Technical Note

Evaluating *SEDCAD* Model Performance on Reclaimed Coal Mine Lands in East Tennessee

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Abstract: The *Sediment, Erosion, Discharge by Computer Aided Design* (*SEDCAD*) program is extensively used in the mining industry for engineering site layout plans with best management practices (BMPs) for erosion control. Although *SEDCAD* is the primary BMP design tool used in this industry, very limited published information is available on its performance estimating site runoff and sediment yields. This study compared sediment yields from three surface coal mining sites in east Tennessee with *SEDCAD* modeled outputs. Study sites included active mining operations on steep slopes (>20°) where after mining, approximate natural hillslope contours were reconstructed by using loose spoil materials on top of slope, at shallow depths of 1–2 m, following the Forest Reclamation Approach. The *SEDCAD* model inputs included the site-derived hydrologic curve number (CN) of 59 and average erodibility K factors ranging from 0.001–0.034 $\mathrm{Mg \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}}$ varying on the basis of pre- and postrill development periods and mining site. The *SEDCAD* overestimated sediment yields as a function of erosivity (R) up to 1.6 times greater than the minimally measured yields in two of the three study sites. A sensitivity analysis of input parameters found CN selection can greatly affect modeled outputs for sediment yield. For example, a 40% deviation in selecting a CN would double the computed sediment yield. Results from this study provide design engineers using *SEDCAD* a better understanding of the uncertainty with model outputs to improve selection and design of erosion BMPs on surface coal mining sites. **DOI: 10.1061/(ASCE)IR.1943-4774.0000540.**

CE Database subject headings: Sediment; Runoff; Hydrology; Coal mining; Tennessee; Land reclamation.

Author keywords: Sediment yield models; *Sediment, Erosion, Discharge by Computer Aided Design* (*SEDCAD*) program; Revised universal soil loss equation (RUSLE); Erodibility; Surface coal mining reclamation; Erosion control; Runoff hydrology.

Introduction

In the surface coal mining industry, the *Sediment, Erosion, Discharge by Computer Aided Design (SEDCAD)* program is extensively used for developing engineered plans with best management practices (BMPs) for erosion control [U.S. Department of the Interior (USDOI 2010)]. As required by the Surface Mining Control and Reclamation Act of 1977 (SMCRA), mining permit applications consist of site layout designs that embrace reclamation practices where back-to-contour spoil placement approximates natural slopes. In addition to slope reclamation, BMPs for erosion control are designed into layout plans to minimize environmental impacts from probable hydrological consequences. Mining and consulting engineers submit *SEDCAD* program outputs with their mining permits, and outputs are reviewed by regulatory authorities. The U.S. Office of Surface Mining (OSM) provides *SEDCAD* software and training through their Technical Innovation and Professional Services (TIPS) program to 24 states with primacy under SMCRA, in which it is used for permit review and remediation project design at bond forfeitures and abandoned mine lands sites. Although *SEDCAD* is the primary BMP design tool used in this industry, very limited published information is available on its performance estimating site runoff and sediment yields.

The *SEDCAD* is an event-based distributed hydrology model using CN rainfall-runoff relationships and integrates runoff routing with the revised universal soil loss equation (RUSLE) to estimate sediment yields (Warner et al. 1998). It was developed at the University of Kentucky, Lexington, and now maintained by Civil Software Design©, Ames, Iowa. Specifically, *SEDCAD* evaluates: (1) hydrologic capacity of a system of drainage channels and hydraulic and sediment control structures; (2) channel stability for designs using riprap and grassy vegetation; and (3) effectiveness of sediment control structures, i.e., detention ponds, check dams, grassy swales, and silt fences, with respect to sediment trap efficiency and effluent sediment concentration prediction.

The OSM is currently promoting Forest Reclamation Approach (FRA) at surface coal mining sites because traditional reclamation methods relied on heavily compacted spoils to achieve a more stable slope with a low erosion potential, commonly resulting in poor forest establishment caused by difficulties in tree root penetration (Angel et al. 2006; Taylor et al. 2009). Swiegard et al. (2007) describes grading practices under the FRA on steep slopes where spoils are compacted for slope stability in terraced layers following the natural topography and surface finished with 1–2 m of a loose spoils and top soil with minimal grading. Low-compacted loose spoils and top soils enhance tree growth. Natural slopes in the Appalachian coal region can exceed 20° and commonly are in the order of 30–35°, and loose spoils are more prone to erosion (Hoomehr et al. 2012a, b). Before this study, application of FRA on steep slopes had not been assessed in hydrological and erodibility conditions and whether *SEDCAD* can be applied to such conditions.

The study objective was to evaluate *SEDCAD* performance predicting runoff and sediment yield by comparing model outputs

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with measured values at surface coal mining sites that have applied FRA. In addition, a sensitivity analysis was conducted for *SEDCAD*'s hydrologic CN and erodibility K factor input parameters. Understanding confidence ranges with *SEDCAD* model predictions is important so that BMPs can adequately protect surface waters from sediment impairment, whereas in the Appalachian Coal Region more than 600,000 ha have been surface mined and currently about 10,000 ha are mined each year (Zipper et al. 2011).

Methods and Material

Study Design

To compare measured versus model estimates for runoff and sediment yield, three active coal mining sites north of the city of Knoxville in east Tennessee were selected for study (Fig. 1; Table 1). Named according to mining company ownership, the three sites were (1) *Premium*, located in Anderson County at N 36° 6′ 36″, W 84° 19′ 30″; (2) *National*, located in Campbell County at N 36° 30′ 30″, W 84° 16′ 12″; and (3) *Mountainside*, located in Claiborne County at N 36° 31′ 30″, W 83° 57′ 23″. In general, mine spoils consisted of silty-clay soils mixed with larger gray shale and brown sandstone rocks. The spoil materials at all three sites were classified by the Unified Soil Classification System (USCS) and were found to be gravel with significant clay fines (GC). The spoil materials were a mix of shales and sandstones. Average % rock (gravel) defined as coarser than 25.4 mm: Premium: 24.8%, National: 24.6%, and Mountainside: 11%. Average % gravimetric water content was measured as: Premium: 15%, National: 9.7%, and Mountainside: 7.9% (Table 2). The average plot slope in National was 20.25°, in Premium 28.5°, and in Mountainside was 27.8°. Specific CN and K factor values were generated for these sites over a 14-month monitoring period from May 2009 through July 2010, the period in which re-contoured slopes were essentially devoid of vegetation (Hoomehr et al. 2010, 2012a, b). Rill development was most active during the first three months of this period. The K factors, used as inputs for the *SEDCAD* model, included a range of 0.01–0.034 $Mg \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ for a 3-month period with rapid rill development and a K factor range of 0.001–0.004 $Mg \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ for an 11-month postrill development period, varying on the basis of mine site. To meet the study objectives, the following tasks were conducted:

1. Rainfall depths, basin hydrology (CN), and erodibility (K) parameters on the basis of the site monitoring data were entered as *SEDCAD* inputs; other hydrologic and RUSLE model input parameters were estimated by using standard methodologies (Warner et al. 1998), or they were automatically computed in *SEDCAD*;
2. The *SEDCAD* modeling was performed for two periods, during rill development (May, June, and July 2009) and postrill development (August 2009 through July 2010). At each period and for each study site, sediment yields were computed for a series of model runs by varying rainfall depths to get erosivity values (R) from *SEDCAD* that matched the range of observed R values. Sediment yields grouped by R classes (>548, 548, 480, 286, and <129 $MJ \cdot mm \cdot h^{-1} \cdot ha^{-1}$) and measured sediment yields within each R class were averaged to compare measured and modeled yields with similar erosivities. R classes were chosen on the basis of the resolution of erosivity values that *SEDCAD* automatically computes and reports on the basis of the rainfall input data; and
3. The *SEDCAD* model output, sediment yield, was assessed for its sensitivity to CN and RUSLE K factor input values. To do this, the estimated values of these two parameters, estimated by using the monitored data, were used as a baseline for input parameters, and then, any change in model outputs based on deviation from this baseline was recorded.

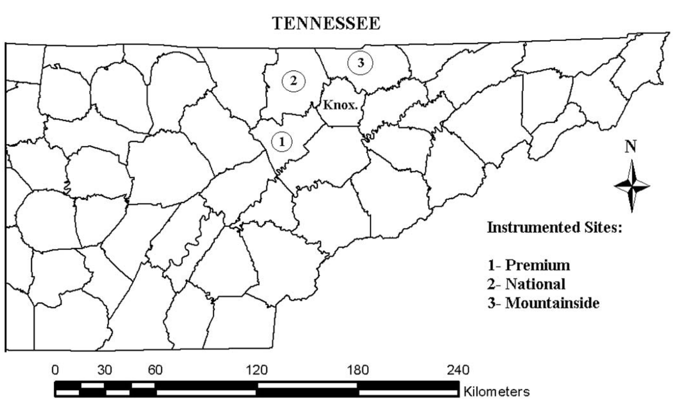


Fig. 1. Location of three study sites in east Tennessee at active coal mining operations for Premium (Anderson County), National (Campbell County), and Mountainside (Claiborne County)

Table 2. Average Percentage Rock (Gravel) and Average Percentage Gravimetric Water Content for National, Premium, and Mountainside Study Sites

Study site	Average % rock (gravel)[a]	Average % gravimetric water content
National	24.6	9.7
Premium	24.8	15
Mountainside	11	7.9

[a]Average % rock (gravel) defined as coarser than 25.4 mm.

Table 1. *SEDCAD* Input Values for Erodibility (K) Factor, Length–Slope Factor, CN, Average Slope Steepness and Length for National, Premium, and Mountainside Study Sites and Basin Area

Study site	KLS[a,b]	CN	Average slope length (m)	Average slope (°)	Area (m^2)
Mountainside	0.2 0.02	59	45.4	27.8	1,054
Premium	0.07 0.02	59	32.15	28.5	850
National	0.32 0.04	59	48.35	20.3	1,156

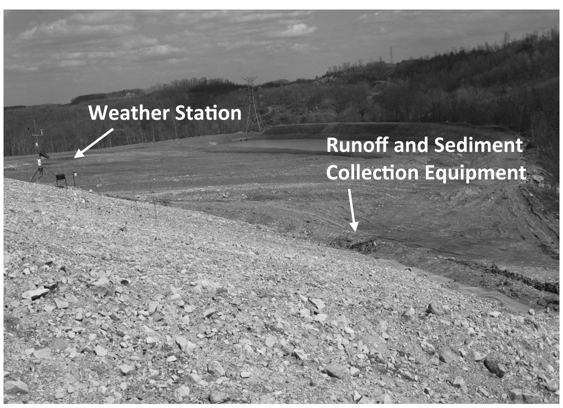
[a]K unit is Mg.ha.h.(ha MJ mm)$^{-1}$; for National and Mountainside avg. K factor of both sites were used for simulation in Fig. 4. LS is length-slope factor which is unit less.
[b]Top value: prerill development; bottom value: postrill development value.

Site Monitoring for Runoff and Sediment Yield

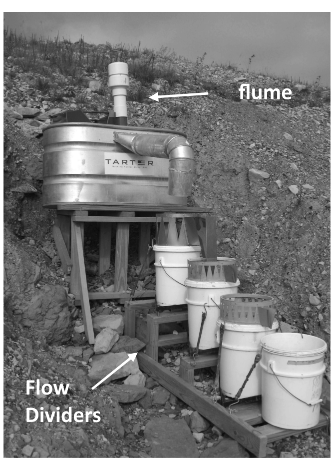
Premium, National, and Mountainside study sites consisted of four plots with earthen berms and rubber-mat chevrons directing runoff and eroded sediment to 0.23-m(3/4 ft) standard USDA H-type flumes (Fig. 2). Downstream of each H-flume, runoff was directed into a pre-sedimentation tank and then into a collection system of 18.9-L (5 gal) flow divider buckets (Fig. 3). Flow divider buckets were constructed on the basis of Pinson et al. (2004), which are a system that allows simultaneous measurement of runoff volumes and sediment yields. Study sites were also equipped with full weather stations. Hoomehr et al. (2012a, b) provide a detailed descriptions of the field equipment used to measure rainfall, runoff volumes, sediment yields, and data analyses for determining estimates of CN and *K* specific to FRA mining sites.

SEDCAD Model Setup

To estimate sediment yields at a designated catchment outlet, *SEDCAD* input parameters include: catchment size, slope length and gradient, channel slope and roughness, storm frequency, catchment hydrology, erodibility, and type of control practices (Warner et al. 1998). The catchment area used in modeling was the average of four field plots per study site (Table 1). The NRCS Storm Type II with 241 point distribution was used for this study. The design storm frequency (years) and duration (h) was chosen by setting rainfall depth and hyetograph duration equal to observed values for the range observed during site monitoring.



(a)



(b)

Fig. 2. National study site showing (a) a catchment plot with weather station and a runoff and sediment collection equipment; (b) H flume, course sediment trap, Pinson et al. (2004) runoff and sediment flow dividers, and 5-gal collection buckets

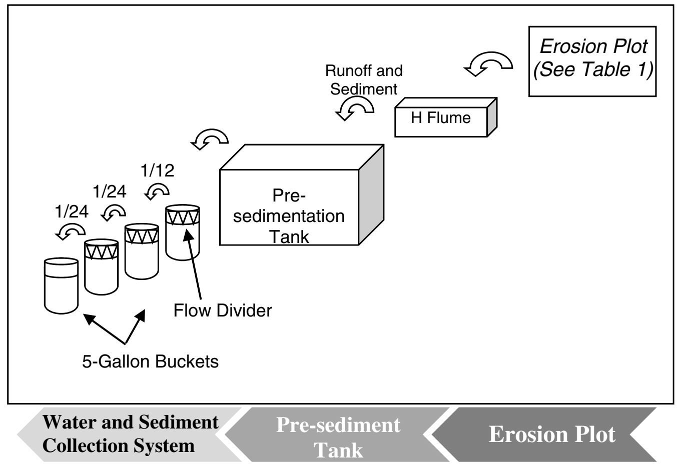


Fig. 3. Schematic of the runoff and sediment collection equipment used at each of the four plots per study site

Catchment Hydrology

Runoff volume and peak flow are calculated by the curve number methodology by using the Soil Conservation Service TR-55 Emulator. The *SEDCAD* is event based and limited to the production of a 50-h hydrograph, which is sufficient for small catchments less than 100 ha. The hydrology module in *SEDCAD* requires the following parameters: CN, time of concentration, and selection of a dimensionless unit hydrograph shape. A CN of 59 was used for the *SEDCAD* model input to test performance (Table 1). Hoomehr et al. (2012a) estimated CN values between 58.5 and 60 for low-compaction, steep-sloped reclaimed surfaces by using the asymptotic method proposed by Hawkins (1993). The asymptotic method recombines rainfall and runoff data based on the frequency matching to back-calculate CN values, in which the frequency matching method is based on equating return periods of rainfall and runoff events. The asymptotic method assumes that when the data do not show a constant CN, but a trend toward steady state is recognizable, that trend can be extended to a constant value by using asymptotic least squares fitting. Differences between mean CN values of three study sites were not statistically significant. Although the authors could not find a standard CN used by mining engineers for low-compacted spoils on steep slopes, SEDCAD program's manual recommends a CN range of 70–90, in which the model user selects a value on the basis of the professional judgment. The SECAD assumes an initial abstraction coefficient of 0.20 ($\lambda = 0.20$) and calculates time of concentration by using the input values for land cover, slope steepness, and length of catchment. For this study the nearly bare and untilled condition was selected from the list of default Land Flow Conditions within *SEDCAD*. Average slope steepness and plot length for the four plots per study site were used as input values (Table 1). The selected dimensionless unit hydrograph shape was fast hydrograph response.

Soil Erodibility

SEDCAD estimates sediment yields from surface erosion using RUSLE by

$$A = R \cdot K \cdot \mathrm{LS} \cdot C \cdot P \qquad (1)$$

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where A = amount of soil loss or yield (kg/m^2); R = rainfall and runoff erosivity factor; K = soil erodibility factor, which is a soil loss rate per erosivity index unit for a specified soil as measured on a standard plot (22.13 m length and 9% slope) under annual tilled management conditions; LS = combined length-slope factor; C = cover management factor; and P = erosion control practice factor (Wischmeier and Smith 1978; SWCS 1993). The *SEDCAD* automatically calculates rainfall-runoff erosivity factor (R) on the basis of the hydrological inputs. The R factors were also computed from measured precipitation data, in which they ranged between 10.09–986.2 MJ · mm · (ha · h)$^{-1}$ (Hoomehr et al. 2012b). The average K-factor for the pre- and postrill development periods were used per site as input values for *SEDCAD*. Average K factors were ranging from 0.001–0.034 Mg · ha · h · ha^{-1} · MJ^{-1} · mm^{-1}, varying on the basis of pre- and postrill development periods and mining site. The model computes LS factors on the basis of tabulated values in the USDA Agricultural Handbook Number 703 (Renard et al. 1997). The LS factor for National was 9.5, for Premium was 9.27, and for Mountainside was 11.5. The value for KLC factors and slope length and steepness are reported per site in Table 1. Because there was no vegetative cover on the study plots and no erosion control practices, C and P were equal to 1 in the *SEDCAD* model.

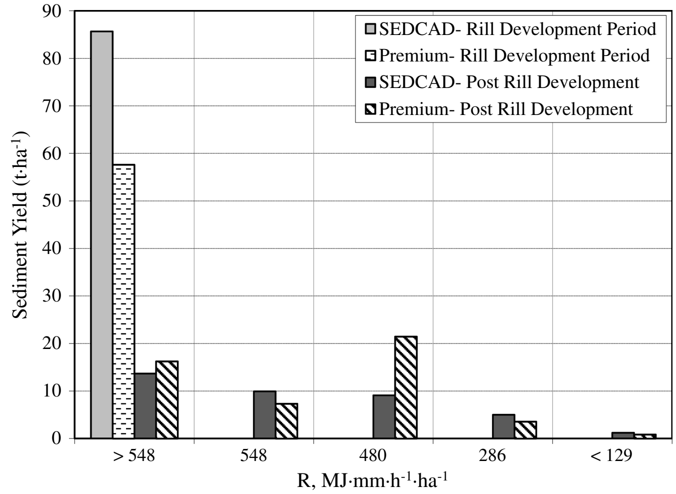

Fig. 5. Sediment yields in t · ha^{-1} from measured amounts at Premium study site and *SEDCAD* calculated amounts, grouped by erosivity (R) classes: >548, 548, 480, 286, and <129 MJ · mm · h^{-1} · ha^{-1}; the *SEDCAD* simulation and comparison was made for pre- and postrill development period

Results and Discussion

There were a total of 54 sampling events for all three sites. Cumulative rainfall depths between two sampling events ranged from 14.6–242.6 mm. The median cumulative rainfall was 60 mm, 25% quantile for cumulative rainfalls was 39 mm, and 75% quantile was 101 mm. The cumulative rainfall durations between two sampling events varied between 3.6–104.4 h. On the basis of condition-specific CN and K factors developed in Hoomehr et al. (2012a, b) for low-compacted steep-sloped reclaimed surface mining sites, sediment yields generated by *SEDCAD* increased with increase in erosivity relative to measured yields (Figs. 4 and 5). Generally, *SEDCAD* tended to overestimate sediment yields compared with measured estimates, except for the National site and especially during rill development period. Measured sediment yields varied greatly among the three study sites. For example, within the 548 MJ · mm · h^{-1} · ha^{-1} R class and the postrill development period, sediment yields at the National site were 3% more than the *SEDCAD* estimate, whereas at the Premium and Mountainside sites it was 35% less and 60% less than what *SEDCAD* estimated, respectively. Although the K factors used in the *SEDCAD* model runs included the effect of rill development on erodibility, the variability of measured sediment yields among the three study sites was likely caused by various factors influencing rill development and stabilization (Yao et al. 2008; Zhang et al. 2009; Berger et al. 2010). The factors include spoil bulk density and % surface exposed large rock, soil moisture, and hydraulic roughness. Because the *SEDCAD* uses RUSLE equation to estimate erosion (Equation 1), the relationship between erosion rate and erodibility is linear; therefore, selection of the K factor affects computed sediment yields linearly, and percent differences between computed and measured are directly proportional.

Traditionally, the K factor would be constant per soil type and standard RUSLE unit plot conditions, and the C factor would be adjusted (Barfield et al. 1988; Haan et al. 1994). However, in the mining industry, K has been used to reflect site erodibility before the establishment of vegetative cover (Mcintosh and Barnhisel 1993; Toy et al. 1999). Hoomehr et al. (2012b) observed

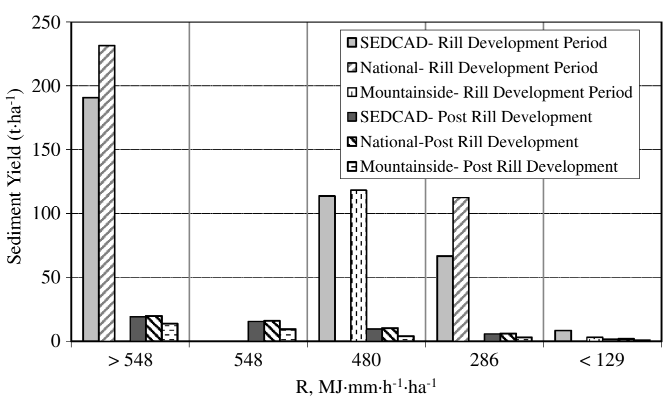

Fig. 4. Sediment yields in t · ha^{-1} from measured amounts at National and Mountainside study sites and *SEDCAD* calculated amounts, grouped by erosivity (R) classes: >548, 548, 480, 286, and <129 MJ · mm · h^{-1} · ha^{-1}; the *SEDCAD* simulation and comparison was made for pre- and postrill development period

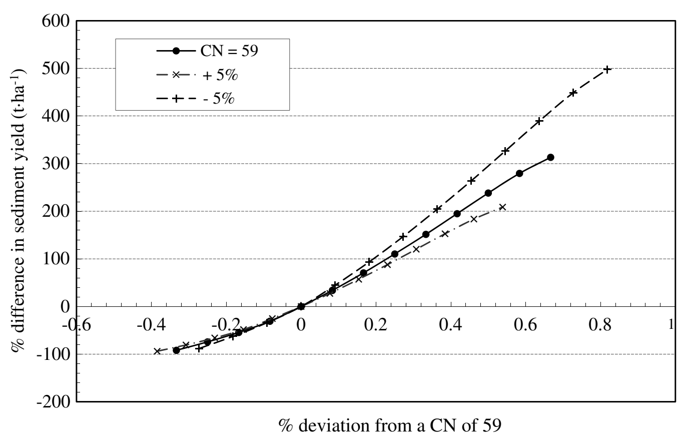

Fig. 6. Percent difference in amount of estimated sediment yields (t · ha^{-1}) relative to a percent deviation in CN selection from the measured estimate of 59 for loose compaction spoils on reclaimed surface coal mining sites (this figure relates to Table 3)

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Table 3. Percent Difference in Estimated Sediment Yields from the *SEDCAD* Model Relative to CN Selection Deviating from an Average Estimate of 59

		CN deviation			% Difference in sediment yields		
CN	Yield t/ha	CN = 59[a]	+5%[b]	−5%[c]	CN = 59[a]	+5%[b]	−5%[c]
40	1.1	−0.33	−0.38	−0.27	−0.92	−0.94	−0.88
45	3.5	−0.25	−0.31	−0.18	−0.74	−0.81	−0.63
50	6.2	−0.17	−0.23	−0.09	−0.54	−0.66	−0.34
55	9.4	−0.08	−0.15	0.00	−0.31	−0.48	0.00
59	13.6	0.00	−0.08	0.09	0.00	−0.25	0.45
65	18.2	0.08	0.00	0.18	0.34	0.00	0.94
70	23.2	0.17	0.08	0.27	0.71	0.27	1.47
75	28.6	0.25	0.15	0.36	1.10	0.57	2.04
80	34.2	0.33	0.23	0.45	1.51	0.88	2.64
85	40.1	0.42	0.31	0.55	1.95	1.20	3.27
90	46	0.50	0.38	0.64	2.38	1.53	3.89
95	51.6	0.58	0.46	0.73	2.79	1.84	4.49
100	56.2	0.67	0.54	0.82	3.13	2.09	4.98

[a]The CN of 59 was estimated from site measurements using the asymptotic method (Hoomehr et al. 2012a).
[b]+5% increase in estimating value of CN from 59.
[c]−5% increase in estimating value of CN from 59.

erodibility reduced over a 14-month period from a period of rill development to rill stabilization, in which K reduced from about 0.034–0.001 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$. In this SECAD model study, the 14-month monitoring period was divided into pre- and postrill development periods. In each period, average erodibility reflected the measured K factor reduction, and because the *SEDCAD* uses those average values, sediment yield outputs did reflect that reduction phenomenon.

Sensitivity of CN selection on sediment yields computed from *SEDCAD* was investigated by using a CN of 59; deviations from this CN were used in this analysis. A CN of 59 is the best estimate for the surface mining reclamation sites consisting of loose spoils on steep slopes (Hoomehr et al. 2012a). The percent change in sediment yield, computed by *SEDCAD*, caused by departure from a CN of 59 was estimated, and results are shown in Fig. 6. The *SEDCAD* appears to be sensitive to CN selection, in which moderate changes in CN selection generate large changes in sediment yield. For example, a 40% deviation in CN will double the computed sediment yield. To examine the level of uncertainty for CN selection, complimentary curves for ±5% confidence intervals are also shown in Fig. 6. Table 3 summarizes values used to construct Fig. 6. The range in CN selection was determined by considering the range of CN values obtained from monitoring study sites and the *SEDCAD* ability to reflect that change in its outputs.

Conclusions

The *SEDCAD* predicted sediment yield from hillslope erosion within ranges commonly observed from sediment models, although *SEDCAD* underestimated the sediment yields from two sites during rill development period and did tend to overestimate sediment yields up to 1.6 times greater than the minimally measured yields as a function of erosivity for the postrill development period. This finding is based on mining site conditions that utilized FRA on low-compacted spoils and steep slopes, where hydrology and erodibility factors were derived from field studies as a CN of 59, a K of 0.01–0.034 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ during rill development, and a K of 0.001–0.004 $t \cdot ha \cdot h \cdot ha^{-1} \cdot MJ^{-1} \cdot mm^{-1}$ for the post rill development period (Hoomehr et al. 2012a, b). This study illustrated the importance of selecting CN and K factors that reflect specific mining site conditions. Reasonable estimates of sediment yield from *SEDCAD* were found to be relatively sensitive to CN selection. This study did not assess *SEDCAD* performance with respect to channel sediment transport and sediment basin settling routines. As an outcome of this study, *SEDCAD* users are provided useful information to aid in interpreting model outputs for the design of runoff and sediment control structures on reclaimed surface mining sites. However, the derived CN, K, and R values were specific to east Tennessee, and further regional studies are needed to generate a range of values as *SEDCAD* inputs to be applicable across the Appalachian coal mining area.

Acknowledgments

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