed that the rate of mass input of constituents from the background is constant and is directly proportional to the rainfall rate. Complete mixing of runoff water, rainfall, and pollutants is also assumed, so that the pollutant concentration of infiltrating water is equal to that in runoff water (Overcash et al., 1981).

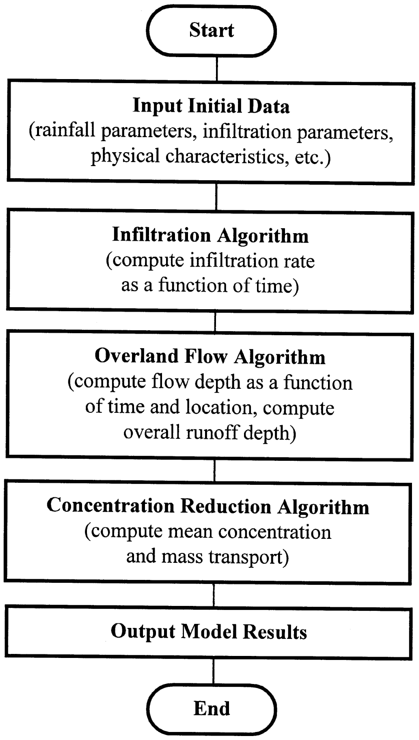


Figure 1–Flow chart of the model.

Model Validation

Experimental Data

Data from an experimental field plot study (Srivastava et al., 1994) were used to validate the model. This study involved nine plots having dimensions 1.5 m × 24.4 m (long axes oriented down slope) constructed on a Captina silt loam soil (fine-silty, mixed, mesic, *Typic Fragiudult*) at the Main Agricultural Experiment Station of the University of Arkansas, Fayetteville. Each plot was cross-leveled and had a uniform slope of 3% along the long axis. Fescue (*Festuca arundinacea* Schreb.) was the dominant grass cover. Wooden gutters were installed across each plot at every 3.1 m down-slope to collect runoff samples at those locations. The experimental design was an unbalanced factorial with three pollutant area (poultry litter applied) lengths (6.1, 12.2, and 18.3 m) and six VFS lengths (0, 3.1, 6.1, 9.2, 12.2, 15.3, and 18.3 m). The maximum VFS length investigated varied with pollutant source area length. As shown in figure 2, VFS lengths of up to 18.3, 12.2, and 6.1 m were tested down-slope of corresponding pollutant source area lengths of 6.1, 12.2, and 18.3 m, respectively. Simulated rainfall (50 mm/h) was applied to the plots immediately following poultry litter application until 1 h after the start of runoff at the down-slope end of each plot. Runoff was sampled and analyzed for ortho P (PO_4-P), total P (TP), ammonia N (NH_3-N), and total kjeldahl N (TKN). A detailed description of the methods of analyses and results of the study was given by Srivastava et al. (1996).

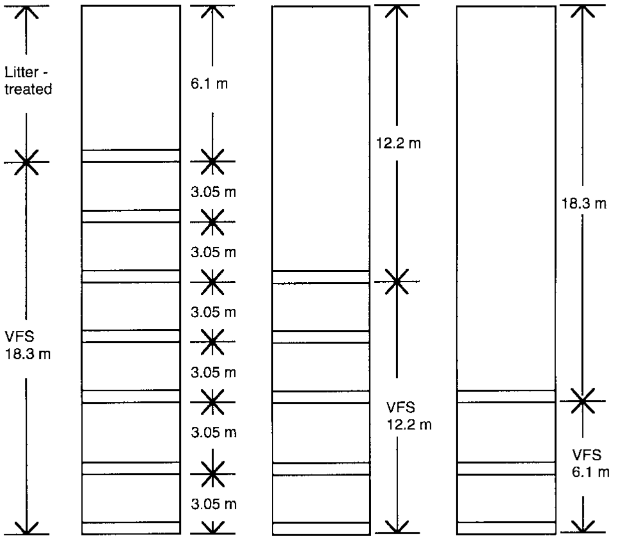


Figure 2–Schematic (not to scale) of plots used for each litter-treated pollutant source area. Lines across the plots indicate runoff collection gutters.

SIMULATION PROCEDURE

The concentration data at 0 m VFS (quality of runoff collected upstream from VFS) from the field study were used as input to the model to generate predicted concentration and mass transport values at different downslope VFS lengths. The model was then executed for concentration and mass transport predictions in three modes: uncalibrated mode, calibrated mode, and using observed values of runoff (rather than predicted runoff). The model was executed using observed values of runoff to isolate the performance of nutrient transport equations developed by Overcash et al. (1981). Background nutrient concentrations input to the model were based on the data reported by Edwards and Daniel (1993, 1994) on runoff concentrations of various parameters from untreated plots.

The model was executed in uncalibrated mode using the average value of 12 mm/h for saturated hydraulic conductivity (K_s), 24 mm for product of initial soil moisture deficit and average suction across the wetting front (MS_{av}) for Captina silt loam soil as reported by Thiesse (1984), and 0.5 for Manning's n as reported by Huggins et al. (1982). Runoff values at different locations in VFS were calculated using the overland flow routing and infiltration components. Average values of runoff were then used to predict concentrations and mass transport at different VFS lengths.

Model calibration was performed to identify values of K_s, MS_{av}, and n (table 1) that minimized the sum of squared differences between observed and predicted runoff at the lower-end of each plot. A direct search algorithm was used in which values of K_s, MS_{av}, and n were varied iteratively. The model was also executed using measured runoff values in predicting concentrations and mass transport of nutrients.

Linear regression analyses were performed on the predicted versus observed values of concentrations and mass transport of various poultry litter constituents past different VFS lengths to assess the accuracy of model predictions. Zero bias between predicted and observed values would be exhibited by a regression line having a slope of 1.0 and intercept of 0.0. Hypothesis testing was performed on the regression line slopes and intercepts to detect any bias between predicted and observed values.

Table 1. Calibrated values of hydraulic parameters K_s, MS_{av}, and n

	Plot*								
	1	2	3	4	5	6	7	8	9
L† (m)	6.1	6.1	6.1	12.2	12.2	12.2	18.3	18.3	18.3
K_s (mm/h)	21	17	25	2	15	21	5	15	17
MS_{av} (mm)	10	140	80	180	20	10	50	150	20
n	0.75	0.02	0.46	0.28	0.33	0.18	0.69	0.52	0.43

* Plots 1, 2, 3 correspond to 6.1 m litter-treated length, plots 4, 5, 6 to 12.2 m litter-treated length, and plots 7, 8, 9 to 18.3 m litter-treated length.

† Litter-treated length.

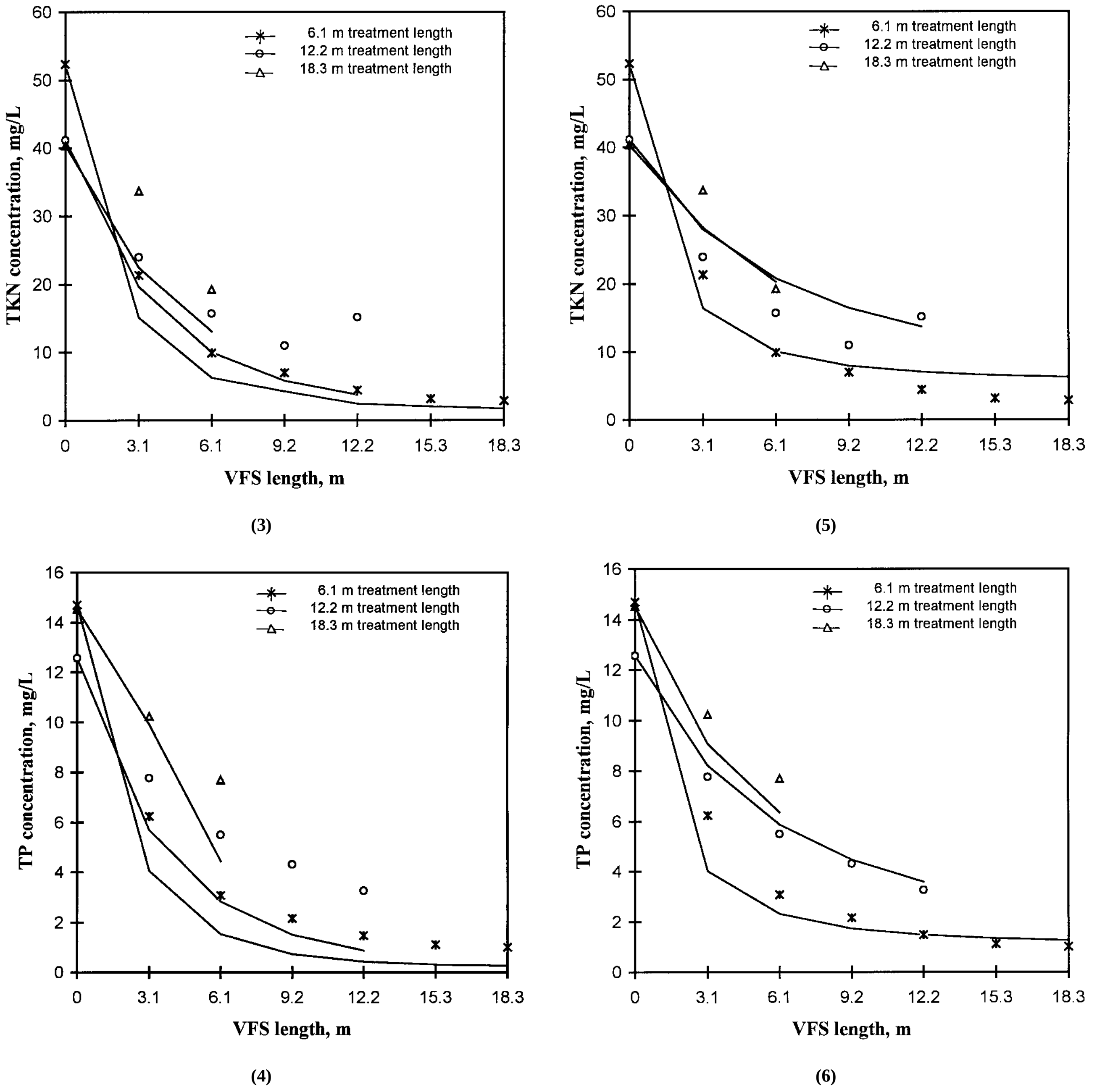
RESULTS AND DISCUSSION

CONSTITUENT CONCENTRATION PREDICTIONS

The observed concentrations of TKN and TP and the corresponding predicted (predicted using the uncalibrated runoff component) concentrations for various litter treated lengths (6.1, 12.2, and 18.3 m) and VFS lengths (0 to 18.3 m) are plotted in figures 3 and 4, respectively. As indicated in figures 3 and 4, concentrations of parameters entering the VFS were identical for the three different litter-treated lengths. However, predicted concentrations at subsequent lengths were different for the three litter-treated lengths. This might be due to differences in runoff. This finding was consistent with the observed concentrations found by Srivastava et al. (1996).

In order to quantify the relationship between predicted (predicted using uncalibrated runoff component) and observed constituent concentrations for the 6.1 m litter-treated plots, simple linear regression analyses were performed where the dependent variable was observed concentration and independent variable was predicted concentration. The coefficients of determination (R^2) (table 2) ranged from 0.68 to 0.90 and were highly significant ($p < 0.01$). This indicated that there was a significant linear relationship between the observed and predicted constituent concentrations. Null hypotheses (that the intercept = 0 and that the slope = 1) were performed to test for a difference between the regression line and a line of perfect agreement. For all the constituents (TKN, NH_3-N, PO_4-P, and TP), the fitted slope values were significantly ($p < 0.05$) greater than one. This indicates that constituent concentrations were underpredicted by the uncalibrated model.

In order to obtain a better fit between observed and predicted concentrations, the runoff component of the model was calibrated using the observed values of runoff measured at the lower-end of plots. Uncalibrated, calibrated, and measured runoff values are shown in table 3. The measured runoff values are the end-values linearly distributed along the plot lengths. Estimates of the hydraulic parameters (K_s, MS_{av}, and n, table 1) that minimized the sum of squared differences between the observed and predicted runoff amount at that point were identified. The observed concentration of TKN and TP and the corresponding predicted (predicted using calibrated runoff component) concentrations for various litter-treated lengths (6.1, 12.2, and 18.3 m) and VFS lengths (0 to



(3) (5)

(4) (6)

Figure 3, 4, 5, 6–Mean observed and predicted concentrations for various litter-treated and VFS lengths. Figures on left represent uncalibrated model, and figures on right represent calibrated model. Lines represent predicted concentrations and symbols represent observed concentrations.

18.3 m) are plotted in figures 5 and 6. For all the constituents except PO_4-P, the fit between observed and predicted concentrations improved (higher R^2 values, table 2); however, the slopes of the regression lines remained significantly ($p < 0.05$) greater than one. This indicated that concentrations of constituents were underpredicted even with calibrated runoff parameters.

In order to test the pollutant transport component (Overcash et al., 1981) of the model independently from the infiltration and overland flow routing components, the observed values of runoff were also used to predict concentration of constituents at various VFS lengths. The statistical results from the regression analyses are summarized in table 2. The R^2 values, ranging from 0.88 to 0.97, were found to be highly significant ($p < 0.01$) indicating a significant linear relationship between the observed and predicted constituent concentrations. For all the constituents, the null hypothesis that slope = 1 was rejected ($p < 0.05$), and the null hypothesis that intercept = 0 was also rejected ($p < 0.05$) except for PO_4-P. This indicated a significant bias in the predictions with concentrations being under-predicted, particularly at higher concentrations (slope significantly greater than 1).

MASS TRANSPORT PREDICTIONS

The observed mass transport of TKN and TP and the corresponding predicted (predicted using uncalibrated runoff component) mass transport for various litter-treated

Table 2. Results of regression analysis of observed and predicted poultry litter constituent concentrations (for 6.1 m litter-treated length)

Parameter	Mode†	Intercept	Slope	R^2
TKN	U	1.01	1.37**	0.68‡
	C	–7.31*	1.71**	0.99‡
	K	–9.72*	2.14**	0.96‡
NH_3-N	U	0.76	1.65**	0.72‡
	C	–1.31*	1.78**	0.94‡
	K	–2.01*	2.31**	0.95‡
PO_4-P	U	0.32	1.75**	0.90‡
	C	–0.04	1.24	0.81‡
	K	–0.47	1.75**	0.88‡
TP	U	–0.56	1.59**	0.80‡
	C	–0.53	1.51**	0.91‡
	K	–1.15*	2.03**	0.97‡

* Significantly ($p < 0.05$) different from zero.

** Significantly ($p < 0.05$) different from one.

† Mode of prediction.
U = Predicted with runoff estimated from the uncalibrated model.
C = Predicted with runoff estimated from the calibrated model.
K = Predicted using the observed values of the runoff.

‡ Regression was highly significant ($p < 0.01$).

Table 3. Measured and predicted (using calibrated an uncalibrated model) runoff volumes at sample collection points.

	Plot†								
Location*	1	2	3	4	5	6	7	8	9
(m)	L								
	Measured Runoff								
6.1	182	122	55	–	–	–	–	–	–
9.1	272	183	82	–	–	–	–	–	–
12.2	363	245	109	544	390	364	–	–	–
15.3	454	306	137	680	487	455	–	–	–
18.3	544	367	164	816	584	546	690	263	508
21.4	635	428	191	952	682	637	805	307	592
24.4	727	490	219	1089	781	728	920	351	677
	Predicted Runoff (Calibrated)								
6.1	201	127	77	–	–	–	–	–	–
9.1	295	189	109	–	–	–	–	–	–
12.2	386	250	137	583	427	386	–	–	–
15.3	476	310	161	715	521	475	–	–	–
18.3	562	371	183	844	611	562	735	289	536
21.4	646	431	204	968	699	646	776	322	608
24.4	728	490	219	1089	782	728	920	351	677
	Predicted Runoff (Uncalibrated)								
6.1	173	173	173	–	–	–	–	–	–
9.1	245	245	245	–	–	–	–	–	–
12.2	310	310	310	310	310	310	–	–	–
15.3	366	366	366	366	366	366	–	–	–
18.3	419	419	419	419	419	419	419	419	419
21.4	466	466	466	466	466	466	466	466	466
24.4	505	505	505	505	505	505	505	505	505

* Location shown is distance measured from upper end of the plot to the runoff sampling point.

† Plots 1, 2, 3, correspond to 6.1 m litter-treated length, plots 4, 5, 6 to 12.2 m litter-treated length, and plots 7, 8, 9 to 18.3 m litter-treated length.

lengths (6.1, 12.2, and 18.3 m) and VFS lengths (0 to 18.3 m) are plotted in figures 7 and 8, respectively. Results indicated that the uncalibrated model mostly underpredicted mass transport for all the poultry litter constituents at various litter-treated lengths along the length of VFS. Since nutrient transport component demonstrates that mass transport is dependent on concentration, underprediction in concentration might be the reason for underprediction of mass transport. Underprediction of runoff (or in other words, overprediction of infiltration) might also be the reason for underprediction of mass transport.

The relationship between predicted and observed constituent mass transport was quantified in the same way as for the constituent concentrations. The R^2 values (table 4), ranging from 0.41 to 0.71, were highly significant ($p < 0.01$). For all the constituents, the fitted slope values were significantly ($p < 0.05$) greater than one, indicating underprediction of constituent mass transport by the uncalibrated model.

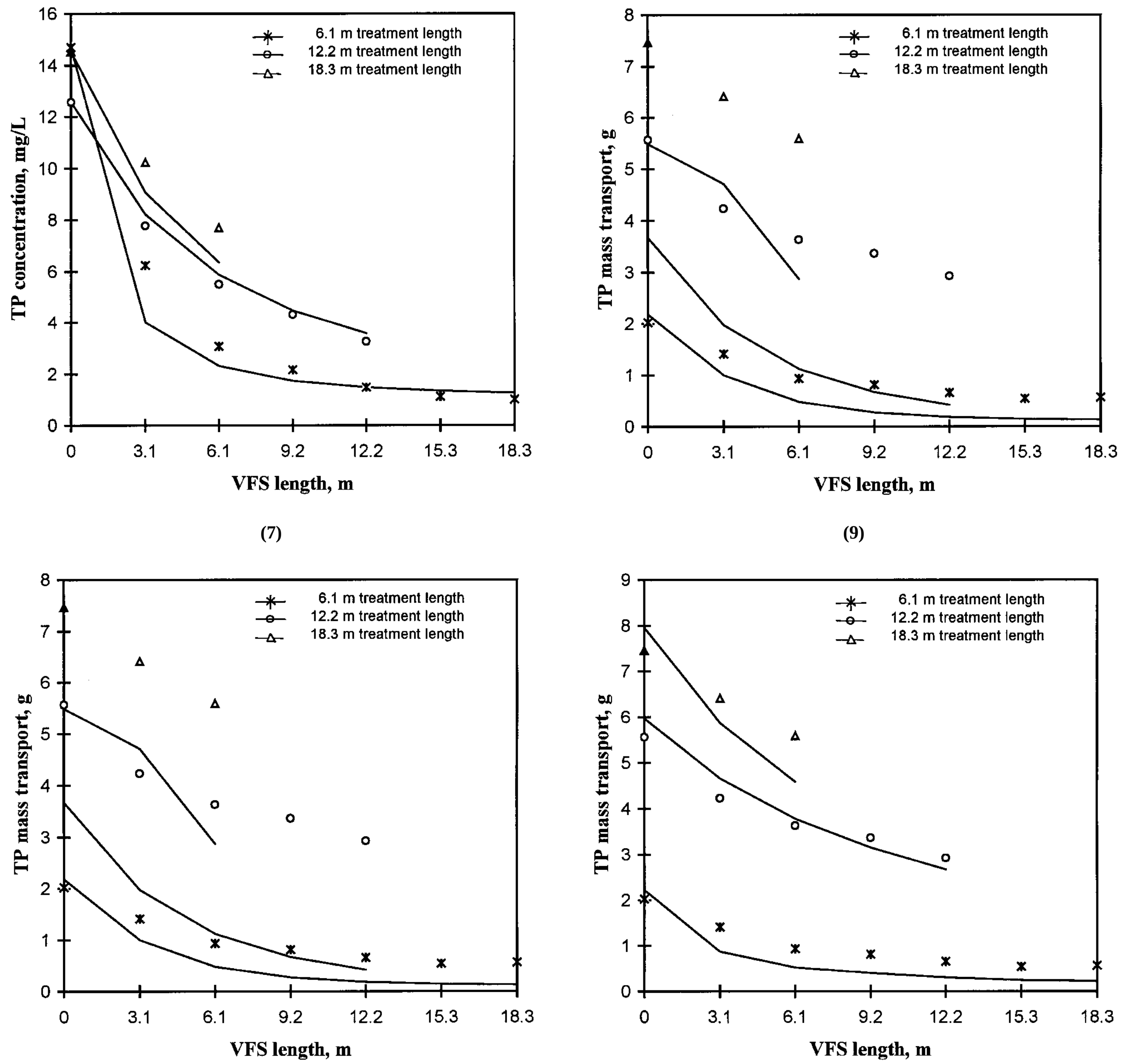
The observed mass transport of TKN and TP and the corresponding predicted (predicted using calibrated runoff component) mass transport for various litter-treated lengths (6.1, 12.2, and 18.3 m) and VFS lengths (0 to 18.3 m) are plotted in figures 9 and 10. For all the constituents, except PO_4-P, the fit improved when calibrated model (described earlier) was used (higher R^2 values, table 4); however, the slopes of the regression lines remained significantly ($p < 0.05$) greater than one. This indicated that mass transport of constituents was underpredicted even with calibrated runoff parameters.

The statistical results from the regression analyses using the observed values of runoff are summarized in table 4. The R^2 values, ranging from 0.79 to 0.93, were highly significant ($p < 0.01$), indicating a significant linear relationship between the observed and predicted constituent mass transport. For all the constituents, the null hypothesis that the slope = 1 was rejected ($p < 0.05$), and the null hypothesis that the intercept = 0 was also rejected ($p < 0.05$) except for PO_4-P. This indicated a significant bias in the predictions with mass transport being underpredicted particularly at higher mass transport (slope significantly greater than 1).

Since the constituent concentrations were underpredicted, it was expected that mass transport would be underpredicted. However, the increase in fit (higher R^2 value) between observed and predicted constituent concentrations and mass transport of poultry litter constituents indicate that accurate prediction of runoff and infiltration is important for accurate prediction of constituent concentrations and mass transport. This finding was similar to those found by Chaubey et al. (1995). Furthermore, since a significant linear relationship was found in observed and predicted values, the nutrient transport component seems to follow the behavior of VFS. However, significant bias between predicted and observed values indicate that there is a need to improve the nutrient transport component, too.

SUMMARY AND CONCLUSIONS

Attempts have been made in this study to validate the event-based model (Chaubey et al., 1995) that simulates soluble nutrient transport in VFS. This model links three sub-models: modified Green-Ampt infiltration, non linear kinematic wave overland flow routing, and a nutrient transport component. The model assumes infiltration as the only mechanism of pollutant removal by which VFS performs. Data collected from an experiment by Srivastava et al. (1994) were used to validate the model. This field plot study investigated three different litter-



(7) (9)

(8) (10)

Figure 7, 8, 9, 10–Mean observed and predicted mass transport for various litter-treated and VFS lengths. Figures on left represent uncalibrated model, and figures on right represent calibrated model. Lines represent predicted mass transport and symbols represent observed mass transport.

treated lengths (6.1, 12.2, and 18.3 m) with a corresponding VFS lengths of up to 18.3, 12.2, and 6.1 m. The model was tested using uncalibrated runoff component, calibrated runoff component, and measured runoff. Model validation with the measured runoff was performed to test the validity of Overcash's nutrient transport component separately.

The concentration predictions along the length of VFS were different for the three different litter-treated lengths even though the concentrations of the poultry litter constituents entering the VFS were similar. This finding was consistent with the observed data. Model underpredicted concentrations and mass transport when uncalibrated, calibrated runoff components, and measured runoff were used. However, the fit between the observed and predicted concentrations and mass transport increased when calibrated runoff and measured runoff component was used. This finding suggests that accurate prediction of infiltration and runoff is important for accurate prediction of concentration and mass transport. Surprisingly, model execution with the measured runoff underpredicted concentration and mass transport along the length of VFS. This finding was not consistent with the results reported by Chaubey et al. (1995) which used a fixed length of litter-treated area. However, a significant linear relationship between observed and predicted values indicate that the nutrient transport component seems to follow the behavior of VFS. Whereas, a significant bias between predicted and

Table 4. Results of regression analysis of observed and predicted poultry litter constituent mass transport (6.1 m litter-treated length)

Parameter	Mode*	Intercept	Slope	R^2
TKN	U	0.43	1.36**	0.41‡
	C	0.14	1.28**	0.94‡
	K	–1.54*	1.56**	0.79‡
NH_3-N	U	0.40	1.57**	0.46‡
	C	0.32	1.58**	0.93‡
	K	–0.53*	2.17**	0.91‡
PO_4-P	U	0.09	1.88**	0.71‡
	C	0.35*	0.53**	0.56‡
	K	–0.08	1.52**	0.86‡
TP	U	0.27*	1.49**	0.44‡
	C	0.26*	1.32**	0.94‡
	K	–0.21*	1.76**	0.93‡

* Significantly ($p < 0.05$) different from zero.

** Significantly ($p < 0.05$) different from one.

† Mode of prediction
U = Predicted with runoff estimated from the uncalibrated model.
C = Predicted with runoff estimated from the calibrated model.
K = Predicted using the observed values of the runoff.

‡ Regression was highly significant ($p < 0.01$).

observed values indicate that there is a need to improve the nutrient transport component in addition to infiltration component and flow routing component.

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