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Use of the Soil-Plant-Air-Water Model to Predict Hydraulic Performance of Vegetative Treatment Areas Controlling Open Lot Runoff

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Abstract

Alternative treatment systems to control runoff from open beef feedlots may enhance environmental security and protect water quality. Several Midwestern states have issued National Pollution Discharge Elimination System permits allowing beef feedlots to use vegetative treatment systems (VTSs) to control and treat feedlot runoff. Monitoring VTSs has provided data to validate performance modeling strategies. The objective of this study was to evaluate the ability of the Soil-Plant-Air-Water (SPAW) model to predict the hydraulic performance of vegetative treatment areas (VTAs). Two approaches, one using the field module and the other the pond module of the SPAW model, were investigated. The model results from the SPAW field and pond modules were compared to monitored performance data from five VTAs in Iowa. Modeling statistics were calculated to evaluate SPAW's ability to predict VTA hydraulic performance. Based on the 18 site-years of data collected, the Nash-Sutcliffe efficiency (NSE), percent bias (BIAS), and ratio of the root mean square error to the standard deviation (RSR) were 0.95, 8%, and 0.22, respectively, on an annual basis. The NSE, BIAS, and RSR for the field module were 0.32, 32%, and 0.83, respectively. The results showed that the SPAW model could be used successfully to predict the hydraulic performance of VTAs, with the pond module being more successful than the field module.

Keywords

Hydraulic modeling, Runoff control, SPAW, Vegetative treatment areas, Vegetative treatment systems

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Comments

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USE OF THE SOIL-PLANT-AIR-WATER MODEL TO PREDICT HYDRAULIC PERFORMANCE OF VEGETATIVE TREATMENT AREAS CONTROLLING OPEN LOT RUNOFF

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ABSTRACT. *Alternative treatment systems to control runoff from open beef feedlots may enhance environmental security and protect water quality. Several Midwestern states have issued National Pollution Discharge Elimination System permits allowing beef feedlots to use vegetative treatment systems (VTSs) to control and treat feedlot runoff. Monitoring VTSs has provided data to validate performance modeling strategies. The objective of this study was to evaluate the ability of the Soil-Plant-Air-Water (SPAW) model to predict the hydraulic performance of vegetative treatment areas (VTAs). Two approaches, one using the field module and the other the pond module of the SPAW model, were investigated. The model results from the SPAW field and pond modules were compared to monitored performance data from five VTAs in Iowa. Modeling statistics were calculated to evaluate SPAW's ability to predict VTA hydraulic performance. Based on the 18 site-years of data collected, the Nash-Sutcliffe efficiency (NSE), percent bias (BIAS), and ratio of the root mean square error to the standard deviation (RSR) were 0.95, 8%, and 0.22, respectively, on an annual basis. The NSE, BIAS, and RSR for the field module were 0.32, 32%, and 0.83, respectively. The results showed that the SPAW model could be used successfully to predict the hydraulic performance of VTAs, with the pond module being more successful than the field module.*

Keywords. *Hydraulic modeling, Runoff control, SPAW, Vegetative treatment areas, Vegetative treatment systems.*

Runoff from open-lot animal feeding operations (AFOs) has been recognized as a potential pollutant to receiving waters because it contains nitrogen, phosphorus, organic matter, solids, and pathogens. As a result, the U.S. Environmental Protection Agency (EPA) developed a set of effluent limitation guidelines (ELGs) that described the design and operating criteria for feedlot runoff control systems on concentrated animal feeding operations (CAFOs) (Anschutz et al., 1979). These effluent limitation guidelines historically required collection, storage, and land application of feedlot runoff. Recent modifications allowed the use of alternative treatment systems when the performance, based on the mass of nutrients released, of the alternative systems was equivalent to or exceeded that of an appropriately sized containment system (EPA, 2006). One method of making this comparison is to use simulation models, along with site-specific climate and wastewater characterization data, to determine the pollutant discharge level that the alternative treatment system and the containment basin system would achieve (EPA, 2006).

Vegetative treatment systems (VTSs) are one possible alternative runoff control technology that has been proposed. A VTS is a combination of treatment components, at least one of which utilizes vegetation, to manage runoff from open lots (Moody et al., 2006). Vegetative treatment areas (VTAs) and vegetative infiltration basins (VIBs) are two possible treatment components for VTSs. A sloped VTA is an area level in one dimension, with a slight slope along the other dimension to facilitate sheet flow, that is planted and managed to maintain a dense stand of vegetation (Moody et al., 2006). Operation of a VTA consists of applying solid settling basin effluent uniformly across the top of the vegetated area and allowing the effluent to sheet-flow down the slope (Moody et al., 2006). Gross and Henry (2007) proposed a modification to VTAs, called a "sprinkler VTA," that used a sprinkler system to apply the effluent more evenly over the length of the VTA. Ikenbery and Mankin (2000) identified several possible methods in which effluent was treated by VTAs, including settling solids, infiltrating runoff, and filtering effluent as it flowed through the vegetation. A VIB is a flat area, surrounded by berms, and planted to permanent vegetation (Moody et al., 2006). VIBs use a flood effect to distribute effluent over the surface. These areas have drainage tiles located 1 to 1.2 m (3.4 to 4 ft) below the soil surface to encourage infiltration of effluent. The tile lines collect effluent that percolates through the soil profile. The effluent then receives additional treatment, often from a VTA. Nutrient and pathogen removal in the VIB relies on

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effluent filtration as it percolates through the soil, plant uptake of nutrients, and microbial degradation of the nutrients and pathogens by soil fauna (Moody et al., 2006).

Koelsch et al. (2006) suggested that VTSs may be effective in a variety of situations. Modeling VTS performance provides a cost-effective method to evaluate specific situations where VTSs can be successfully implemented. Moreover, modeling VTS performance plays a key role in optimizing system design and is required to permit the facility. Recently, Tolle (2007) developed a series of models that have been used to simulate VTS performance in Kansas. Similarly, Wulf and Lormior (2005) developed a series of models, referred to here as the Iowa State University (ISU) models, to predict VTS performance in Iowa. Smith et al. (2007) performed a sensitivity analysis of the ISU-VTA model to determine which parameters had the most significant impact on VTS performance. They (Smith et al., 2007) found that VTS hydraulic performance was most sensitive to soil texture and bulk density. Khanijo et al. (2007) compared the ability of the ISU-VTA and ISU-VIB/VTA model to predict effluent discharge volumes and nutrient mass releases from four VTSs in Iowa. They (Khanijo et al., 2007) found that the ISU models greatly overpredicted both VIB and VTA hydraulic performance. These models are currently undergoing revisions to improve predictive ability. Along with improving the performance of these models, ISU has been looking at other available models that could be utilized to aid in both the design and analysis of VTSs. One possible model, as suggested by Gross and Henry (2007), that may be useful for designing VTAs is the Soil-Plant-Air-Water (SPAW) model.

The SPAW model was developed to perform a one-dimensional water budget on agricultural fields using a daily time step (Saxton et al., 2006). SPAW performs this water budget in the vertical dimension and focuses the simulation on major components in the water balance, such as runoff, infiltration, evapotranspiration, percolation, and the water content of the soil profile (Saxton and Willey, 2004). Saxton (1983) used SPAW to simulate soil moisture in a variety of situations. These simulations (Saxton, 1983) showed that SPAW could be used to simulate the temporal soil moisture patterns as a function of soil texture, vegetation type, and hydraulic inputs. Thus, it may be possible to use SPAW to assess the expected hydraulic performance of vegetative treatment areas in different hydrologic situations. Gross and Henry (2007) reported using the SPAW model to design VTSs on small feedlots in Nebraska. They used SPAW to assess the pore space available to infiltrate feedlot runoff; however, they did not evaluate how well SPAW performed in predicting actual VTA performance.

Objective

The objective of this investigation was to test and evaluate the ability of the SPAW model to simulate the hydraulic performance of the VTA component of a VTS. This study focused only on the hydrology of the VTA; nutrient transport into and through the system was not considered. The predicted VTA hydraulic performance was compared to the monitored VTA performance for 18 site-years. Hydraulic performance of the VTA was modeled with two different methods. The first method utilized the field module of the SPAW model, while the second method utilized the pond module. The results of the modeling options were evaluated against monitored performance data to determine which option was most effective in predicting VTA hydraulic performance.

Materials and Methods

Iowa State University monitored the performance of five vegetative treatments systems located in Iowa. The vegetative treatment systems at these sites were divided into pilot (instrumented and monitored by ISU) and non-pilot (monitored by the producers) portions. Table 1 shows the VTS configuration, the number of head, and the areas of the feedlot, VIB (where applicable), and VTA for the pilot systems.

Two different VTS configurations were monitored. These were a solid settling basin (SSB) followed by a VTA (SSB-VTA), and an SSB followed by a VIB in series with a VTA (SSB-VIB-VTA). In the SSB-VTA systems, runoff was collected from the beef feedlot and temporarily stored in a solid settling basin. Effluent from the solid settling basin was then released to the VTA. The VTA utilized gravity flow to spread the effluent down the length of the VTA. In the SSB-VIB-VTA systems, a solid settling basin captured the feedlot runoff. Solid settling basin effluent was released onto the VIB, and tile lines located 1 m below the VIB surface collected effluent draining through the VIB soil profile. This effluent was pumped onto a VTA for further treatment.

Site Descriptions

Full descriptions of these sites are available in Andersen et al. (2009). A brief description of each pilot portion of the sites is provided here.

Central Iowa 1 was a 3.09 ha feedlot permitted for 1,000 head of cattle. Runoff effluent drained into a solid settling basin designed to hold 4,300 m^3 of effluent. A gate valve on the SSB outlet was used to control release volumes and rates onto the VTA. The VTA was 48 m wide × 311 m long.

The VTS at Central Iowa 2 consisted of an SSB, VIB, and VTA. Runoff from the 1.07 ha feedlot drained into a concrete SSB with a volume of 50 m^3. Prior to reaching the SSB outlet

Table 1. Description of pilot VTSs monitored by ISU including site name, number of head, VTS configuration, and size of the feedlot, settling basin (SSB), vegetative infiltration basin (VIB), and vegetative treatment area (VTA).

Site	No. of Head	System Configuration	Feedlot Area (ha)	SSB Volume (m^3)	VIB Area (ha)	VTA Area (ha)
Central Iowa 1	1,000	1 SSB - 2 VTA	3.09	4,300	NA	1.52
Central Iowa 2	650	1 SSB - 1 VIB - 1 VTA	1.07	50	0.32	0.20
Northwest Iowa 1	1,400	1 SSB - 1 VTA	2.91	3,700	NA	1.68
Northwest Iowa 2	4,000	1 SSB - 1 VIB - 1 VTA	2.96	110	1.01	0.60
Southwest Iowa 2	1,200	1 SSB - 1 VTA	3.72	6,300	NA	3.44

pipe, the effluent flowed through a "fence" of round bales. A gate valve controlled when, how much, and at what rate effluent was released. The outlet from the settling basin released effluent into the 0.32 ha VIB. Effluent from the VIB was pumped onto a 0.2 ha VTA.

Northwest Iowa 1 was a 2.91 ha feedlot permitted to hold 1,400 head of cattle. Feedlot runoff was collected in a 1.2 m deep SSB having a volume of 3,700 m^3. The SSB outlet pipe discharged effluent uniformly along the top width of the 1.68 ha VTA. A valve was used to actively control release of effluent from the SSB to the VTA.

Northwest Iowa 2 had an SSB-VIB-VTA system designed to control runoff from a 2.96 ha concrete feedlot. A settling basin with 100 m^3 capacity collected the runoff. Effluent from the settling basin was released onto a 1.01 ha VIB. The VIB had 15 cm diameter perforated tiles installed 1.2 m deep and spaced 4.6 m apart. Flow from the tile lines was collected in a sump and pumped onto the VTA. A gated pipe was used to spread flow evenly across the top width of the VTA. The 0.6 ha VTA was divided into two 27 m wide channels. At a given time, effluent was pumped onto only one of the VTA channels. The channel receiving effluent was switched manually by the producer.

Southwest Iowa 2 was a 3.72 ha feedlot. Runoff drained into a solid settling basin designed to hold a 25-year, 24 h storm. A gate valve was installed on the settling basin outlet to control effluent release onto the VTA. The 3.44 ha VTA was constructed with small ridges along the length. The ridges slowed the flow of effluent through the system, providing time for infiltration to occur.

Monitoring Methods

Performance data at Central Iowa 1, Central Iowa 2, Northwest Iowa 1, and Northwest Iowa 2 have been collected since June 2006. Data collection at Southwest Iowa 2 began in 2007. The data collected included daily high and low temperatures, daily precipitation, effluent volumes released from each component of the VTS, and the nutrient concentrations of the effluent. Complete descriptions of the monitoring methodologies can be found in Moody et al. (2006), Khanijo (2007), and Andersen et al. (2009). Temperature measurements were collected on an hourly basis using Hobo temperature loggers (Onset Computer Corp., Bourne, Mass.). These measurements were used to determine daily maximum and daily minimum temperatures. Data from the Iowa Environmental Mesonet (http://mesonet.agron.iastate.edu/) were used as a substitute for any missing values. Precipitation depths were measured using an ISCO 674 tipping-bucket rain gauge (Teledyne ISCO, Lincoln, Neb.). A passive rain gauge installed on site was used to ensure rainfall data accuracy. Iowa Environmental Mesonet data were used to determine precipitation depths for events occurring between 1 November and 1 April.

The monitoring method used at the settling basin was dependent on the outlet design. An ISCO 750 low-profile area-velocity sensor (Teledyne ISCO, Lincoln, Neb.) was used at settling basins with pipe outlets. An ISCO 720 submerged probe (Teledyne ISCO, Lincoln, Neb.) in conjunction with a 0.45 m (1.5 ft) H-flume was used to monitor outflow for the other locations.

At sites with a VIB, the effluent captured in the tile lines was collected in a sump and pumped onto the VTA. The pumped volume was measured using a Neptune 5 cm (2 in.) turbine flowmeter (Neptune Technology Group, Tallassee, Ala.). An ISCO sampler was interfaced to the turbine meter with an ISCO 780 Smart 4-20 analog interface module (Teledyne ISCO, Lincoln, Neb.). This allowed the amount of effluent applied to the VTA to be calculated on a daily basis.

Flow monitoring at the VTA outlet was accomplished using similar methods as those at the settling basin outlet. An ISCO 750 low-profile area-velocity sensor (Teledyne ISCO, Lincoln, Neb.) was used on sites where the VTA had a pipe outlet, and an ISCO 720 submerged probe (Teledyne ISCO, Lincoln, Neb.) in conjunction with a 0.45 m (1.5 ft) H-flume was used on the other VTAs.

Groundwater depth was tracked in monitoring wells in or near the VTA using a Global Water WL16 level logger (Global Water Instrumentation, Gold River, Cal.). The level logger was lowered to the bottom of the monitoring well; the logger then recorded the depth of water above the pressure transducer. Groundwater depth was determined by subtracting the depth of water above the pressure transducer from the distance the transducer was lowered below the VTA. Starting in 2008, a WL 500 water level sounder (Global Water Instrumentation, Gold River, Cal.) was used to measure groundwater depth on a monthly basis.

Methodology

SPAW Field Module

The field module of the SPAW model (Saxton, 2008) was used to perform a water balance on five VTAs. The VTA hydraulic processes included in this water balance were infiltration, runoff, evapotranspiration, percolation, and storage of water in the soil profile. Effluent application onto the VTA was simulated by adding the equivalent depth of effluent applied to the VTA to the daily precipitation depth. This was done because many of the effluent applications had equivalent depths that were at, or below, the irrigation depths that SPAW was capable of simulating. Runoff was simulated using the NRCS/SCS curve number method. Runoff predictions were sensitive to curve number selection; thus, accurate knowledge of the curve number was important to accurately predict the VTA release volumes. The curve number was selected based on the hydraulic soil group and the land cover. The hydraulic soil group was determined using a soil survey map (Soil Survey Staff, 2008), and land cover was chosen to be a cool season grass. Additionally, the water table depth below the VTA was input into the SPAW model soil file and used as a constant boundary condition for the modeled VTA. The water table depth was taken as the average depth measured using the water level sounder data from 2008 and 2009.

One critical assumption for the SPAW field module was that the model assumed uniform effluent distribution over the VTA. Effluent application would rarely be uniform for gravity-flow VTAs, as more effluent was applied to the upper end of the VTA (near the settling basin or VIB outlet) than the lower end of the VTA. Additionally, for smaller runoff events, the distributed effluent may not cover the entire treatment area; instead, the wetting front would only traverse a fraction of the entire length of the VTA. Furthermore, there was a potential for channeling to develop throughout the VTA, which would reduce the uniformity of effluent application.

Another limitation was that the water table depth was set as a constant boundary condition. This assumption was necessary, as the water table depth was not known *a priori* and the SPAW model does not solve for the water table depth as part of the solution. This assumption was particularly limiting for shallow water table locations where the water table would be expected to fluctuate as a result of each rainfall event and for locations with a seasonal high water table that differed significantly from the seasonal low water table.

SPAW Pond Module

The second method of modeling the hydraulic performance of the Iowa VTAs utilized the SPAW pond module. This approach used an analogy between the soil-water system and a storage reservoir. When the reservoir was completely filled, overflow (i.e., runoff) would occur. There were several methods in which water was added to the reservoir; these included rainfall and effluent application from the settling basin or vegetative infiltration basin. Furthermore, there was no need to make the assumption of uniform effluent application, only that the applied effluent occupied a certain portion of the space available in the reservoir, i.e., in the soil profile. Three mechanisms for effluent removal from the storage reservoir were included in the model: evaporation, seepage losses, and reservoir overflow. Evaporation represented evapotranspiration from the VTA, seepage losses represented the amount of water lost due to a decline in water table elevation, and reservoir overflow represented release from the VTA. Appropriate values for several parameters needed to be determined to use this analogy; these included the storage capacity of the soil profile, the amount of water originally in the profile, and the seepage/percolation rate of water from the soil water reservoir. The soil water reservoir concept was successfully used by Nachabe et al. (2004) to model the amount of moisture stored in the soil profile and the movement of a shallow water table. Thus, this modeling perspective may provide insight into VTA performance in locations where saturation overland flow is the dominant mechanism causing VTA release.

Storage capacity of the soil water reservoir was approximated as the pore space in the soil profile to a depth of 2.44 m (8 ft). This depth was chosen because it was deeper than the water table at the sites with shallow water tables. The depth chosen should be either the water table or the depth of the impeding layer. The calculation used to determine the storage capacity volume is shown in equation 1:

$$Storage = d\eta Area_{VTA} \tag{1}$$

where d represents the depth of the water table, η represents the porosity of the soil, and $Area_{VTA}$ is the area of the VTA.

The soil porosity was determined based on field measurements. Three soil cores, 7.6 cm (3 in.) in diameter and 7.6 cm (3 in.) long, were collected from each VTA to determine the bulk density of the soil. Bulk density was determined by drying the soil in a 105ºC oven for 24 h and then measuring the mass of the soil sample. A subsample of the dried soil was used to measure particle density with a pycnometer. The bulk density and particle density were used to calculated soil porosity.

The initial amount of water in the reservoir was determined by assuming the soil profile to have an equilibrium water condition with a specified water table depth. The formula used to determine this volume is shown in equation 2:

$$Initial\_Volume = Area_{VTA} \int_0^d \theta_v dz \tag{2}$$

where θ_v is the volumetric soil water content, which is a function of soil water matric potential. The value of d was estimated using the average water table depths measured in 2008 and 2009.

A soil moisture-tension model (Saxton and Rawls, 2006) was used to determine the relationship between the soil water matric potential and the soil water content. This was a three-part model; it assumed complete saturation for all tensions below the air-entry tension, a linear model from the air entry tension to 33 kPa of matric tension, and a power law relationship above 33 kPa of matric tension. This model is shown in equation 3:

$$\theta_v = \begin{cases} \theta_s & h \le h_a \\ \left(\dfrac{33\,\text{kPa} - h}{33\,\text{kPa} - h_a}\right)(\theta_s - \theta_{33}) + \theta_{33} & h_a < h < 33\,\text{kPa} \\ \left(\dfrac{h}{h_a}\right) & h \ge 33\,\text{kPa} \end{cases} \tag{3}$$

where θ_s is the volumetric water content at soil saturation (assumed to be the soil porosity), θ_{33} is the volumetric water content at a tension of 33 kPa, h_a is the air-entry tension (kPa), λ is the pore size distribution index, and h is the soil water matric tension. Values for the water content at 33 kPa tension, the air entry pressure, and the pore size distribution index were determined using the regression equations provided by Saxton and Rawls (2006) and measurements of soil texture.

Monitoring of the groundwater level versus time was used to determine the seepage rate from the soil-water reservoir. The water table recession rate (m d^{-1}) was determined by calculating the height difference for two different water table positions, d_1 and d_2. The amount of water stored in the soil profile, assuming equilibrium soil moisture profiles, for each of the water table positions was then calculated. The amount of potential evapotranspiration occurring between the two water table elevation readings was subtracted from the change in soil moisture stored in the soil profile. The resulting value was then divided by the amount of time between the two water table depth readings to determine the seepage rate. The groundwater data were analyzed for a time period when no rainfall occurred. This method follows from the method described by Hillel (1998), analysis of a falling water table, with the additional assumption of equilibrium moisture profiles at both groundwater table positions and a correction for the amount of evapotranspiration occurring during the fall of the water table.

Data Analysis Methods

Modeling statistics and graphical comparisons were used to determine the ability of the SPAW field and pond modules to predict monitored outflow amounts. As recommended by Moriasi et al. (2007), three modeling statistics and graphical

Table 2. SPAW field and pond module inputs used for simulating VTA performance at the five sites.

	Field Module			Pond Module		
Site	Hydrologic Soil Group	SCS CN	Water Table Depth (m)	Storage Volume (m^3)	Initial Volume (m^3)	Seepage Rate ($m\ d^{-1}$)
Central Iowa 1	B	61	1.2	15,500	15,000	0.0001
Central Iowa 2	C	74	1.4	2,600	2,500	0.0005
Northwest Iowa 1	B	61	1.7	18,000	17,000	0.0005
Northwest Iowa 2	B	61	4.3	7,300	4,800	0.0003
Southwest Iowa 2	B	61	2.4	44,800	41,000	0.001

comparisons were used to assess the agreement between the modeled and measured results. The modeling statistics used were the Nash-Sutcliffe efficiency (NSE), the percent bias (BIAS), and the ratio of the root mean square error to the standard deviation of the monitored results (RSR). These statistics were calculated based on annual, monthly, and daily flow volumes, including months, years, and days when no VTA outflow was modeled or measured.

The NSE provided a measure of how the measured versus the predicted data fitted the one-to-one line, i.e., how well the predicted values followed the trends of the monitored data (Moriasi et al., 2007). The BIAS measured the average tendency of the predicted data as compared to the monitored data. The RSR provided an index to evaluate the residual variations (Moriasi et al., 2007). Moriasi et al. (2007) also provided guidelines for when these statistics, based on monthly data, indicated satisfactory model performance; for flow modeling, these were NSE > 0.50, RSR < 0.70, and PBIAS of less than ±25%.

Results and Discussion

The input values calculated for the field and pond modules are shown in table 2. The storage volume represents the pore space available in the top 2.44 m of the soil profile; the initial volume is the amount of pore water estimated in the soil profile using equation 2 at the specified water table depth, and the seepage rate was calculated as described earlier in the SPAW Pond Module section. Weather files including daily maximum and minimum temperatures and daily precipitation depth were created from the monitoring data. Equivalent VTA application volumes were added to the daily precipitation depths on the days when actual SSB and VIB releases onto the VTA were observed. Potential evapotranspiration data collected at nearby (but not on-site) weather stations were included in the weather file.

The field module generalized local site conditions by grouping all systems according to hydrologic soil group. The inputs for the pond module were more site specific; thus, model results were tailored more to the specific conditions encountered at the locations. As seen by the initial and total storage volumes listed in table 2, hydraulic performance at many of these locations may have been limited by the storage space available in the soil profile. Siting VTAs in shallow water table locations has been shown to negatively impact system performance. Sites with shallow water tables should be evaluated to determine expected performance and the risk they pose to groundwater quality.

The SPAW model was run for each of the five locations. The equivalent volume of release (the volume of release divided by the area of the VTA) was calculated for each site-year of the model results and compared to the monitored equivalent volume of release for that site-year. A graphical comparison for the field and pond modules is shown in figure 1. In this figure, the modeled equivalent release volume is plotted against the monitored equivalent release volume. Ideally, these values would fall along the one-to-one line plotted in the figure. Based on this figure, it appears that the pond module was better than the field model at predicting annual release volumes. This was verified by the modeling statistics in table 3. Based on the modeling statistics, the pond module results were good, while the field model results were satisfactory. The pond model followed the trends in annual performance (as evidenced by the high NSE), had very little bias (based on the BIAS), and was able to explain most of the variability in the data (as indicated by the low RSR). The field module results were satisfactory but showed a tendency to underestimate the actual release volume.

Additionally, model performance was evaluated on a monthly basis. Figure 2 shows a graphical comparison of modeled and monitored results on a flow equivalent basis. Model statistics are shown in table 4. The pond module had satisfactory performance for both the NSE and RSR, with very good performance for the BIAS. The field module performance was unsatisfactory according to all three criteria; however, the statistics were just outside the acceptable range in all three cases.

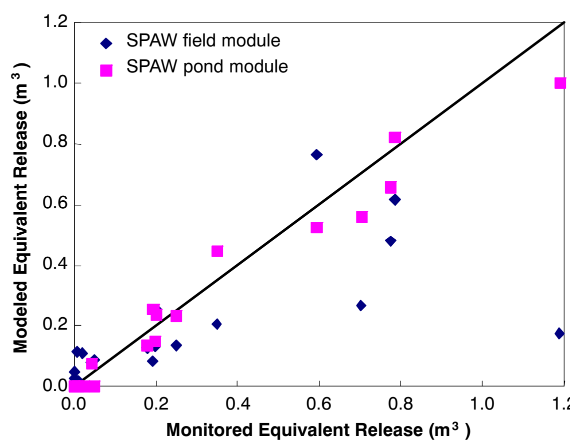

Figure 1. Graphical comparison of the SPAW field and pond module equivalent release volumes to monitored release volumes.

Table 3. Nash-Sutcliffe efficiency (NSE), percent bias (BIAS), and root mean square error to standard deviation ratio (RSR) for annual model performance. Model statistics were calculated based on 18 site-years of data.

Modeling Statistic	Field Module	Pond Module	Ideal Performance
NSE	0.32	0.95	1.00
BIAS	32	8	0
RSR	0.83	0.22	0.00

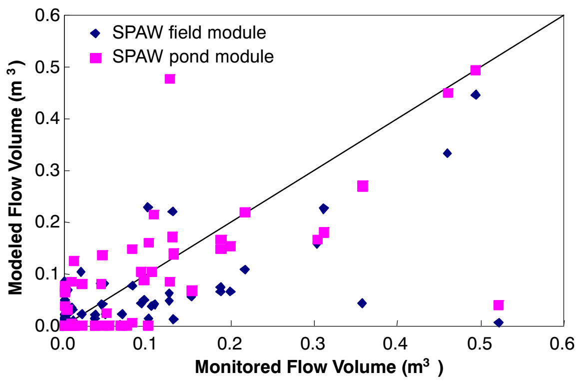

Figure 2. Graphical comparison of the SPAW field and pond module equivalent release volumes to monitored release volumes.

Table 4. Nash-Sutcliffe efficiency (NSE), percent bias (BIAS), and root mean square error to standard deviation ratio (RSR) for monthly model performance. Model statistics were calculated based on 119 site-months of data.[a]

Modeling Statistic	Field Module	Pond Module	Satisfactory
NSE	0.46	**0.52**	>0.50
BIAS	32	**7**	<±25
RSR	0.73	**0.69**	<0.7

[a] Values in **bold** type indicate that models meet criteria for satisfactory performance according to Moriasi et al. (2007).

Table 5. Nash-Sutcliffe efficiency (NSE), percent bias (BIAS), and root mean square error to standard deviation ratio (RSR) for each site based on monthly model performance.[a]

	Field Module			Pond Module		
Site	NSE	BIAS	RSR	NSE	BIAS	RSR
Central Iowa 1	**0.71**	26	**0.54**	**0.69**	**2**	**0.55**
Central Iowa 2	**0.72**	**22**	**0.53**	**0.84**	**6**	**0.40**
Northwest Iowa 1	**0.99**	-42	**0.12**	**0.99**	**25**	**0.07**
Northwest Iowa 2	-0.06	67	1.03	-0.08	**6**	1.04
Southwest Iowa 2	**0.54**	**9**	**0.68**	**0.95**	**25**	**0.21**
Satisfactory	>0.50	<±25	<0.7	>0.5	<±25	<0.7

[a] Values in **bold** type indicate that models meet criteria for satisfactory performance according to Moriasi et al. (2007).

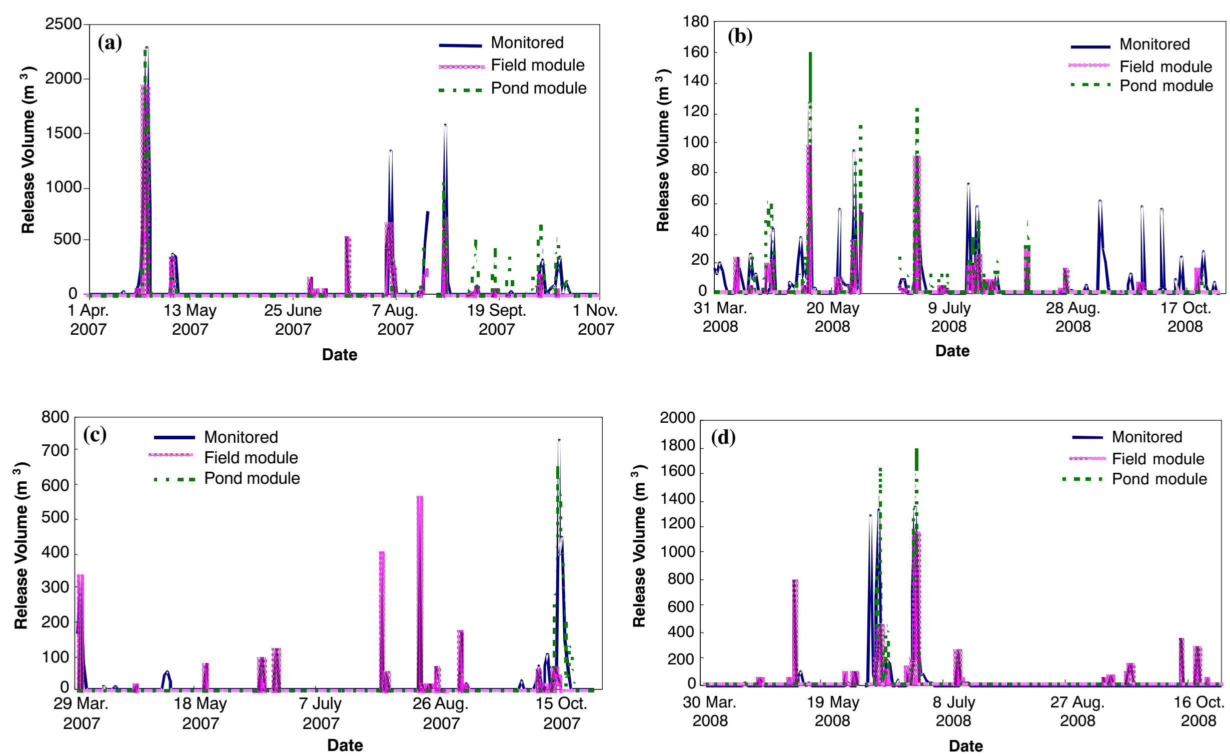

Figure 3. Graphical comparison of monitored and modeled daily performance for (a) Central Iowa 1 in 2007, (b) Central Iowa 2 in 2008, (c) Northwest Iowa 1 in 2007, and (d) Southwest Iowa 2 in 2008.

The monthly data were also evaluated on a site-by-site basis to determine if model results were better for certain sites. Results of this analysis are shown in table 5. The pond module met or exceeded the criteria of Moriasi et al. (2007) for satisfactory model performance for all three categories except for Northwest Iowa 2. The field module also was successful for the NSE and RSR for all sites except Northwest Iowa 2; however, the field module again failed to meet the satisfactory criteria for the BIAS statistic. These data provide a strong indication that SPAW can successfully be used to model VTA hydraulic performance. Moreover, it appears that the pond module was most successful for sites where shallow water tables may restrict VTA performance; however, it may not be sufficient for modeling deep water table locations. Further studies at deep water table locations are needed to verify this conclusion.

Finally, the model was evaluated on a daily basis. Graphical analysis of yearly data sets is shown in figure 3. These graphs are for (a) Central Iowa 1 in 2007, (b) Central Iowa 2 in 2008, (c) Northwest Iowa 1 in 2007, and (d) Southwest Iowa 2 in 2008. In general, both field and pond modules adequately simulated the timing and amounts of runoff that occurred.

Conclusions

The use of the SPAW model, both the pond and the field modules, to predict hydraulic performance of five VTAs was investigated. It was determined that the SPAW field and pond modules both provided reasonable predictions of VTA hydraulic performance; however, the pond module was more effective. The inputs for pond module simulations included water table depth, water table seepage rate, and an approximation of the soil-water retention curve. This allowed calculation of the storage capacity of the soil-water reservoir, the initial amount of water in the reservoir, and the rate at which water was seeping from the reservoir. Inputs for the field module simulations included water table depth, a description of the soil profile (texture and layer thicknesses), and a curve number for the VTA.

Three modeling statistics were used to assess model performance: the Nash-Sutcliffe modeling efficiency (NSE), the percent bias (BIAS), and the ratio of the root mean square error between the simulation and the monitored results divided by the standard deviation of the monitored release (RSR). For the pond module, the NSE, BIAS, and RSR were 0.95, 8%, and 0.69, respectively, on an annual basis. The field module results were 0.32, 32%, and 0.86, respectively. Results were similar when the models were investigated on a monthly basis. Thus, based on this study, it appears that SPAW can successfully model VTA hydraulic performance, specifically for shallow water table locations. Further studies are needed to confirm this conclusion for deep water table locations.

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