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Hydrologic modeling of runoff from a livestock manure windrow composting site with a fly ash pad surface and vegetative filter strip buffers

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Abstract

Windrow composting of livestock manure materials provides a strategy for converting organic wastes into a recyclable soil fertility product that is less hazardous to the environment. Although outdoor windrow composting can produce runoff that is detrimental to surface water quality, vegetative filter strip (VFS) buffers were reported to significantly reduce runoff and contaminants from a windrow composting research site. To estimate the efficacy of VFS buffers and other best management practices on runoff from future windrow composting facilities, a computer hydrologic model may provide a valuable tool for predicting runoff losses from these proposed sites. This research evaluated a windrow composting/vegetative filter strip buffer (WCVFS) hydrologic model for estimating runoff volume losses from a livestock manure-based windrow composting site with a fly ash composting pad surface and VFS buffers. Runoff and physical attribute data from six rainfall events during 2002 to 2004 at a central Iowa windrow composting research site were used in the WCVFS model evaluation. Three rainfall events were designated as "wet" composting period events (2002 and 2003 seasons), and three were designated as "dry" composting period events (2004 season). Runoff data were comprised of average observed runoff volumes from three compost windrow area:VFS buffer area ratio treatments that included 1:1, 1:0.5 (large and small VFS buffer areas, respectively), and a 1:0 (no buffer) control. The WCVFS model performance was good to very good for the 2003 wet composting period model validation rainfall event with no significant differences among 1:1, 1:0.5, and 1:0 ratio treatments for simulated versus observed runoff volumes. In contrast, WCVFS model performance was unsatisfactory for the 2004 dry composting period validation event with significantly higher simulated runoff volume from the 1:0.5 ratio treatment versus observed runoff volumes. There were no significant differences for the 1:1 and 1:0 treatments. The WCVFS model effectively estimated 1:1, 1:0.5, and 1:0 treatment runoff volumes from the earlier wet composting period and 1:1 and 1:0 treatment runoff volumes from the later dry composting period rainfall events. However, the soils data-derived VFS buffer runoff and infiltration functions in the WCVFS model flow routing component may not have sufficiently accounted for some short-term hydrologic changes in VFS buffer soil and fly ash pad surfaces. This could have resulted in overestimation of dry composting period simulated runoff volume from the smaller 1:0.5 ratio VFS buffer area treatment. Consequently, the use of other alternatives to soils data-derived VFS buffer runoff and infiltration functions should be evaluated in future WCVFS model simulation trials to potentially improve runoff volume prediction accuracy.

Keywords

fly ash, hydrologic modeling, livestock manure window composting, surface runoff, vegetative filter strip (VFS) buffers, water resources

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Abstract: Windrow composting of livestock manure materials provides a strategy for converting organic wastes into a recyclable soil fertility product that is less hazardous to the environment. Although outdoor windrow composting can produce runoff that is detrimental to surface water quality, vegetative filter strip (VFS) buffers were reported to significantly reduce runoff and contaminants from a windrow composting research site. To estimate the efficacy of VFS buffers and other best management practices on runoff from future windrow composting facilities, a computer hydrologic model may provide a valuable tool for predicting runoff losses from these proposed sites. This research evaluated a windrow composting/vegetative filter strip buffer (WCVFS) hydrologic model for estimating runoff volume losses from a livestock manure-based windrow composting site with a fly ash composting pad surface and VFS buffers. Runoff and physical attribute data from six rainfall events during 2002 to 2004 at a central Iowa windrow composting research site were used in the WCVFS model evaluation. Three rainfall events were designated as "wet" composting period events (2002 and 2003 seasons), and three were designated as "dry" composting period events (2004 season). Runoff data were comprised of average observed runoff volumes from three compost windrow area:VFS buffer area ratio treatments that included 1:1, 1:0.5 (large and small VFS buffer areas, respectively), and a 1:0 (no buffer) control. The WCVFS model performance was good to very good for the 2003 wet composting period model validation rainfall event with no significant differences among 1:1, 1:0.5, and 1:0 ratio treatments for simulated versus observed runoff volumes. In contrast, WCVFS model performance was unsatisfactory for the 2004 dry composting period validation event with significantly higher simulated runoff volume from the 1:0.5 ratio treatment versus observed runoff volumes. There were no significant differences for the 1:1 and 1:0 treatments. The WCVFS model effectively estimated 1:1, 1:0.5, and 1:0 treatment runoff volumes from the earlier wet composting period and 1:1 and 1:0 treatment runoff volumes from the later dry composting period rainfall events. However, the soils data-derived VFS buffer runoff and infiltration functions in the WCVFS model flow routing component may not have sufficiently accounted for some short-term hydrologic changes in VFS buffer soil and fly ash pad surfaces. This could have resulted in overestimation of dry composting period simulated runoff volume from the smaller 1:0.5 ratio VFS buffer area treatment. Consequently, the use of other alternatives to soils data-derived VFS buffer runoff and infiltration functions should be evaluated in future WCVFS model simulation trials to potentially improve runoff volume prediction accuracy.

Key words: fly ash—hydrologic modeling—livestock manure windrow composting—surface runoff—vegetative filter strip (VFS) buffers—water resources

Land application of livestock manure to agricultural fields can elevate runoff concentrations of nutrients such as nitrogen, carbon, and phosphorus (Westerman et al. 1987; Edwards and Daniel 1993; Heathwaite et al. 1998; Burton and Turner 2003; James et al. 2007). Nutrients in the runoff stream from these agricultural areas are a major source of water pollution in surface waters in the United States (Parry 1998). One strategy that has been demonstrated to minimize adverse effects of livestock manure on the environment is windrow composting.

Windrow composting consists of placing manure and other raw materials in long narrow piles or windrows, which are agitated or turned on a regular basis (Rynk et al. 1992). Studies have shown that composted manure was less hazardous to the environment (Eghball and Power 1999; Vervoort et al. 1998) and that much of the mineral nitrogen was converted to more stable organic forms (Rynk et al. 1992). However, one of the disadvantages of windrow composting is nutrient loss during the composting process, which can occur through leaching, runoff, and volatilization (Christensen 1983, 1984; Richard and Chadsey 1994; Eghball et al. 1997; Tiquia et al. 2000; Michel et al. 2004; Parkinson et al. 2004; Peigne and Girardin 2004).

Windrow composting sites can produce runoff that includes nutrients such as nitrate-nitrogen, which move through the soil and into streams as subsurface flow or leach down to the groundwater (Tiquia et al. 2002; Garrison et al. 2001). Consequently, a composting pad surface material with barrier properties to reduce infiltration may be effective in mitigating contaminant transport into the soil strata and redirecting runoff flow to a detention basin or vegetative treatment area like a vegetative filter strip (VFS) buffer. Richard (1996) suggested that composting pad surface materials—including gravel, asphalt, or concrete—may be appropriate for some windrow composting facilities. Sikora and Francis (2000) reported that lime and fly ash materials produced a hardened, nearly impervious surface layer for windrow composting sites.

Fly ash is a byproduct derived from combustion of bituminous coal at power

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generating stations that is generally disposed in landfills at a significant cost (Kalinski et al. 2005). These surface materials also are capable of supporting windrow composting equipment and are more economical than a comparable-sized concrete pad surface (Sikora and Francis 2000). Parker et al. (2001) and Kalinski et al. (2005) reported that lime and fly ash materials provided a suitable surface for livestock feedlot areas. Feedlots are similar to windrow composting areas regarding the presence of livestock manure and significant surface compaction and deformation from animal traffic and heavy equipment use.

Vegetative filter strip (VFS) buffers are bands of vegetation located downslope of cropland or other potential pollutant source areas. These vegetative buffer strips provide erosion control and filter nutrients, pesticides, sediment, and other pollutants from agricultural runoff by reducing the sediment carrier and via interception-adsorption, infiltration, and degradation of pollutants dissolved in water (Dillaha et al. 1989). A VFS buffer system is a best management practice (BMP) that has been extensively shown to reduce sediment and nutrient losses in a range of agricultural settings, including crop fields and feedlots (Magette et al. 1989; Patty et al. 1997; Wenger et al. 1999).

The effectiveness of VFS buffers as BMPs in controlling pollutants from agricultural land has been assessed by many researchers (Dillaha et al. 1985; Mickelson and Baker 1993; Lee et al. 2000; Schultz et al. 2004; Wang et al. 2005; Hay et al. 2006). These researchers found that VFS buffers can significantly improve water quality of runoff. Webber et al. (2009) also found VFS buffers significantly reduced runoff, sediment, and nutrient losses from the central Iowa windrow composting research site used as a source of observed runoff volume data for this hydrologic modeling study.

Hydrologic models have been used for over 30 years to simulate sediment and nutrient transport in surface runoff through various natural and simulated vegetation systems, including VFS buffers (Tollner et al. 1976; Delgado et al. 1992; Srivastava et al. 1998). However, few reports exist regarding the use of hydrologic models for predicting runoff losses from windrow composting sites. Governo (2001) developed a spreadsheet-based computer program to assist in the design phase of windrow composting facilities but did not include a hydrologic modeling component. Tollner and Das (2004) evaluated hydrologic models that applied the USDA Natural Resources Conservation Service (NRCS) Curve Number (CN) method for predicting runoff volume from a yard waste windrow composting site. Kalaba et al. (2007) used the unit hydrograph method to model runoff volume from a small livestock manure/vegetative byproducts windrow composting site with a paved pad surface. Although these research efforts described and successfully tested hydrologic modeling approaches for windrow composting sites, they did not include runoff and infiltration functions for VFS buffers.

Wilson et al. (2004) reported that approximately 68% of rainfall incident on saturated compost windrows from both natural and simulated rainfall events resulted in runoff. This percentage value is expressed as a decimal fraction runoff coefficient of 0.68, equaling the volume of runoff and leachate collected divided by the total rainfall volume applied to the compost windrow. Webber et al. (forthcoming) derived an average runoff coefficient of 0.63 (used in this hydrologic modeling research) from compost windrow cross-section prototype samples under simulated rainfall conditions. The laboratory apparatus used in this study contained compost samples from the actual windrow composting/VFS buffer site, where observed field runoff data were collected for use in this hydrologic model evaluation.

Few research efforts have addressed the development and application of a computer hydrologic model for simulating surface runoff flow from a livestock manure-based windrow composting site. Although the modeling software platform used in this research included input/output components for simulating sediment and nutrient transport, this study only used infiltration and runoff functions in the windrow composting/vegetative filter strip (WCVFS) hydrologic modeling system.

The priorities for this research project included calibration and validation evaluations for compost windrow, fly ash pad surface, and VFS buffer runoff and infiltration functions. The future incorporation of runoff contaminant transport functions into the WCVFS model also could provide useful estimates of runoff pollutant data. However, this would require specific compost sediment and nutrient dynamics data, some of which have yet to be determined. Moreover, Srivastava et al. (1998) reported that accurate simulation of infiltration and runoff is an important initial step for accurate prediction of contaminant mass transport.

Materials and Methods

Hydrologic Model Description. The hydrologic model calibrated and validated in this study was modified from the Vegetated Treatment Area Model version 1.003 developed at Iowa State University (Wulf and Lorimor 2005) that simulates runoff from an open livestock feedlot as the effluent progresses down the length of the vegetated treatment area. This hydrologic model was chosen because of the flexible software platform and similarities between feedlots and windrow composting sites. These similarities include the relatively impervious surface of these sites due to animal and machinery traffic and the presence of livestock manure.

The VTA hydrologic model used in this study has been redesignated as the WCVFS model. The WCVFS model runs in the ModelMaker version 4.0 modeling software environment (ModelKinetix 2000). The WCVFS model accounts for runoff (either from snowmelt or rainfall) from the compost windrow and composting pad area, direct precipitation falling on the VFS buffer area, and soil infiltration. The model then estimates runoff outflow volume from the end of the VFS buffer. For input parameters, the WCVFS model uses weather data text files to estimate runoff volume. The model also uses physical attributes that include VFS buffer size (width, length, and area), soil infiltration rate, soil depth, water table depth, soil slope, and vegetation type (Wulf and Lorimor 2005).

For infiltration and runoff from compost pad and windrow surfaces, the WCVFS model used the USDA NRCS CN Method (Plummer and Woodward 1998; Fangmeier et al. 2006) to simulate hydrologic conditions during single rainfall events. The WCVFS model incorporated a laboratory-derived runoff coefficient of 0.63 from a compost windrow cross-section prototype and simulated rainfall events (Webber et al. forthcoming). Although the WCVFS model also is compatible with the Green-Ampt infiltration equation (Green and Ampt 1911) for use with continuous hydrologic modeling applications, Lamont (2006) reported that the CN method should be confined to single-event modeling (as was done in this study) since it reflects runoff totals based on a 24-hour duration.

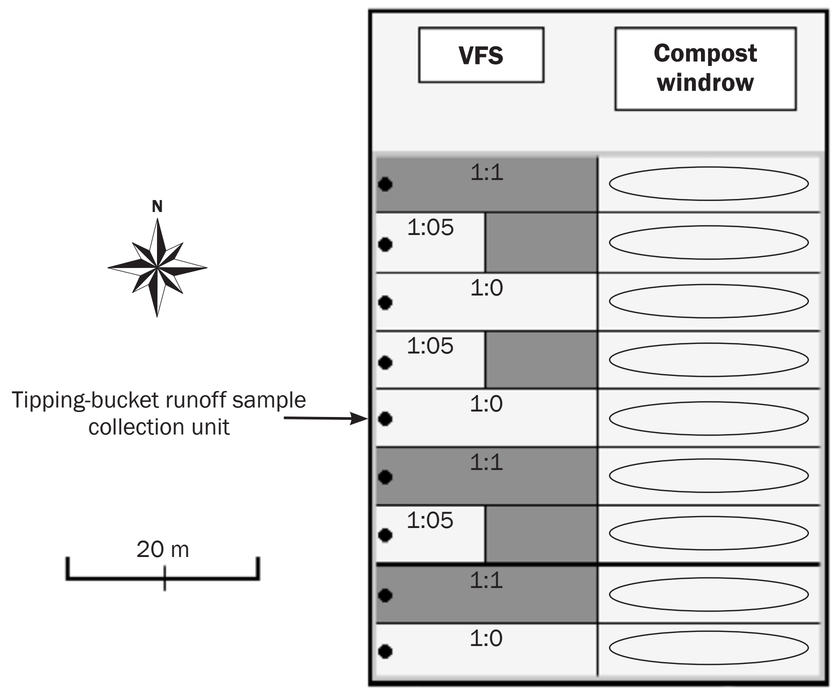
The WCVFS model VFS buffer area flow routing component included large and small VFS buffer areas (1:1 and 1:0.5, respectively; compost windrow area:VFS buffer area ratio) that consisted of 100 equal segments (1:1 VFS buffer segment = 6.0 m wide × 0.23 m long [20 × 0.7 ft]; 1:0.5 VFS buffer segment = 6.0 m wide × 0.12 m long [20 × 0.4 ft]) and routes the flow down the length of the VFS buffer in five-minute increments. In each segment, the model accounts for key hydrologic assumptions that include inflow from the segment immediately upslope, direct precipitation, infiltration into four soil layers, and surface outflow onto the surface of the next segment (Wulf and Lorimor 2005).

Research Site and Rainfall Data. During the 2002 to 2004 windrow composting/VFS buffer field runoff analysis project period, the study was located at the former Iowa State University (ISU) Dairy Teaching Farm in Ames, central Iowa, United States (42°0'34"N, 93°39'16"W). Dairy cow manure and associated straw bedding materials were used in constructing the compost windrows. However, horse and sheep manure components were included in compost windrow construction for the final 2004 field research season due to a shortage of dairy cow manure (Webber et al. 2009). The compost windrow and VFS buffer plot layout diagram is depicted in figure 1.

The study site total area was 0.25 ha (0.62 ac) that included runoff plots consisting of three compost windrow area:VFS buffer area ratio treatments (1:1, 1:0.5 [VFS buffer plots], and a 1:0 [no buffer plot] control). The treatments were equally replicated to comprise a total of nine plots distributed in a randomized complete block design, with each plot corridor (combined composting pad and VFS buffer areas) measuring 6.0 m wide × 46.0 m long (20.0 × 150 ft). The 1:1 and 1:0.5 VFS buffer plots were 6.0 × 23.0 m (20.0 × 75.0 ft) and 6.0 × 12.0 m (20.0 × 37.5 ft), respectively. The research plot area was selected on terrain with an average slope of 5% in the VFS buffer plots to improve surface drainage. Runoff volume was measured using a polyvinyl chloride (PVC) collector pipe and tipping-bucket flow meter system (Hansen and Goyal 2001) located at the downslope (west) end of each plot (figure 1).

Figure 1

Compost windrow and vegetative filter strip (VFS) buffer (1:1, 1:0.5, and 1:0 no buffer [control] compost windrow:VFS buffer area ratios) research site plot layout at the former Iowa State University Dairy Teaching Farm, Ames, Iowa, United States. Runoff volume data from this site was used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations. The downslope direction and tipping-bucket runoff sample collection units are on the left (west) side of the plot diagram.



Dominant vegetation included smooth brome (*Bromus inermis* Leyss.) and switchgrass (*Panicum virgatum* L.) and a trace of mixed broadleaf species. Smooth brome occupied approximately 75% of each 1:1 VFS buffer plot, primarily in the upslope areas, and approximately 100% of the 1:0.5 VFS buffer plots. Switchgrass in the downslope areas occupied approximately 25% of each 1:1 VFS buffer plot, but only a trace was observed in the 1:0.5 VFS buffer plots. The average tiller population for VFS buffer grass species was determined to be 2.7 million tillers ha^{-1} (6.7 million tillers ac^{-1}). Tiller population was estimated using a method from Arora et al. (2003). In contrast, Brueland et al. (2003) and Arora et al. (2003) determined tiller counts of 9.0 million and 50 million tillers ha^{-1} (22 million and 124 million tillers ac^{-1}), respectively, from two other central Iowa research sites that included similar vegetation types.

The major soil association at the research site is the Clarion-Webster-Nicollet association, with the minor soil association of Hayden-Lester-Storden in the area (Dewitt 1984). All soils were formed in glacial till and local alluvium from till, with Clarion loam (a fine-loamy, mixed, mesic Typic Hapludolls) the dominant soil at the research site and with minor areas of Webster soil (a fine-loamy, mixed, mesic Typic Haplaquolls). However, when more than one soil type comprises a research site (i.e., Clarion and Webster), the WCVFS hydrologic model requires using the soil type of lowest hydraulic conductivity (Webster) (Wulf and Lorimor 2005). The upslope composting pad surface area of the site consisted of approximately 390 m^3 (13,773 ft^3) of fly ash, a byproduct of combustion from coal-fired power plants provided by Alliant Energy, Inc., Marshalltown, Iowa, United States. The 0.13 ha (0.32 ac) composting pad area (figure 1) was constructed by machine grading to approximately a 2% slope to augment drainage, and fly ash was compacted with heavy equipment to a depth of 31 cm (12 in).

There were a total of six rainfall events used in the WCVFS hydrologic model evaluation. Rainfall volume for each event at the field research site was measured using a tipping-bucket rain gauge (Onset Computers

Table 1
Rainfall event data, composting period ("wet" composting period events W1, W2, and W3; "dry" composting period events D4, D5, and D6), and model simulation designations (calibration and validation) used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Event number	Event date	Rainfall depth	Composting period	Model simulation
W1	Aug. 5, 2002	35 mm	Wet	Calibration
W2	June 25, 2003	81 mm	Wet	Calibration
W3	July 5, 2003	61 mm	Wet	Validation
D4	July 3, 2004	46 mm	Dry	Calibration
D5	Aug. 26, 2004	33 mm	Dry	Calibration
D6	Sept. 6, 2004	46 mm	Dry	Validation

Table 2
Rainfall event data, composting period ("wet" composting period events W1, W2, and W3; "dry" composting period events D4, D5, and D6), and estimated compost windrow moisture content values for each rainfall event from dry-based (kg) and wet-based (%) moisture content analyses.

Event number	Event date	Composting period	Compost moisture content dry-based water mass (kg)	Compost moisture content wet-based water volume (%)
W1	Aug. 5, 2002	Wet	15,839	74
W2	June 25, 2003	Wet	8,963	64
W3	July 5, 2003	Wet	7,230	62
D4	July 3, 2004	Dry	4,800	63
D5	Aug. 26, 2004	Dry	3,052	53
D6	Sept. 6, 2004	Dry	2,575	49

Table 3
Weather data file (table 4) input parameter value descriptions and abbreviations used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Weather file input parameter description	Input parameter abbreviation
Time	t, year, month, and day (Julian)
Temperature maximum	Tmax (°F)
Temperature minimum	Tmin (°F)
Daily precipitation	precip (in)
Dewpoint	Dewpoint (°F)
Potential daily evapotranspiration	Potevt (in)
Daily evaporation	Dailyevap (in)
Evaporation coefficient	Evapcoeff (dimensionless)

Inc., Massachusetts, United States) and three plastic column-style depth rain gauges. Three rainfall events (W1, W2, and W3) during the 2002 to 2003 "wet" composting period and three events (D4, D5, and D6) during the 2004 "dry" composting period were used for calibrating and validating the WCVFS model. Rainfall data from events W1 and W2 were used in wet period calibration simulations, and event W3 data were used in the wet period validation simulation. Rainfall data from events D4 and D5 were used in dry period calibration simulations, and event D6 data were used in the dry period validation simulation. Rainfall event depth and compost moisture content data are shown in tables 1 and 2, respectively.

Simulation Procedure and Statistical Analysis. The WCVFS hydrologic model simulation procedure was initiated by accessing and selecting site-specific weather data. These actions were followed by responding to a series of user-input dialog windows outlined by Wulf and Lorimor (2005). Compost windrow, pad, VFS buffer size parameters, and other physical attributes were either entered manually in each of the remaining dialog windows or were preentered in the user input default mode allowing rapid clicking through the dialog window sequence.

Weather data input values for the WCVFS model are in a text file format organized in a required columnar series (USEPA 2009; NCDC 2009). Table 3 includes site-specific meteorological parameter descriptions and abbreviations of minimum values for each rainfall event. An example weather data file used in this study is shown in table 4. Other fixed and variable attribute data descriptions and input parameter values are shown below with respective literature sources for parameter derivation information and are included in tables 5 to 8.

The fixed input parameters needed for each of the four soil layers in the soils database of the WCVFS model are included in table 5 (USDA NRCS 2009). Fixed vegetation input data for running WCVFS model simulations included parameters listed in table 6 (Wulf and Lorimor 2005). Fixed physical attribute input data for running WCVFS model calibration and validation simulations were collected from the ISU windrow composting research site during 2002 to 2004 (Webber et al. 2009) and are included in table 7. Table 8 shows actual variable physical attribute input data used in WCVFS model calibration and validation simulations. These included compost windrow and pad CN ranges, VFS buffer length, and seasonal water table depth range values (DeWitt 1984).

Hydrologic model calibration and validation during this study were conducted manually as described by Moriasi et al. (2007). The calibration process involved adjusting four variable attribute input parameters (table 8) independently throughout a series of WCVFS hydrologic model simulations to approximate average observed runoff volumes recorded during ISU field research site rainfall events. An approximation was determined if the simulated runoff volume value was not significantly different ($p < 0.05$) than the respective average observed runoff volume value based on observed runoff vol-

Table 4
Weather data file example used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations. Parameter abbreviations are defined in table 3.

t	Year	Month	Day	Tmax	Tmin	Precip	Dewpoint	Potevt	Dailyevap	Evapcoeff
1	2004	6	23	79.7	58.0	0	65.0	0.285	0.31	0.78
2	2004	6	24	60.9	48.4	0	61.3	0.098	0.24	0.78
3	2004	6	25	72.1	42.7	0	64.4	0.247	0.16	0.78
4	2004	6	26	76.5	49.3	0	61.1	0.248	0.25	0.78
5	2004	6	27	74.0	57.1	0	63.9	0.128	0.29	0.78
6	2004	6	28	75.0	51.9	0	58.2	0.245	0.18	0.78
7	2004	6	29	79.1	53.1	0	57.9	0.256	0.29	0.78
8	2004	6	30	80.0	54.0	0	62.0	0.265	0.23	0.78
9	2004	7	1	85.1	60.9	0	65.5	0.258	0.38	0.78
10	2004	7	2	78.4	67.3	0	63.2	0.110	0.28	0.78
11	2004	7	3	73.0	64.6	1.8	63.7	0.064	0.21	0.78
12	2004	7	4	83.2	62.8	0	71.5	0.235	0.14	0.78

Table 5
Fixed soils data descriptions and input parameter values used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Fixed input parameter description	Input parameter value
Soil name (and number) used due to lowest hydraulic conductivity	Webster (94)
Bulk density	1.43 gm cm^{-3}
Wilting point expressed as percent volumetric moisture at 1,520 kPa	(0.19%)
Available water capacity	0.13%
Clay	25.7%
Sand	37.1%
Organic carbon	1.58%
Nitrogen	0.14%
Depth to bottom of soil layer	84 cm

Table 6
Fixed vegetation data descriptions and input parameter values used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Fixed input parameter description	Input parameter value
VFS buffer vegetation name (and number)	Bromegrass (9)
Nitrogen uptake high	225 ppm
Nitrogen uptake low	120 ppm
Phosphorus uptake high	26 ppm
Phosphorus uptake low	10 ppm
Manning n surface roughness value	0.05
Retardance class number	3
Plant spacing	0.17 cm

ume and least squares mean statistical analysis results from Webber et al. (2009).

The WCVFS model simulations were conducted using six rainfall events (table 1) from the ISU field research project (Webber et al. 2009). Moriasi et al. (2007) suggested that rainfall events should be divided into wet and dry time periods, if possible, to potentially improve model prediction accuracy. Consequently, the six events from this study were equally divided into a "wet" composting period and "dry" composting period. Initially, both calibration and validation simulations required the 1:1 and 1:0.5 VFS buffer length input parameters of 23.0 m (75.0 ft) or 12.0 m (37.5 ft), respectively.

The compost windrow CN was calibrated by adjusting the CN to correspond with a compost windrow runoff volume fraction that equaled the laboratory-derived average runoff coefficient of 0.63 (Webber et al. forthcoming). The composting pad CN then was adjusted to equal a runoff value not significantly different ($p < 0.05$) than the observed 1:0 (no buffer) control treatment average runoff volume. Finally, the seasonal water table depth variable parameter was adjusted to equal a runoff value not significantly different ($p < 0.05$) than the observed average runoff volume from the 1:1 and 1:0.5 VFS buffer plots. However, water table depth input parameter adjustments in the calibration simulations were consistent with Story County, Iowa Soil Survey water table depth ranges of 0.3 to 1.8 m (1.0 to 6.0 ft) for the Webster soil type (lowest hydraulic conductivity) present at the field research site (DeWitt 1984).

The model validation process was conducted using calibration input parameter data for each wet and dry composting period rainfall event. Compost windrow CN parameters for validation simulations were derived from averaging the CN values used during the calibration process (Moriasi et al. 2007). This average CN value approximated the laboratory-derived 0.63 runoff coefficient value (Webber et al. forthcoming). Composting pad CN values for validation simulations were selected for lowest hydraulic conductivity, which were consistent with the WCVFS model requirement of selecting the soil type at the site with the lowest hydraulic conductivity (Wulf and Lorimor 2005). This generally

Table 7
Fixed physical attribute data descriptions and input parameter values used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Fixed input parameter description	Input parameter value
Compost windrow length	16 m
Compost windrow width	2.4 m
Compost pad length	23 m
Compost pad width (for individual windrow)	6.0 m
Compost pad average slope	2.0%
VFS buffer width	6.0 m
VFS buffer average slope	5.0%
VFS buffer effective width (calculated from model vegetation spacing data)	80%
VFS buffer macroporosity value (1 = calculated by model)	1
Water table seepage rate (from lowest value at composting research site)	0.64 cm day^{-1}

Note: VFS = vegetative filter strip.

Table 8
Variable physical attribute data descriptions, input parameter, and range values used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations.

Variable input parameter description	Input parameter value
Compost windrow curve number range	87 to 95
Compost pad curve number range	66 to 89
1:1 ratio VFS buffer length	23 m
1:0.5 ratio VFS buffer length	12 m
Seasonal water table depth range	0.5 to 1.2 m

involved selecting the highest CN value used during the wet and dry composting period calibration simulations.

Seasonal water table depth input parameters also were selected for validation simulations based on soil type with the lowest hydraulic conductivity, which corresponded to the shallowest water table depth parameter used during a wet or dry composting period calibration simulation process in a single project season. However, for this study, the wet composting period included two years (2002 and 2003), and the initial 2002 season research was conducted shortly after fly ash composting pad construction, field preparation, and planting of the VFS buffer plots. Since research site construction activities resulted in compacted composting pad and VFS buffer surfaces, the seasonal water table input parameter used for the wet composting period validation simulation was averaged over the water table values used during all wet composting period calibration simulations.

Calibration and validation simulation runoff volume data were compared to average observed data using the General Linear Model Procedure and Least Squares Mean Test (SAS 2004) and statistical criteria described by Moriasi et al. (2007). Standard regression (R^2) has been a useful statistical criterion describing degree of collinearity between simulated and measured data. However, R^2 tends to be oversensitive to outlier values and insensitive to additive and proportional differences between model predictions and measured data (Legates and McCabe 1999). Consequently, R^2 was not used in the statistical analysis for this study.

Three statistical criteria recommended by Moriasi et al. (2007) that were used in this study included Nash-Sutcliffe efficiency (NSE), root mean square error-observation standard deviation ratio (RSR), and percent bias (PBIAS). The NSE ranges between $-\infty$ and 1 (1 inclusive) with NSE = 1 being the optimal value. Values > 0 indicate "minimal acceptable" performance, whereas values < 0 indicate the mean observed value is a better predictor than the simulated value. The RSR is calculated as the ratio of root mean square error and standard deviation of measured data. The RSR varies from the optimal value of 0, which indicates zero root mean square error or residual variation and therefore represents a perfect model simulation, to a large positive value. The lower the RSR, the lower the root mean square error and the better the model simulation performance. The PBIAS criterion measures average tendency of simulated data to be larger or smaller than their observed counterparts. The optimal PBIAS value is 0.0 with low magnitude values indicating accurate model simulation. Positive and negative values indicate model underestimation and overestimation bias, respectively (Moriasi et al. 2007). General performance rating ranges for NSE, RSR, and PBIAS criteria were adapted from Moriasi et al. (2007) and given in table 9.

Results and Discussion

Average observed and simulated runoff volumes (L) from calibration and validation simulations for the 1:1 and 1:0.5 VFS buffer and 1:0 (no buffer control) compost windrow area:VFS buffer area ratio plot treatments listed with rainfall event data, model simulation trials, and statistical analysis results are shown in table 10. The WCVFS model calibration simulation performance was very good for wet and dry composting period rainfall events with no significant differences ($p < 0.05$) between simulated and observed runoff volume data for 1:1 and 1:0.5 VFS buffer and 1:0 control treatments. The statistical criteria values NSE, RSR, and PBIAS for calibration simulation wet and dry composting period results are 0.99, 0.05, and –2.35; and 0.98, 0.13, and –2.91, respectively.

Validation simulation performance was good to very good for the wet composting period rainfall event (0.97, 0.19, and 11.0 for NSE, RSR, and PBIAS, respectively), resulting in no significant differences ($p < 0.05$) between simulated and observed runoff volume data for 1:1 and 1:0.5 VFS buffer and 1:0 control treatments. In contrast, validation simulation performance was unsatisfactory for the dry composting period event (–0.004, 1.00, and –104 for NSE, RSR, and PBIAS, respectively), primarily due to significantly higher ($p < 0.05$) 1:0.5 VFS buffer plot simulated versus observed runoff volumes. However, dry composting period event results for 1:1 VFS buffer and 1:0 control plot runoff volumes were not significantly different ($p < 0.05$) between simulated and observed runoff data.

Table 9

General performance ratings for recommended quantitative criteria (stat) that include Nash-Sutcliffe efficiency (NSE), root mean square error observations standard deviation ratio (RSR), and percent bias (PBIAS) value ranges, assuming typical uncertainty in measured data adapted from Moriasi et al. (2007).

Performance rating	NSE stat (unitless)	RSR stat (unitless)	PBIAS stat (%)
Very good	0.75 < NSE ≤ 1.00	0.00 ≤ RSR ≤ 0.50	PBIAS < ±10
Good	0.65 < NSE ≤ 0.75	0.50 < RSR ≤ 0.60	±10 ≤ PBIAS < ±15
Satisfactory	0.50 < NSE ≤ 0.65	0.60 < RSR ≤ 0.70	±15 ≤ PBIAS < ±25
Unsatisfactory	NSE ≤ 0.50	RSR > 0.70	PBIAS ≥ ±25

Dry composting period validation simulation results included a highly significant overestimation of runoff volume from 1:0.5 VFS buffer plots (indicative of the relatively high-magnitude negative PBIAS value = –104) and no significant differences in 1:1 VFS buffer and 1:0 control plot simulated versus observed runoff volumes. Webber et al. (2009) found that runoff percent of rainfall from the 1:0 control plots was significantly lower, and 1:1 and 1:0.5 VFS buffer plots also trended towards significantly lower runoff percent of rainfall values for dry composting period compared to wet composting period runoff data results from the ISU windrow composting research site. These results also are reflected in the substantially lower compost moisture content values from the dry composting period (2004) rainfall events versus wet composting period (2002 to 2003) events (table 2).

These results may reflect significant short-term runoff and infiltration changes in composting pad and VFS buffer surface materials. Consequently, these documented changes in runoff percent of rainfall coupled with results from VFS buffer soils data-derived WCVFS model flow routing calculations could have functioned in the highly significant overestimation of simulated runoff volume from the 1:0.5 VFS buffer treatment. Dosskey et al. (2007) found that most change in VFS buffers occurred within three growing seasons after establishment, and infiltration characteristics accounted for most of that change.

Fly ash composting pad material was observed to crack and slough off of the pad surface during the 2002 to 2004 project seasons. These surface deformation conditions probably were due to freeze/thaw action and various machinery operations involved with compost windrow construction and removal, sampling, and process management. Cracks in the fly ash pad surface could have increased preferential flow pathways, significantly reducing runoff volume losses from the 1:0 control plots. Loose fly ash granules also were observed to move downslope with surface runoff and accumulate in the lower margins of all composting pad plots and upper margins of the 1:1 and 1:0.5 VFS buffer plots. This accumulation of fly ash granules was noticeably greater during the final dry composting period (2004) and could have provided additional water-absorbent substrate for further runoff volume reductions from 1:1 and 1:0.5 VFS buffer and 1:0 control plots.

Fly ash has been reported to include chemical and physical properties that enhance soil fertility and water retention capacity (PAU 1993; Pathan et al. 2003). During the 2002 to 2004 windrow composting study, downslope movement of loose fly ash granules into VFS buffer plots at the ISU windrow composting research site could have resulted in fly ash accumulating and mixing with VFS buffer soils, possibly functioning as a water-absorbent soil amendment. Punjab Agriculture University researchers reported the application of fly ash as a soil amendment increased available water content of loamy sand soil by 120% and of sandy soil by 67% (PAU 1993). These water-absorbent soil amendment effects of fly ash granules on VFS buffer soils also may have contributed to the WCVFS hydrologic modeling of a highly significant overestimation of simulated runoff volume from the dry composting period 1:0.5 VFS buffer treatment.

Summary and Conclusions

Windrow composted-livestock manure materials have been shown to be less hazardous to the environment than uncomposted manure. However, outdoor windrow composting sites can produce runoff that is detrimental to surface water quality. The use of VFS buffers has been demonstrated to significantly reduce runoff and contaminants from a windrow composting research site. This study evaluated a windrow composting/VFS buffer (WCVFS) computer hydrologic model for estimating runoff volume losses from a windrow composting site with VFS buffers and a fly ash composting pad surface.

Hydrologic simulation results from the WCVFS model evaluations indicated a satisfactory performance for the 2003 wet composting period model validation rainfall event and 1:1, 1:0.5 (VFS buffer) and 1:0 (no buffer control) compost windrow area:VFS buffer area ratio treatments. In contrast, WCVFS model performance was unsatisfactory for the 2004 dry composting

Table 10

Rainfall event number (W1, W2, and W3; D4, D5, and D6), composting period (wet/dry), calibration (Cal) and validation (Val) model simulations, and 1:1, 1:0.5, and 1:0 no buffer (control) composting pad:VFS buffer runoff treatment observed (obs) and simulated (sim) runoff volumes in liters (L) used for windrow composting/vegetative filter strip (WCVFS) hydrologic model calibration and validation simulations. Significant obs and sim runoff volume differences ($p < 0.05$) within and among VFS buffer treatments are indicated by a different letter (b). Statistical criteria (stat) values include Nash-Sutcliffe efficiency (NSE), root mean square error observations standard deviation ratio (RSR), and percent bias (PBIAS).

Event number	Composting period	Model sim	1:1 obs (L)	1:1 sim (L)	1:0.5 obs (L)	1:0.5 sim (L)	1:0 obs (L)	1:0 sim (L)	NSE stat	RSR stat	PBIAS stat (%)
W1, W2	Wet	Cal	81a	110a	531a	585a	2,516b	2,506ba	0.99	0.05	–2.35
W3	Wet	Val	436a	0.0b	758a	827ab	3,661b	3,501ba	0.97	0.19	11.0
D4, D5	Dry	Cal	5.7a	11a	4.5a	29a	343b	323ba	0.98	0.13	–2.91
D6	Dry	Val	3.9a	0.0a	2.3a	567ba	744b	964ba	–0.004	1.00	–104

period validation event from the 1:0.5 VFS buffer treatment compared with respective observed runoff volume data. The observed data used in these comparisons reflected documented short-term (i.e., < three years) increases in composting pad and VFS buffer plot surface infiltration and a possible increase in water-absorption capacity of downslope-accumulated loose fly ash material. This fly ash accumulation most likely was due to freeze/thaw conditions, runoff, and pad surface compaction and deformation effects from heavy equipment used for composting windrow construction and removal, sampling, and process management during a three-year study.

The WCVFS model effectively estimated all VFS buffer and control treatment runoff volumes from the earlier 2002 to 2003 wet composting period rainfall events. However, the soils data-derived VFS buffer runoff and infiltration functions in the WCVFS model flow routing component may not have sufficiently accounted for some short-term hydrologic changes in VFS buffer soil and fly ash pad surfaces. This could have resulted in overestimating the later 2004 dry composting period simulated runoff volume from the smaller (1:0.5 area ratio) VFS buffer plot treatment. Consequently, the use of other alternatives to soils data-derived VFS buffer runoff and infiltration functions should be evaluated in future WCVFS model simulation trials to potentially improve runoff volume prediction accuracy.

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