EVALUATION OF WEPP FOR RUNOFF AND SEDIMENT YIELD PREDICTION ON NATURAL GAS WELL SITES

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ABSTRACT. *Natural gas exploration and production requires land-disturbing construction activities that have the potential to accelerate soil loss due to land cover modifications, increased slopes, and flow concentration. In the U.S., nearly 30,000 new gas wells are drilled each year. Erosion modeling has been successfully used for decades to predict soil loss and conservation effects on agricultural fields, rangelands, and forests, although much less research has been conducted on the application of erosion models for disturbed construction site conditions. The objective of this research was to evaluate Water Erosion Prediction Project (WEPP) runoff and sediment yield predictions relative to measured data from two natural gas well sites (referred to as GW1 and GW2) in north central Texas. Model parameters were adjusted from WEPP default parameters based on available literature and model observations. A low effective hydraulic conductivity value (0.75 mm h^{-1}) resulted in successful runoff predictions. Agreement between predicted and measured sediment yields was accomplished by increasing rill and interrill erodibility values and decreasing critical shear stress values from default values. WEPP performance was evaluated with the Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE)-observation standard deviation ratio (RSR), and percent bias (PBIAS), as well as modified versions of NSE and RSR that consider uncertainty in measured validation data. For GW1, NSE and RSR evaluation of WEPP performance was considered "good" for runoff (NSE = 0.68 and RSR = 0.56) and "satisfactory" for sediment yield (NSE = 0.63 and RSR = 0.61). For GW2, NSE and RSR values were "very good" for runoff (NSE = 0.76 and RSR = 0.49) but "unsatisfactory" for sediment yield (NSE = 0.32 and RSR = 0.83). Use of modified NSE and RSR to consider measurement uncertainty improved model performance to "very good" for all instances. PBIAS values were relatively low and considered "very good" for GW1 and GW2 runoff and sediment yield predictions. These results demonstrate that WEPP can effectively model runoff and sediment yields from natural gas well sites, thus making it a useful tool for evaluating potential sediment impacts and management alternatives to minimize sediment yields from natural gas well sites.*

Keywords. *Construction site, Gas well, Model calibration and validation, Runoff, Sediment, Storm water, WEPP.*

Sediment is the leading source of water quality impairment for rivers and streams in the U.S. and is the third most ubiquitous source of impairment in U.S. lakes and reservoirs after nutrients and metals (USEPA, 2000). Although the movement of sediment into water bodies is a natural process, its severity can be amplified by land-disturbing construction activities. Toy and Hadley (1987) estimated construction activities had disturbed nearly 1.7% of all U.S. land by 1980. Estimates of annual sediment delivery into U.S. surface waters resulting from construction activities has ranged from 80 million tons (73 million tonnes) (USDOI, 1970) to 5 billion tons (4.5 billion tonnes) (Willett, 1980). Erosion rates from construction have been estimated to be 10 to 100 times the rate of agricultural land use (Goldman et al., 1986), and construction sites are by far the leading source of sediment in developing areas, with sediment yields ranging from a few tonnes to over 1100 tonnes ha^{-1} year^{-1} (USEPA, 2002).

Negative impacts from erosion and sedimentation result when excess sediment is suspended in the water column or deposited in stream channels and lake bottoms. Suspended sediment can reduce in-stream photosynthesis, while nutrients in eroded soils can contribute to algal blooms and lake eutrophication (Goldman et al., 1986). Highly turbid water may result in the loss of sediment-intolerant fish species (Poff and Allen, 1995), dramatically increase water treatment costs (AWWA, 1990), and diminish direct and indirect recreational experiences (Clark et al., 1985). Once deposited, sediment can substantially alter stream ecosystems by smothering benthic communities, reducing fish egg survival rates, reducing channel capacity, exacerbating downstream bank erosion and flooding, and reducing storage in reservoirs (Schueler, 1997). It has been estimated that the cost of physical, chemical, and biological damage from erosion and sedimentation in North America may exceed $16 billion annually (Osterkamp et al., 1998).

Natural gas exploration and production is a land-disturbing activity that requires construction of a well site, access roads, and pipelines. These construction activities have the potential to accelerate soil loss due to land cover modifications, increased slopes, and flow concentration. In

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2006, almost 30,000 natural gas wells were drilled nationwide (API, 2007), which is a substantial number considering that each well site disturbs approximately 1 to 2 ha of land surface. While it is fairly well documented that typical residential and commercial construction activities greatly increase erosion and sedimentation, little is known about erosion and sedimentation from natural gas exploration and production activities. Currently, oil and gas field operations and construction activities are exempt from federal National Pollutant Discharge Elimination System (NPDES) permitting requirements (USEPA, 2006). Since the NPDES requires erosion and sediment control Best Management Practices (BMP) to minimize off-site movement of sediment from construction sites, potential impacts from unregulated oil and gas sites may be a concern for state and local governments responsible for ensuring water quality.

Erosion models have been used for decades to predict soil loss and land management effects from cropland, rangeland, and, to a lesser extent, disturbed site conditions. Two commonly used models for predicting are the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) and Version 2 of the Revised Universal Soil Loss Equation (RUSLE2) (Foster, 2005). WEPP provides a few advantages over RUSLE2, including: (1) the ability to estimate spatial distributions of both soil loss and deposition along a hillslope, (2) an interface to predict runoff and sediment yield from single storm events in addition to annual averages, and (3) the capability of estimating erosion and deposition on hillslopes and small watersheds. For construction sites, the most appropriate erosion prediction models are process-based and maintain both empirical and physical relationships within a physically based structure (Moore et al., 2007). WEPP meets these criteria and has been used for modeling soil loss and sediment yield from disturbed land cover conditions.

Several researchers have evaluated WEPP parameters with measured data from agricultural fields (Liebenow et al., 1990; Risse et al., 1994, 1995a, 1995b; Zhang et al., 1995a, 1995b; Nearing et al., 1996; Zhang et al., 1996; Tiwari et al., 2000; Bhuyan et al., 2002), rangelands (Nearing et al., 1989; Simanton et al., 1991; Wilcox et al., 1992; Savabi et al., 1995), small watersheds (Nearing and Nicks, 1997; Liu et al., 1997), and forests (Morfin et al., 1996; Tysdal et al., 1997; Elliot 2004; Covert et al., 2005; Dun et al., 2006).

In contrast to other land use practices such as agriculture, rangeland, and forest applications, few studies have tested WEPP on land disturbed by construction activities. Lindley et al. (1998) developed algorithms and computer code for the hydraulic portions of the WEPP Surface Impoundment Element (WEPPSIE) to evaluate practices to reduce erosion such as ponds, terraces, and check dams. The WEPPSIE sediment algorithms were verified against data collected on two experimental impoundments consisting of a total of 11 model runs. Laflen et al. (2001) provide recommendations for soil and management parameters for construction site conditions, such as paved surfaces, crushed rock, and erosion mats, but parameters were not verified with measured data. WEPP model predictions were found to be reasonable for three single storm event intensities on research plots for three land use treatments representing construction site conditions (rotary hoed, rolled smooth, and topsoil restored) (Pudasaini, 2004). Recently, Moore et al. (2007) were successful in developing and applying WEPP input parameters for construction and post-construction phases of a commercial construction site on a small 4 ha watershed. Soil and management parameters were tested and adapted based on 37 runoff samples and three sediment samples. Best model efficiencies for runoff and sediment yields resulted from replacing the surface soil horizon characteristics with subsurface horizon characteristics and supplementing the cut slope management parameters with experimental bare soil inputs.

WEPP's ability to model both temporal and spatial distribution of soil loss and deposition provides important model functionality for disturbed site conditions. WEPP can simulate runoff and sediment yields daily, monthly, annually, or by event. The temporal flexibility of the model is important for evaluating management alternatives. Laflen et al. (2001) used WEPP to estimate potential soil loss from a highway construction site for a variety of construction timeline scenarios to determine the critical time of year for severe erosion. The authors found that WEPP was applicable to construction sites in their application, although the model could be improved with some additional modifications including the ability to change materials and topography during the WEPP run. In terms of reducing source loads from disturbed areas, management alternatives may include planning construction to coincide with those seasonal weather cycles that are least likely to generate erosive storm events. Moore et al. (2007) illustrated how modeling periods could also be broken down according to changing site conditions, considering different soil and management characteristics and topography, which may be useful for evaluating sediment yields during various site development phases.

The objective of this study was to evaluate WEPP predictions of runoff and sediment yields relative to measured data from two natural gas well sites in north central Texas. Model results were evaluated with Nash-Sutcliffe efficiency (NSE), percent bias (PBIAS), and the ratio of the root mean square error to the standard deviation of measured data (RSR). Comparison of measured and predicted runoff and sediment yield also included consideration of uncertainty in the measured calibration and validation data.

Materials and Methods

Site Description

Input data for model calibration and validation were collected from two natural gas well sites located in the Grand Prairie physiographic region of north central Texas approximately, at 97.23° N and 33.16° W. Grand Prairie physiography consists of gently sloping grasslands with scattered shrubs, and trees primarily along creek bottoms. Site soil was classified as Medlin stony clay (fine, montmorillonitic, thermic, Vertisols) on slopes of 5% to 12% (USDA-SCS, 1980). This soil type is moderately alkaline and has very low permeability, high runoff potential, and severe erosion potential (USDA-SCS, 1980).

Both gas well sites were constructed on 5% slopes, which required leveling the surface for the gas well pad surface, resulting in site profiles consisting of a cut slope, pad surface, and fill slope that was approximately 100 m in length (fig. 1). The pad surface is relatively flat and is used for drilling activities and equipment storage. The term "cut slope" generally refers to the face of an excavated bank required to lower the ground to a desired profile. In contrast, a "fill slope" refers to a surface created by filling an area with soil. All slopes were

Figure 1. Gas well pad surface (GW1) on modified hillslope.

compacted with a mechanical roller and an all-weather surface of Grade 1 Flex Base was applied to the pad surface. Flex Base is a gravelly aggregate commonly used for temporary roads, base material underneath asphalt and concrete paving, and construction pad caps. The Flex Base surface application was approximately 0.3 m in depth and covered an area approximately 0.5 ha. The soil on the cut and fill slopes covered an area of approximately 0.5 ha and was left exposed after compaction. It is important to note that infiltration rates can be reduced by up to 99% on construction sites compared to predevelopment conditions (Gregory et al., 2006). Site characteristics are described in table 1.

Site Monitoring

Flow-interval (1.0 mm of volumetric runoff depth) storm water samples were collected with ISCO 6712 automated samplers (ISCO, Inc., Lincoln, Neb.). This method is recommended for small watershed sampling according to Harmel et al. (2006a). Samples were taken at a single intake point near the bottom of a partially contracted sharp-crested 90° V-notch weir located at the edge of each pad surface. A barrier was installed along the downslope portion of the pad surface to direct flow through the weir. This sampling design captures runoff from the cut slope and pad surface but does not capture runoff from the fill slope (fig. 1). Flow volume was monitored with ISCO 4250 velocity flowmeters (ISCO, Inc., Lincoln, Neb.) placed 1 m upstream from the outfall of each weir. Rainfall at each site was monitored with an ISCO 674 tipping-bucket rain gauge (ISCO, Inc., Lincoln, Neb.). Both flow and rainfall data were logged at 5 min intervals.

Table 1. Gas well site characteristics.

	Gas Well 1 (GW1)		Gas Well 2 (GW2)	
	Cut Slope	Pad Surface	Cut Slope	Pad Surface
Slope length (m)	34.6	77.4	10.0	79.2
Average slope (%)	9.0	1.5	31.0	0.6
Soil series	Medlin	Custom	Medlin	Custom
Disturbed area (ha)	2.1		1.9	
Sampled area (ha)	0.45		0.36	
Management	Cut slope		Cut slope	
Storm events sampled	12		8	
Sampling period (2006)	2 Feb. to 5 Nov.		20 Mar. to 29 Nov.	

Fifteen storms generated a total of 20 sediment and runoff sampling events at the two sites (table 2).

Total suspended solids (TSS) concentrations were analyzed in collected samples using Standard Method 2540D (APHA, 1992). Because water samples were taken on consistent flow intervals, the arithmetic average of TSS concentrations represents the event mean concentration (EMC). Total storm loads were calculated by multiplying the TSS EMC by the total storm flow.

Model Description

WEPP (v2006.5) is a process-based, distributed parameter, continuous simulation model based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan et al., 1995). Infiltration is calculated using the Green-Ampt-Mein-Larson (GAML) model (Mein and Larson, 1973; Chu, 1978) for unsteady rainfall. Runoff is routed overland using a semi-analytical solution of the kinematic

Table 2. Precipitation parameters for sampling events.

Site	Sampling Date (2006)	Precip. (mm)	Peak Intensity (mm h^{-1})	Storm Duration (h)	Time to Peak (%)
GW1	24 Feb.	48.5	7.0	23.0	40
	20 Mar.	23.1	18.0	3.0	55
	21 Apr.	30.7	9.4	30.0	5
	5 May	21.6	2.9	17.0	18
	6 May	10.4	3.8	4.3	90
	17 June [a]	25.4	24.9	1.1	40
	27 Aug.	14.7	49.0	0.3	60
	29 Aug. [a]	14.2	2.3	12.5	25
	18 Sept.	21.1	8.3	11.0	60
	10 Oct.	21.8	17.5	1.5	5
	15 Oct.	25.4	4.1	10.0	50
	5 Nov.	14.0	13.0	1.1	70
GW2	20 Mar. [a]	23.1	18.0	3.0	55
	21 Apr.	30.7	6.9	30.1	5
	29 Apr.	28.4	14.7	15.0	57
	5 May	19.0	15.0	3.1	23
	6 May	11.4	4.1	5.0	60
	17 June	20.0	15.0	2.0	45
	5 July	17.0	28.3	0.6	40
	29 Nov.	35.8	17.1	9	40

[a] Storm event used for calibration.

Table 3. WEPP input management parameters.

	Cut Slope		Pad Surface	
	Default Input File	Modified Input File	Default Input File	Modified Input File
Darcy Weisbach friction factor	5	1	5	1
Days since last tillage	0	0	0	200
Days since last harvest	0	0	0	2000
Cumulative rainfall since last tillage (mm)	0	1000	0	1000
Initial interrill cover (%)	5	0	5	5
Initial ridge height after last tillage (cm)	1	1	1	2
Initial rill cover (%)	5	0	5	5
Initial roughness after last tillage (cm)	1	1	1	2
Rill spacing (cm)	0	60	0	0

wave model (Stone et al., 1992). WEPP's erosion component uses a steady-state sediment continuity equation that considers both interrill and rill erosion processes. Interrill erosion involves soil detachment and transport by raindrops and shallow sheet flow, while rill erosion processes describe soil detachment, transport, and deposition in rill channels (Flanagan and Nearing, 1995).

Input Parameters

Major inputs for WEPP include climate data, topography, management conditions, and soil attributes. WEPP's stochastic climate generator, CLIGEN (v4.3), uses four precipitation parameters (precipitation, storm duration, peak intensity, and time to peak) to generate a single storm climate file for each event at each site.

Slope profiles for each site were derived from high-resolution digital terrain models created from gas well site surveys. Slope profiles were simplified and entered into the WEPP using the slope editor (table 1).

A management input file for a cut slope surface is available in the WEPP software and was used for the cut slope portion of the site. The WEPP default cut slope management parameters represent limited vegetation growth on a smooth soil surface. For pad surfaces, the initial plant parameters in the cut slope management file were modified to represent a rock surface. The principle characteristics of a rock surface are that it is extremely dense and has an extremely low decomposition rate (Laflen et al., 2001). Prior to model calibration, management file parameters as described above were further modified to represent gas well site conditions. Additional parameters modified in the management file are listed in table 3.

Table 4. Calibration range for soil parameters for the cut slope and pad surface.

	Cut Slope (Medlin)		Pad Surface (Flex Base)	
	Min.	Max.	Min.	Max.
Interrill erodibility K_i (kg sec m^{-4})	5.0×10^5	12.0×10^6	1.0×10^2	1.0×10^7
Rill erodibility Kr (sec m^{-1})	0.002	0.05	1.0×10^{-5}	1.0×10^{-3}
Critical shear stress τ (Pa)	0.03	7.0	10	100
Hydraulic cond. K_{ef} (mm h^{-1})	0.1	2.0	0.1	0.5

Soil parameters for the cut slopes were obtained from WEPP's Medlin soil series input file. Soil information for any soil in the U.S. can be obtained from the USDA-NRCS Soil Survey Geographic database (USDA-NRCS, 2007). For the pad surface soil parameters, a custom soil file was created using parameters suggested by Laflen et al. (2001) for soils underlying crushed rock in construction applications. This type of soil surface yields high runoff values with low soil loss.

Soil Parameter Calibration

Ideal model calibration involves: (1) using data that include a range of conditions (Gan et al., 1997), (2) using multiple evaluation techniques (Legates and McCabe, 1999), and (3) calibrating all constituents to be evaluated (Moriasi et al., 2007). Using a similar approach to Bhuyan et al. (2002), model calibration was conducted using the smallest, middle, and largest sediment yield events over the study period to account for variation in the measured data. Soil parameters sensitive to model response were manually adjusted to bring the predicted runoff and sediment yield values within the range of observed values. Typically, calibration involves sensitivity analyses; however, several researchers (Nearing et al., 1990; Alberts et al., 1995; Bhuyan et al., 2002) have already found that baseline rill and interrill erodibility, effective hydraulic conductivity, and critical shear stress are sensitive model parameters in WEPP. These parameters were adjusted in order of their relative sensitivities to model response, with the most sensitive parameter adjusted first. Both predicted runoff and sediment yield were calibrated with these four parameters. The range of values used for calibration of soil erodibility for cut slopes were kept within suggested limits for cropland (Alberts et al., 1995). For gas well pad surfaces, the range of values was based on literature values for impervious site conditions (Laflen et al., 2001) and values provided in the WEPP management file for a "graveled road surface on clay loam." Ranges of soil parameter values used for calibration are shown in table 4. Default and calibrated WEPP soil parameters are listed in table 5.

Table 5. Default and calibrated WEPP input soil parameters.

Soil Parameter	Soil Texture	Hydrologic Class	Interrill Erodibility K_i (kg sec m^{-4})	Rill Erodibility K_r (sec m^{-1})	Crit. Shear Stress τ (Pa)	Hydraulic Conductivity K_{ef} (mm h^{-1})	Sand (%)	Clay (%)	CEC (meq 100 g^{-1})	Rock (%)
Medlin[a]	Clay loam	C	3.58×10^6	0.0069	3.5	0.73	30	45	39	3
Medlin[b]	Clay loam	C	9.58×10^6	0.03	2.35	0.75	30	45	39	3
Flex Base[a]	n/a	n/a	1.0×10^3	0.0001	100	0.1	10	70	25	90
Flex Base[b]	n/a	n/a	1.0×10^6	0.0001	50	0.1	10	70	25	90

[a] Default soil parameters.
[b] Calibrated soil parameters.

Model Evaluation

Model evaluation techniques for calibration and validation should include at least one dimensionless statistic, one absolute error index statistic, one graphical technique, and other information such as the standard deviation of measured data (Legates and McCabe, 1999). Dimensionless techniques provide model evaluations in relative terms, whereas error indices quantify the differences in units of the data of interest (Legates and McCabe, 1999). Specific model evaluation statistics used in this research were selected based on recommendations according to Moriasi et al. (2007) and included Nash-Sutcliffe efficiency (NSE), root mean square error (RMSE)-observation standard deviation ratio (RSR), and percent bias (PBIAS). The Nash-Sutcliffe model efficiency coefficient (Nash and Sutcliffe, 1970) is expressed in equation 1 as:

$$\text{NSE} = 1 - \left[\frac{\sum_{i=1}^{n} (O_i - P_i)^2}{\sum_{i=1}^{n} (O_i - O)^2} \right] \quad (1)$$

where O_i and P_i are observed and predicted values for the ith pair, and O is the mean of the observed values. NSE ranges from $-\infty$ to 1; a value of 1 indicates a perfect fit between the observed and predicted data. NSE values $\leq$0.5 are considered unsatisfactory (Moriasi et al., 2007), and NSE values $\leq$0 indicate the mean observed value is a better predictor than the simulated values.

Moriasi et al. (2007) developed a model evaluation statistic (RSR) that standardizes RMSE using the standard deviation of the observations. Since the RSR combines the error index and standard deviation, this statistic meets the model evaluation recommends of Legates and McCabe (1999). RSR is the ratio of the RMSE and standard deviation of the measured data, as calculated with equation 2:

$$\text{RSR} = \frac{\text{RMSE}}{\text{STDEV}_{\text{obs}}} = \frac{\left[\sqrt{\sum_{i=1}^{n} (O_i - P_i)^2} \right]}{\left[\sqrt{\sum_{i=1}^{n} (O_i - O)^2} \right]} \quad (2)$$

RSR ranges from 0 to a large positive value. Lower values indicate better model performance, with a value of 0 being optimal. RSR values >0.70 are generally considered unsatisfactory (Moriasi et al., 2007).

PBIAS measures the average tendency of the simulated data derived from the model to be larger or smaller than measured data (Gupta et al., 1999). PBIAS is calculated as shown in equation 3:

$$\text{PBIAS} = \left[\frac{\sum_{i=1}^{n} (O_i - P_i) * (100)}{\sum_{i=1}^{n} (O_i))} \right] \quad (3)$$

Positive values indicate model underestimation bias, and negative values indicate model overestimation bias; a value of zero is optimal and indicates no bias. PBIAS has the ability to clearly indicate model performance (Gupta et al., 1999). PBIAS is generally considered unsatisfactory for runoff if the value is $\geq \pm 25$ and unsatisfactory for sediment if the value is $\geq \pm 55$ (Moriasi et al., 2007).

Measurement Uncertainty

Measurement uncertainty is rarely included in the evaluation of model performance, even though all measured data are inherently uncertain. Harmel and Smith (2007) developed modifications to the deviation term in four goodness-of-fit indicators (NSE, index of agreement, RMSE, and MAE) to improve the evaluation of hydrologic and water quality models based on uncertainty of measured calibration and validation data. Modification 1, which is applicable when the bi-directional probable error range (PER) is known or assumed for each measured data point, was used in this research. Following procedures developed by Harmel et al. (2006b), the PER for runoff and sediment loads was estimated based on the experimental site and data collection methods. For GW1, the PER was ±16% for runoff and ±25% for sediment loads. For GW2, the PER for runoff and sediment loads was ±27% and ±33%, respectively. It is not uncommon for storm water data to consist of partially sampled events, incomplete flow data, or rainfall information obtained from a location other than the sample site, all of which increase measurement uncertainty. Data used in this study, however, were not affected by these issues. These PER estimates are comparable to expected uncertainty from typical sampling scenarios for runoff (±6% to ±19%) and for sediment loads (±7% to ±53%) from Harmel et al. (2006b).

Once estimated, the PER is used in Modification 1 to calculate the upper and lower uncertainty boundary for each measured data point. The uncertainty is assumed to be symmetrical about each measured value and thus bi-directional with equal likelihood of over- and underestimation. If the predicted value is within the uncertainty range, the deviation is set to zero (Harmel and Smith, 2007). For predicted values that lie outside the uncertainty boundaries, the deviation is the difference between the predicted value and the nearest uncertainty boundary; thus Modification 1 minimizes the error estimate for each measured and predicted data pair. In the present study, the Harmel and Smith (2007) modifications were applied to the NSE and RSR goodness-of-fit indicators to consider measurement uncertainty in the evaluation of WEPP performance in calibration and validation.

Results and Discussion

Measured and predicted runoff and sediment yields are shown in table 6. Measured event runoff at GW1 and GW2 ranged from 3.7 to 34.1 mm and from 6.7 to 18.8 mm, respectively. Sediment yield was also greater for GW1, ranging from 51 to 668 kg compared to 53 to 270 kg for GW2. Three storm events were used to calibrate the soil parameters, and the remaining 17 events were used to validate the model. NSE, RSR, and PBIAS, as well as modified versions of NSE and RSR based on Harmel and Smith (2007) that consider measurement uncertainty, were used to evaluate model performance. Model performance ratings were based on guidelines provided by Moriasi et al. (2007). Performance ratings and evaluation statistics are shown in table 7.

Model Calibration

Model parameters were adjusted (parameters and ranges shown in table 4) for the calibration set until model evaluation statistics for both runoff and sediment yield were “satisfactory” or better based on Moriasi et al. (2007) for all

Table 6. Measured and predicted runoff and sediment yield.

Site	Sampling Date (2006)	Runoff (mm) Meas.	Runoff (mm) Pred.	Sediment Yield (kg) Meas.	Sediment Yield (kg) Pred.
GW1	24 Feb.	34.1	28.5	311	190
	20 Mar.	15.0	14.8	500	677
	21 Apr.	12.4	16.3	219	468
	5 May	13.1	13.4	588	590
	6 May	6.0	4.3	84	16
	17 June [a]	13.7	19.5	668	982
	27 Aug.	9.0	8.2	482	508
	29 Aug. [a]	3.7	4.8	51	8
	18 Sept.	13.2	10.6	389	420
	10 Oct.	20.8	14.6	619	650
	15 Oct.	21.4	13.4	109	148
	5 Nov.	12.2	6.8	272	324
GW2	20 Mar. [a]	14.6	14.9	230	271
	21 Apr.	14.7	15.5	54	38
	29 Apr.	17.5	16.4	270	242
	5 May	11.4	10.6	171	54
	6 May	6.9	4.2	56	9
	17 June	13.6	12.7	267	169
	5 July	6.7	10.2	196	275
	29 Nov.	18.8	26.2	247	459

[a] Storm event used for calibration.

evaluation statistics (NSE > 0.50, RSR < 0.70, PBIAS for runoff $\leq \pm$ 25, PBIAS for sediment $\leq \pm$55). Initially, default soil parameter values predicted runoff values in the range of measured values, but predicted sediment yields were substantially lower than measured values. Using default parameters, initial NSE values for runoff and sediment yields were 0.48 and –1.27, respectively, and RSR values for runoff and sediment yields were 0.72 and 1.51, respectively. In order to meet "satisfactory" model performance for sediment yields, interrill and rill erodibility values were increased and critical shear stress was decreased from default Medlin soil parameters. Similarly, interrill erodibility was increased and critical shear stress was decreased from the Flex Base soil parameters (table 3). These changes resulted in higher predicted sediment yields compared to default Medlin and Flex Base soil parameters. Calibrated hydraulic conductivity values for both the Medlin soil and Flex Base were similar to default values. NSE for the calibrated parameters for runoff was similar to the default parameters at 0.52, but NSE improved substantially for sediment yield to 0.49. The RSR for the calibrated parameters for runoff was similar to the default parameters and was 0.70. The RSR for the calibrated parameters improved to 0.72. Improvements in NSE and RSR for sediment yields illustrate the importance of model calibration for land use practices that have not been previously evaluated, parameterized, and validated with the model. While NSE of 0.49 and RSR of 0.72 fell just below the range of "satisfactory" model performance, when the model was evaluated according to the uncertainty limits of the measured data, modified NSE and RSR for runoff and sediment yield performance ratings increased to "very good." PBIAS values indicated that the calibrated model parameters overpredicted both runoff (–23%) and sediment yield (–24%), but model performance was "satisfactory." Model calibration results are illustrated graphically in figures 2a and 2b.

Model Validation

Calibrated model parameters were applied to validation data for GW1 and GW2 separately. Runoff model performance was better for GW2 than for GW1, while sediment yield model performance was better for GW1 than for GW2. Model performance for GW1 was considered "good" with NSE and RSR values of 0.68 and 0.56 for runoff and 0.63 and 0.61 for sediment yield, respectively. Considering measurement uncertainty, Modification 1 resulted in "very good" performance ratings for NSE and RSR. Graphical results were in agreement with the statistical results (figs. 2c and 2d). A general visual agreement between measured and predicted data indicates adequate model performance over the range of constituents being simulated (Singh et al., 2004). PBIAS performance ratings were "good" for runoff and "very good" for sediment yield, with values of 15% and –11%, respectively, that indicate slight underprediction for runoff and slight overprediction for sediment yield.

For GW2, model predictions were "very good" for runoff (NSE = 0.76 and RSR = 0.49) but "unsatisfactory" for sediment yield (NSE = 0.32 and RSR = 0.83). However, Modification 1 improved NSE and RSR performance ratings from "unsatisfactory" to "very good." Graphical results are shown in figures 2e and 2f and were in agreement with the statistical results. Runoff PBIAS estimates were "very good" for runoff (–2%) and "good" for sediment yield (16%). In contrast to GW1, the model underpredicted sediment yield.

Consideration of uncertainty in the measured data provides a realistic evaluation of model performance. If the model is judged solely on its ability to produce values similar to the measured data, instead of values within the uncertainty limits of the measured data, then the model may be assumed to be precise but may not be accurately reproducing actual

Table 7. Evaluation statistics and performance ratings.

	NSE				RSR				PBIAS	
	NSE	Performance Rating[a]	Mod. NSE	Performance Rating[a]	RSR	Performance Rating[a]	Mod. RSR	Performance Rating[a]	PBIAS	Performance Rating[a]
Calibration runoff	0.52	Satisfactory	0.81	Very good	0.70	Satisfactory	0.43	Very good	-23	Satisfactory
Calibration sediment yield	0.49	Unsatisfactory	0.89	Very good	0.72	Unsatisfactory	0.34	Very good	-24	Satisfactory
GW1 runoff	0.68	Good	0.90	Very good	0.56	Good	0.28	Very good	15	Good
GW1 sediment yield	0.63	Satisfactory	0.86	Very good	0.61	Satisfactory	0.38	Very good	-11	Very good
GW2 runoff	0.76	Very good	0.99	Very good	0.49	Very good	0.12	Very good	-2	Very good
GW2 sediment yield	0.32	Unsatisfactory	0.86	Very good	0.83	Unsatisfactory	0.38	Very good	16	Good

[a] Value ranges for performance ratings were provided by Moriasi et al. (2007).

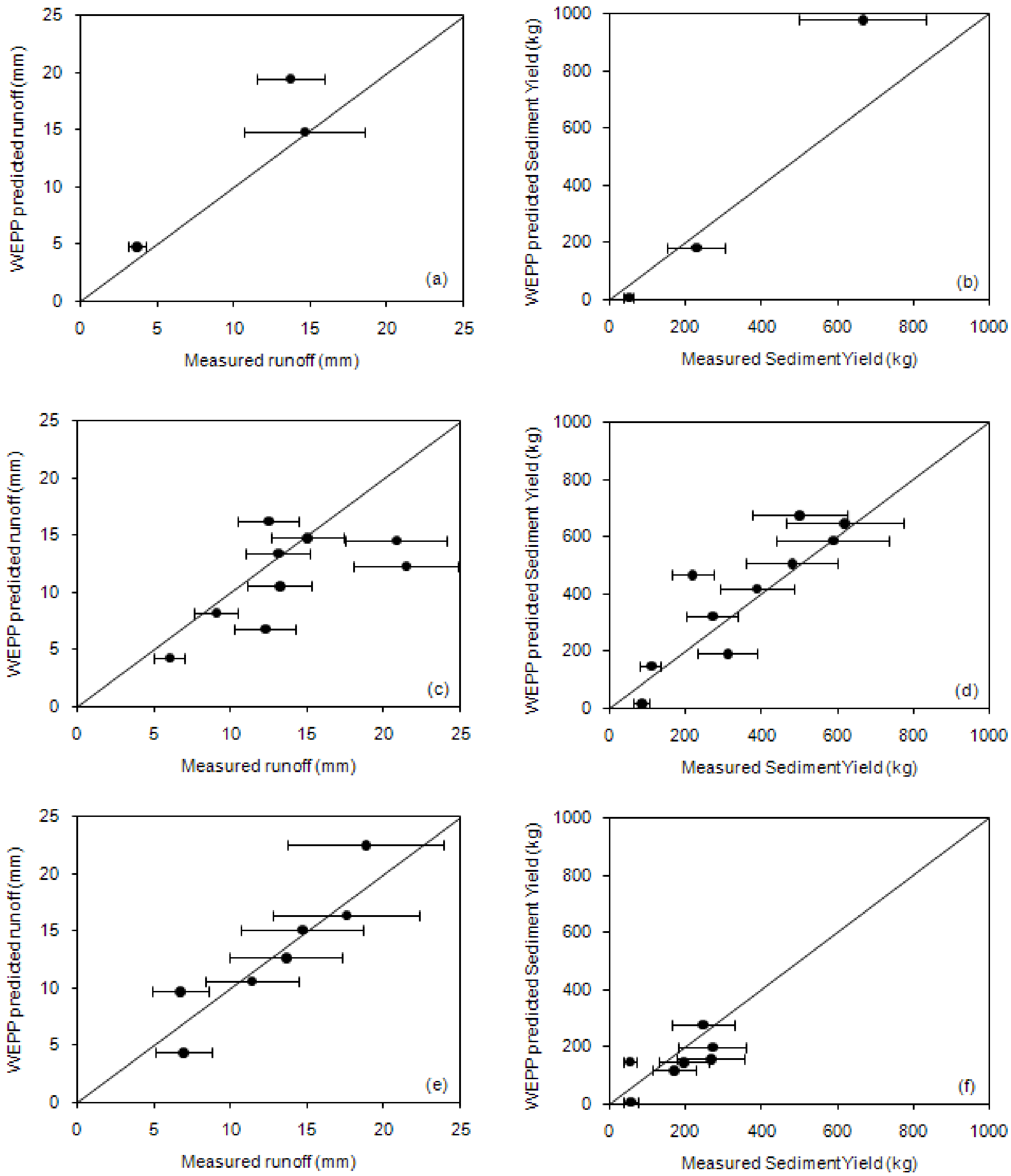

Figure 2. Scatterplots of measured and predicted runoff (mm) and sediment yield (kg) modified with Modification 1 to include the uncertainty range (PER) for each measured value: (a) calibrated runoff (PER = ±16%, ±27%); (b) calibrated sediment yield (PER = ±25%, ±33%); (c) GW1 runoff (PER = ±16%); (d) GW1 sediment yield (PER = ±25%); (e) GW2 runoff (PER = ±27%); and (f) GW2 sediment yield (PER = ±33%).

hydrological and water quality conditions (Harmel et al., 2006b). However, when measurement uncertainty is considered in model evaluation, it is important to estimate uncertainty appropriately without consideration of perceived deficiency for relatively high uncertainty estimates and without attempts to improve assessed model performance with inflated measurement uncertainty.

Model evaluation in this research demonstrates the improvement in assessed model performance that results from the consideration of measurement uncertainty. For runoff, all of the model evaluation statistics and graphical methods indicated "good" to "very good" performance of the calibrated model. For sediment load, the model evaluation statistics and graphical method produced mixed results from "unsatisfactory" to "very good." This mixed result confirms the importance of utilizing multiple evaluation methods to assess overall model performance, as noted by Legates and McCabe (1999) and Moriasi et al. (2007). It is also important to note that (1) the assessment of "very good" model performance when measurement uncertainty was included indicates that simulated results were generally within the uncertainty boundaries of measured data and that (2) the statistics modified to consider measurement uncertainty provide valuable, supplemental information to be used in conjunction with traditionally applied statistical and graphical methods for model evaluation.

Minor differences in GW1 and GW2 evaluation statistics and model performance could be due to numerous factors, including constantly changing micro-topography, slight differences in site construction practices, and the relatively small data set used to calibrate and validate the model. From event to event, runoff and erosion are constantly changing the micro-topography of the site by filling and creating sinks. While this phenomenon occurs to some extent at all scales, the relative effect on sediment yield at a small scale is potentially much greater than effects at larger scales. However, on relatively flat, highly modified surfaces, changing micro-topography is difficult to characterize from event to event. While construction practices are similar from site to site, minor differences in grading, filling, and compaction of the surface all have the potential to affect infiltration and soil erodibility properties. Finally, evaluation statistics used in calibration and validation are sensitive to small sampling populations, although it should be noted that a small number of samples are not uncommon in model evaluations since storm water monitoring is resource intensive.

While there were some minor differences in runoff and sediment yields between sites, the predicted detachment and deposition patterns were similar. The majority of soil losses occur on the cut slopes at both sites. Maximum soil detachment was 51 kg m^{-2} at 27.7 m downslope for GW1 and 104 kg m^{-2} at 8.95 m downslope for GW2. Maximum deposition occurred at the base of both cut slopes and was 20.5 kg m^{-2} at 45.1 m downslope for GW1 and 188 kg m^{-2} at 12.3 m downslope for GW2. Pad surface soil detachment exceeded deposition at both sites but contributed only a small portion to overall sediment yields.

Application of WEPP to Gas Well Sites

In our opinion, the approaches used in this research worked well, and modifying default management files and calibrating default soil parameters is recommended for gas well sites due to their unique characteristics. For these sites, interrill and rill erodibility parameter values were higher than default values and critical shear stress was lower than the default values. One limitation of the study included the technique for modifying land management parameters. Because the parameters for land management files were not calibrated, we can only suggest that the cut slope and pad surface parameters used in this research are appropriate for natural gas well sites based on successful modeling results and professional judgment. Ultimately, the methodology proved to be useful because it was learned that WEPP could effectively model runoff and sediment from natural gas well sites using a small sample population of single storm events.

Event-based simulations allow for calibration and validation of WEPP using a relatively small amount of data, as illustrated in this research, compared to the data required to calibrate erosion models that estimate soil losses on an annual basis. Calibration and validation provides credibility to the model results that may not otherwise exist, which is particularly important when source assessments, load allocations, and management decisions are determined for specific site conditions. However, once the model has been calibrated and validated, WEPP should be run in continuous simulation to obtain an annual average. Annual averages determined from continuous simulation are more accurate because, unlike single storm predictions, continuous simulation can account for the complex overlap of temporal and spatial variability of both the driving force of erosion (i.e., rainfall) and the resisting force of the environment (i.e., erodibility) (Nearing, 2006).

Because sediment yields are commonly reported in annual terms, running the model in continuous simulation to obtain an annual average provides sediment yield predictions that can be compared to other studies. When calibrated gas well parameters were run in continuous simulation, annual predicted sediment yields from GW1 and GW2 were 38.0 and 20.9 t ha^{-1} $year^{-1}$. Wolman and Schick (1967) conducted one of the first studies that attempted to measure annual yields from construction sites. Using measured sediment concentrations and rainfall-flow relationships, sediment yields from two sites were estimated at 253 and 491 t ha^{-1} $year^{-1}$.Based on two years of monitoring, Daniel et al. (1979) reported that average sediment yield from three construction sites was 17.5 t ha^{-1} $year^{-1}$. In another two-year study, sediment yields at three residential construction sites ranged from 39 to 90 t ha^{-1} $year^{-1}$ (Madison et al., 1979). More recently, USGS (2000) sampled runoff from the edge of two small construction sites, one residential (0.14 ha) and one commercial (0.70 ha). Sediment yields for the commercial and residential sites based on one year of data were 7.6 and 1.8 t ha^{-1} $year^{-1}$, respectively. A comparison of predicted annual sediment yields from gas well sites provided in this study to sediment yields reported in previous construction site studies suggests that, in terms of sediment yields, natural gas well sites are similar to construction sites.

Finally, the spatial component of erosion is important for designing the most effective erosion control practices and for targeting the most erodible areas of a hillslope. WEPP Hillslope contains erosion control management practices that are applicable to disturbed areas, including seeding and filter strips, and WEPPSIE has a suite of sediment control practices including terraces, check dams, filter fences, and straw bales. Other erosion control practices not specifically parameterized by default values in the model can be simulated according to specific runoff characteristics. For example, Laflen et al. (2001) explain how the effects of an erosion mat can be mimicked by altering model defaults for plant growth and the critical shear value of soil.

Conclusion

In this study, WEPP runoff and sediment yield predictions were compared to measured data for two natural gas well sites located in north central Texas. Model predictions were evaluated with graphical methods and NSE, RSR, and PBIAS statistics. Model predictions were also evaluated using modified versions of NSE and RSR that account for uncertainty in measured calibration and validation data. WEPP soil parameters were calibrated according to suggested parameters from the WEPP manual, model observations, and previous research. During the calibration process, rill and interrill erodibility, critical shear stress, and hydraulic conductivity were adjusted until predicted runoff and sediment yield values were “satisfactory.” The calibration process resulted in rill and interrill erodibility parameters that were higher than default soil parameters and critical shear values that were lower that default values.

The calibrated model produced “good” to “very good” results for runoff and “unsatisfactory” to “very good” results for sediment yield. These results confirm the importance of utilizing multiple evaluation methods, both statistical and graphical, to assess overall model performance. The measurement uncertainty for the model validation data was estimated to be ±16% and ±27% for runoff and ±25% and ±33% for sediment yields, which is comparable to expected uncertainty from typical sampling scenarios. When measurement uncertainty was included in model evaluation, predictions were "very good" for both runoff and sediment yield. This alternative method, which compares predictions with uncertainty boundaries rather than single, inherently uncertain measured values, provides valuable supplementary information for model evaluation.

Additional monitoring of runoff and sediment yields for the same sites, additional sites located in different regions, and on different soil types and topographies would improve the evaluation of WEPP for natural gas well sites. However, since monitoring is expensive and site conditions may change substantially over time, we recommend that future erosion and runoff research related to gas well sites be conducted on research plots with rainfall simulation using methodologies similar to those that were used in previous WEPP calibration and validation studies.

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