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Purpose, development, and synthesis of the Soil Vulnerability Index for inherent vulnerability classification of cropland soils

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Abstract: The Soil Vulnerability Index (SVI) was developed by the USDA Natural Resources Conservation Service (NRCS) to classify inherent vulnerability of cropland soils based on field sediment and nutrient transport resulting from surface runoff and leaching. The primary purpose of the SVI is to aid conservation planners in more rapidly assessing managed lands and inherent resource concerns. The index is based on hydrologic soil group, slope, and soil erodibility for cultivated cropland soils, with the addition of percentage rock fragments and organic matter when considering leaching. Although the SVI is intended for use throughout the United States, its development was based on the physiographic and rainfall characteristics of the Upper Mississippi and Ohio-Tennessee River basins. The purpose of this study was to evaluate the SVI in areas both in and outside of the area for which it was developed. Thirteen different watersheds were selected to conduct this evaluation. Vulnerability classifications using the SVI were compared with those from on-site experts' knowledge and with model simulations using local data. Four companion papers in this special collection discuss SVI classification based on the effects of land slope, artificial drainage, sediment and nutrient loads, and vulnerability assessment using hydrologic simulation models. Using results from the various sites, the objective of this paper was to synthesize the interpretation of the value and applicability of SVI vulnerability classification to sediment and nutrient loss across various physiographic regions and suggest where improvement in the SVI could be made.

Key words: erosion—leaching—sediment—Soil Vulnerability Index—targeting—threshold

The need to limit soil erosion and improve water quality is fundamental to successful long-term crop management and protection of the environment. Following the Dust Bowl crisis of the 1930s, the US government took an active role in developing improved soil conservation practices (Baveye et al. 2011). Recent attention has expanded to include reducing agricultural pollution. Yet despite significant investment in conservation programs over many years, research indicates that reduction in nonpoint source (NPS) pollution is often beneficial at the field scale (Jokela et al. 2004; Sharpley et al. 2006; Nangia et al. 2010; Douglas-Mankin et al. 2010), but watershed-scale improvements have been more challenging (Park et al. 1994; Inamdar et al. 2002; Chaubey et al. 2010; Tomer and Locke 2011). Many factors can contribute to this difficulty of having or detecting impact at the watershed scale (Meals et al. 2012), but one of the most likely is the need to better target comprehensive conservation planning for improved management in those areas that contribute the majority of NPS pollution. In cases where planning was done at the watershed scale (enabling targeting of conservation practices to respective source areas of constituents and flow paths), it has been possible to attribute stream water quality improvement to conservation practice implementation (Osmond et al. 2012; Lizotte et al. 2017). This indicates that with appropriate levels of conservation implementation targeted to those most vulnerable areas, the potential exists for greater improvements of water quality at the watershed scale.

Although models using geographic information systems (GIS) platforms, such as the Soil and Water Assessment Tool (SWAT) (Arnold et al. 2012), can be used to identify these vulnerable areas, the complexity, data requirements, and required areal distribution often make such models prohibitive for use at the state, county, or local resource management level (Chan et al. 2017). An alternative to this more complicated approach is the application of appropriate indices. Examples of successful application of indices can be found in the improved procedures for targeting buffer placement and the topographic wetness index (TWI). The former has successfully been used to assess buffer placement at the field scale (Dosskey et al. 2011), and the latter to identify areas in a watershed where saturation excess is likely to occur (Beven and Kirkby 1979).

The Soil Vulnerability Index (SVI) was developed by the USDA Natural Resources Conservation Service (NRCS) as part of the Conservation Effects Assessment Project (CEAP) cropland modeling effort that began in 2009. The CEAP Cropland modeling team and the Resource Assessment Division (RAD) GIS laboratory translated key findings on soil vulnerability from the CEAP modeling effort and applied them to the NRCS soils (SSURGO) geospatial database. The goal of the index is to rank respective cropland areas nationwide on their inherent potential vulnerability to surface runoff leading to soil erosion and nutrient transport, and leaching leading to the movement of dissolved nutrients, particularly nitrates (NO_3). Its purpose is to serve as an interpretive tool designed to guide management and conservation for planning purposes at the field level, as well as aggregating results

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to support agency landscape planning, and to prioritize conservation efforts in watersheds or regions. The SVI has been used to target specific landscapes in a number of agency landscape "initiatives" such as the Mississippi River basin, the Chesapeake Bay, and the Great Lakes.

The SVI makes use of map units from the USDA detailed soil survey (SSURGO/gSSURGO). This has the advantage of being robust and readily available, but resolution and consistency of detail may be better in some regions than in others. Structure of the SVI system was to be similar to the NRCS Land Capability Class and to be locally relevant such that soils ranked as low would be less prone to runoff than those classified in the moderate class. The final ranking criteria could then be applied to classify all cropland soils within the United States. Because a single set of criteria was developed, it is possible that some soil vulnerability potentials may not be as well represented in every region (USDA NRCS 2012a). For example, for planning purposes within a field, the relative differences of the SVI are the most critical, e.g., which soils are most prone to runoff or leaching. However, in regional applications the relative differences in SVI classification due to overall landscape and soil property combinations may be insufficient to characterize vulnerability differences. Also, priority areas are likely more easily identified where a range of soil properties and slopes exist compared to more uniform properties. Differences in rainfall intensity and annual rainfall distribution may also influence characterization across regions. Therefore, to better evaluate the usefulness of the SVI over a larger representative range in conditions, a study was conducted to examine the usefulness of employing the SVI in watersheds selected from the CEAP Watershed Assessment Studies (CEAP WAS). This national network of sites spans diverse physiographic and hydrogeomorphic regions in the United States (Duriancik et al. 2008). Scientists who work in these watersheds have the data and watershed process understanding necessary to evaluate the characterizations of the SVI.

The objective of this study was to synthesize the interpretation of the value and applicability of SVI vulnerability classification to sediment and nutrient loss across various physiographic regions and suggest where limitations or improvements in its use could be made. The results presented are in conjunction with results from companion studies that include the following: (1) effect of slope and digital elevation model (DEM) resolution on the usefulness of the SVI as a tool for evaluating vulnerability of sediment and nutrient loss within fields and watersheds at the regional scale (Lohani et al. 2020a); (2) effect of artificial drainage on SVI vulnerability assessment (Baffaut et al. 2020); (3) relationship between nutrient loadings and the fraction of watershed in each vulnerability class (Lohani et al. 2020b); (4) comparison of the SVI runoff classification with aerial images and long-term land use histories (Yasarer et al. 2020); and (5) SVI results compared to sediment-yield estimates generated with the Annualized Agricultural Non-Point Source pollution model (AnnAGNPS) (Yasarer et al. 2020; Yuan et al. 2008).

Development of the SVI

A subset of the National Resources Inventory (NRI) cultivated cropland sites was selected for the enumeration of the CEAP Farmer Survey. As part of the CEAP Cropland component modeling effort based on the detailed farmer survey, the effects of farming and conservation on cultivated cropland were evaluated using the Agricultural Policy Environmental eXtender (APEX) field-scale model to simulate sediment and nutrient losses resulting from surface runoff and infiltration from crop fields (USDA NRCS 2012a). The survey and modeling were restricted to cultivated cropland, therefore the SVI utilizes the National Agricultural Statistics Service (NASS)-cultivated cropland data layer (CDL) to isolate land use, which was particularly useful during the planning stages with individual farmers. The detailed data on farming practices, crop rotations, and conservation treatments collected at these sites were used as input data in the APEX modeling.

The baseline scenario was for no conservation practice, which typically represents high amounts of tillage and low remaining residue. All points that represented minimum tillage or no-tillage systems had tillage added to make them conventional in the development modeling scenarios. The no practice option was generally considered to apply a minimum of 1.8 times more nitrogen (N) than what was removed by crops. In practice, the excess N ranged by major basin, therefore the 1.8 value represents the weighted average for all areas where the N application rate was at least 1.4 times more than removed by crops. No N adjustment was made for legumes unless the farmer had added starter fertilizer, such as might be the case if legumes were used as a waste management practice for dairies. Excess nutrient enrichment was not assumed in the baseline to avoid overproduction of biomass that would subsequently impact runoff and alter or possibly mask improvements from other best management practices (BMPs). Phosphorus (P) application rate was based on the no practice rules published in each basin report such that it was not a limiting growth factor. Based on the results of over 5,200 unique APEX simulation runs from farmer surveys for the previously described cropland sites, a vulnerability classification was ultimately assigned to rank areas as low-, moderate-, moderately high-, and high-risk priority. An additional category was added in areas where insufficient information was available to facilitate SVI classification (e.g., water bodies, miscellaneous land areas, missing data, etc.).

Principal component analyses of simulated sediment and nutrient losses were conducted to determine the most relevant soil properties. Final SVI classification was deemed acceptable if there was at least 75% match between classification based on APEX output and that based on the soil properties. Three significant driving factors were identified as being most important (listed in descending order of importance): hydrologic soil group (A, B, C, and D), slope categories, and soil erodibility (Revised Universal Soil Loss Equation [RUSLE] K-factor). These same properties were identified for contaminant leaching, plus the coarse fragment content, the presence of artificial drainage, and classification of the soil as organic. As a further step to ensure the correct properties were selected, stepwise regression was also applied to the respective data set, and these same three driving factors were identified as being most significant.

Thresholds for vulnerability of sediment and nutrient transport by runoff were determined as follows. For sediment transport, the lower threshold of 4.5 Mg ha^{-1} (2 tn ac^{-1}; conversion factor of 2.24 Mg ha^{-1} = 1 tn ac^{-1}) of sediment loss limit was found to represent about 70% of the area under all conditions, including during years with high precipitation (USDA NRCS 2012a). This was accepted as the upper limit for the low vulnerability classification (e.g., if a soil with no conservation lost less than 4.5 Mg ha^{-1} [2 tn ac^{-1}], its vulnerability was classified as low). Similarly, if a soil with no conservation lost more than 18 Mg ha^{-1} (8 tn ac^{-1}), its vulnerability was classified as high. The scientific basis for this selection was from calibrated APEX simulations for the NRI points classified as Highly Erodible Land (HEL) as determined by NRCS technical guides (USDA NRCS 2012b). Up to 90% of these HEL points had sediment loss greater than 18 Mg ha^{-1} when no conservation was present. The range between the low and high vulnerability thresholds was then equally divided at 11.2 Mg ha^{-1} (5 tn ac^{-1}) for the other two classes of moderate and moderately high vulnerability. Thus, low vulnerability was for sediment loss less than 4.5 Mg ha^{-1}, moderate between 4.5 and 11.2 Mg ha^{-1}, moderately high between 11.2 and 18 Mg ha^{-1}, and high for greater than 18 Mg ha^{-1}.

Thresholds for leaching were examined by considering both the percolation volume and the NO_3-N in percolation. The initial decision was to focus on NO_3-N to account for the nutrient exchange complex. This approach was opposite to the runoff results considered for sediment transport (i.e., low sediment loss due to high infiltration would be considered high vulnerability to leaching) to observe what threshold values for leaching could be gathered from the distribution. Therefore, conditions that enhanced infiltration would be considered as high vulnerability for leaching (i.e., hydrologic soil group A and soil loss less than 4.5 Mg ha^{-1} [2 tn ac^{-1}]). However, modeled N-rates were too variable to be reliable even in the no practice scenario. This was especially true for areas with lower N-need crops, such as cotton (*Gossypium hirsutum* L.) compared to corn (*Zea mays* L.), or hay/pasture in rotation with crops. Therefore, the decision was made to simply use the percolation volume as an indicator of potential leaching and classify that volume directly instead of relying on the runoff classification. Starting with the high vulnerability classification, it was observed that 75% of the NRI points with hydrologic soil group A (coarse textured soils considered to highly leach) with slopes less than 2% had more than 200 mm (7.8 in) of annual percolation. Nearly half of the remaining 25% of soils had hay in their rotation with rotations of three or more years, and therefore, were not a part of the CEAP population. In addition, 200 mm was approximately 25% of the average annual rainfall for the Upper Mississippi, Ohio, and Tennessee region. Thus 200 mm was selected as the logical upper threshold for high vulnerability.

The bottom leaching threshold was determined by examining the conditions for which there was very little leaching, i.e., hydrologic soil group D soils (moderately fine and fine textured). Although not a requirement, many of these soils had greater than 35% clay in the surface layer. No restriction was made due to slope, the logic being that if the field is flat and low leaching exists, then the classification is definitely low. Under these conditions, 85% of the areas had annual percolation less than 50 mm (2 in), and 75% less than 30 mm (1.2 in). The 50 mm value was selected because it is a quarter of the high threshold, similar to the case with soil loss. Again, the midpoint splits the range between the low and high vulnerability to define the other two classes: moderate and moderately high vulnerability. Thus low vulnerability was defined by simulated average annual percolation less than 50 mm, moderate between 50 and 125 mm (4.9 in), moderately high between 125 and 200 mm (7.8 in), and high greater than 200 mm.

Using these assigned thresholds for sediment and percolation, a recursive partitioning procedure was implemented to develop the slope and soil erodibility K-factor breaks within each hydrologic soil group. JMP (version 8.0) statistical software suite (SAS Institute, Cary, North Carolina) was used to develop the primary breaks, with professional judgement applied in selecting the final breaks. The 80th percentile was used as a measure with which a property value threshold was decided. For example, using recursive partitioning, a threshold value for the K-factor was where 80% of those points met the respective sediment loss criteria. For 4.5 Mg ha^{-1} (2 tn ac^{-1}), this resulted in a K-factor less than 0.28. This was repeated for each successive sediment loss value (i.e., 11.2 Mg ha^{-1} [5 tn ac^{-1}], 18 Mg ha^{-1} [8 tn ac^{-1}], and greater than 18 Mg ha^{-1}) to decide the respective K-factor for each vulnerability classification. Slope thresholds were selected for each vulnerability classification in a similar fashion.

The respective criteria of hydrologic soil group, slope, and K-factor for assigning vulnerability classifications of soil runoff potential are shown in table 1. Similar criteria for vulnerability classification for leaching potential are shown in table 2 with the following additional considerations. The vulnerability of organic soils was increased to account for the need for drainage and the fact that oxidation of soil organic matter can potentially release large amounts of N resulting in a higher risk for contributing excessive

Table 1

Soil Vulnerability Index (SVI) criteria for surface runoff vulnerability (adapted from USDA NRCS [2012a]).

	Hydrologic soil group*			
Soil runoff potential	**A**	**B**	**C**	**D**
Low	All area	Slope < 4	Slope < 2	Slope < 2; K-factor† < 0.28
Moderate	None	4 ≤ slope ≤ 6; K-factor < 0.32	2 ≤ slope ≤ 6; K-factor < 0.28	Slope < 2; K-factor ≥ 0.28
Moderately high	None	4 ≤ slope ≤ 6; K-factor ≥ 0.32	2 ≤ slope ≤ 6; K-factor ≥ 0.28	2 ≤ slope ≤ 4
High	None	Slope > 6	Slope > 6	Slope > 4

Note: All slopes measured as percentage.

*Hydrologic soil groups are classified as follows: Group A = sand, loamy sand, or sandy loam soils that have low runoff potential and high infiltration rates even when thoroughly wetted. Group B = silt loam or loam soils that have moderate infiltration rates when thoroughly wetted. Group C = sandy clay loam soils that have low infiltration rates when thoroughly wetted. Group D = clay loam, silty clay loam, sandy clay, silty clay, or clay soils that have very low infiltration rates when thoroughly wetted.

†K-factor refers to the soil erodibility factor (K) found in the Revised Universal Soil Loss Equation. It is a relative index of susceptibility of bare, cultivated soil to particle detachment and transport by rainfall. It is determined by the composition of the soil, saturated hydraulic conductivity, and soil structure.

Table 2
Soil Vulnerability Index (SVI) criteria for leaching vulnerability (adapted from USDA NRCS [2012a]).

Soil leaching potential*†	Hydrologic soil group A	B	C	D
Low	None	None	None	All except organic soils
Moderate	None	Slope ≤ 12 and K-factor‡ ≥ 0.24 or slope > 12	All except organic soils	None
Moderately high	Slope > 12	3 ≤ slope ≤12 and K-factor < 0.24	None	None
High	Slope ≤ 12 or soils classified as organic soils	Slope < 3 and K-factor < 0.24 or soils classified as organic soils	Soils classified as organic soils	Soils classified as organic soils

Note: All slopes measured as percentage.

*Coarse fragments (stones and rocks) in the soil make it easier for water to infiltrate rather than run off. If the coarse fragment content of the soil is greater than 30% by weight, the soil leaching potential is increased two levels (moderate and moderately high increased to high, and low increased to moderately high). If the coarse fragment content is greater than 10% but less than 30%, the soil leaching potential is increased one level.

†Artificial drainage of any kind increases leaching potential by two classes (moderate and moderately high increase to high, and low increase to moderately high).

‡K-factor refers to the soil erodibility factor (K) found in the Revised Universal Soil Loss Equation. It is a relative index of susceptibility of bare, cultivated soil to particle detachment and transport by rainfall. It is determined by the composition of the soil, saturated hydraulic conductivity, and soil structure.

N to streams. Soils were considered organic based on the SSURGO/gSSURGO soil taxonomy definition for Histosols and Histic surface epipedons, typically the A horizon.

In the case of drained soils, the opportunities to filter leachate are greatly reduced, and there are very few ways to trap these losses, so an adjustment to the vulnerability classification was needed. Since many of the hydrologic soil groups are increased one to two classes when artificial drainage is present, an adjustment of two vulnerability classifications for the SVI was used without distinction to either the type (surface or subsurface) or density of the drainage. However, this same adjustment was not applied to soil runoff potential to encourage edge-of-field practices that protect the outlet ditch banks and the runoff protection needed during heavy rain events if outlets are submerged.

Validation Site Descriptions

As previously noted, validation sites were selected to more thoroughly evaluate the differing scales and use of the SVI. For example, at the field scale, conservation planning is provided for an individual farmer, thus relative differences in runoff and leaching are stressed as much as the SVI classification differences. For larger areas, adoption of effective conservation practices are focused on the larger farming community, targeting needed financial and expertise support. In view of these applications, 13 CEAP WAS sites representing different physiographic regions were selected to validate the SVI. The selected sites represent differences in size, topography (i.e., slope), variation in hydrologic soil groups and soil erodibility K-factor, drainage requirements for crop production, presence of streams, and ranges in precipitation. Characteristics of these sites are listed in table 3. Note that sites varied from 1.6 km^2 (0.6 mi^2) to more than 4,100 km^2 (1,580 mi^2). A map of the respective sites across the continental United States is shown in figure 1. Watershed data for the selected sites are discussed below, presented in alphabetical order as they appear in table 3.

Beasley Lake. Beasley Lake is a 6.25 km^2 (2.41 mi^2) oxbow lake watershed in west-central Mississippi, with no contributing streams. The watershed is adjacent but isolated from the Sunflower River. Land use is predominantly row crop, with approximately 14% of the watershed converted to Conservation Reserve Program (CRP, USDA Farm Service Agency [FSA]) in 2003 (Lizotte et al. 2017). Nearly two-thirds of the watershed is in hydrologic soil group D, with nearly another third in group C. There are small amounts of group B, but no group A soils. Slope is very flat in most fields and drainage consists primarily of ditches to transfer water from fields to the oxbow lake. All land area drains into the lake with an outlet pipe draining into the Sunflower River. More than half of the watershed has K-factor erodibility greater than 0.32, and most of the remaining soils have erodibility less than 0.24.

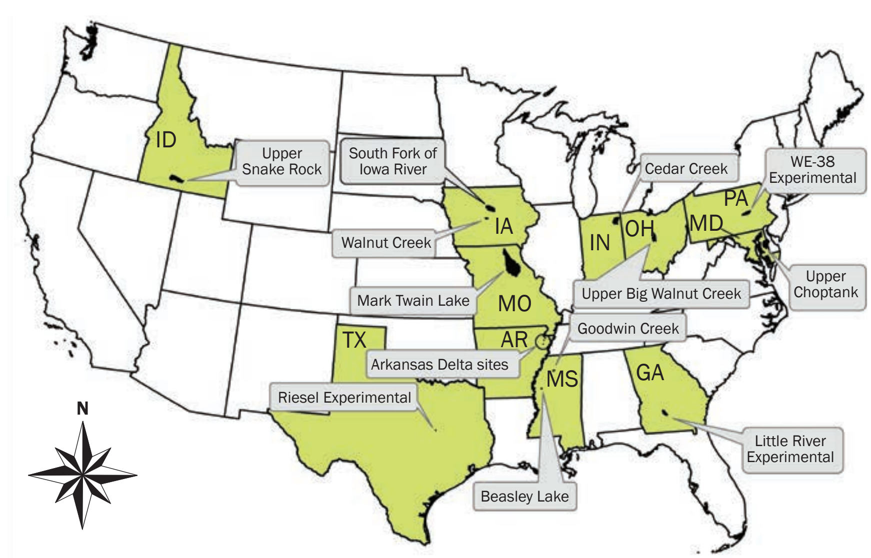
Cedar Creek. The Cedar Creek watershed lies within the St. Joseph River basin in northeast Indiana. It covers an area of 710 km^2 (274.1 mi^2). Most of the land use is row crop, with additional areas of pasture and forest (Smith et al. 2008). Much of the watershed consists of slow permeability soils and small closed depressions or potholes scattered throughout the landscape. Closed depressions and poorly drained fields are often too wet to farm and require the use of artificial drainage to remove excess water during the growing season. The watershed is extensively tiled, and more than 80% of agricultural fields are poorly drained soils that have artificial subsurface drains (Moorman et al. 2015). Over 80% of the watershed is in hydrologic soil group D, 10% in group C, and the remainder equally split between groups A and B. Nearly two-thirds of the watershed has less than 4% slope, but there are areas with slopes greater than 6%. The largest portion of the watershed has a K-factor erodibility greater than 0.32, with much of the remainder between 0.28 and 0.32.

Delta Water Management Research Center. The Delta Water Management Research Center watershed is near Jonesboro, in northeast Arkansas. The watershed includes the Little River Ditches basin in Mississippi County and the Lower St. Francis Basin in Poinsett County. These basins are primarily agricultural, with cropping systems that include rice (*Oryza sativa* L.), corn, and cotton. Sediment and nutrient loads are the major environmental concerns (Aryal and Reba 2017). Study field areas range in size from 7.3 to 30 km^2 (2.8 to 11.6 mi^2). The watershed includes six different fields: Caraway, Leachville, Manilla, Burdette Zero Grade, Burdette Precision Level, and Marked Tree. Soils are primarily in hydrologic group D, with some in group C, and a small amount in group A. The topography is relatively flat, with slopes less than 2%, and some areas less than 0.5%. A small number of fields in the region have been laser leveled to facilitate surface irrigation. All fields

Table 3
Summary of watershed data of the 13 selected sites used for Soil Vulnerability Index (SVI) evaluation.

Site no.	Watershed	Location	Area (km²)	Hydrologic soil group	Slope (%)	K-factor	Description
1	Beasley Lake	Mississippi	6	Mostly D and some C	Mostly flat	Mostly >0.32 or <0.24	Lower Mississippi River basin; presence of artificial surface drainage.
2	Cedar Creek watershed	Indiana	710	Over 80% D	Majority <4	Mostly >0.28	Upper Mississippi River basin; slowly permeable soils with potholes; artificial surface and subsurface drainage.
3	Delta Water Management Research Center	Arkansas	Range of areas	Mostly D with some C	Mostly flat	>0.32 down to <0.24	Mississippi Delta; Lower Mississippi River basin; irrigation; artificial surface drainage.
4	Goodwin Creek	Mississippi	21	Mostly D with some C and B	Nearly half >6	All >0.32	Lower Mississippi River basin; poorly to well drained soils; high erosion risk.
5	Little River Experimental Watershed	Georgia	334	Mostly B with some C	Majority <4	Majority <0.24 with some >0.28	Gulf Atlantic Coastal Plain, shallow surficial aquifers; dense riparian buffers; high precipitation.
6	Mark Twain watershed	Missouri	5,918	Over 90% D	Majority <4	Mostly >0.32	Central Mississippi River basin; poorly drained claypan soils; high runoff potential.
7	Riesel	Texas	~1.6	Mostly D with some C	Majority <3	Mostly 0.28 to 0.32	Texas-Gulf Region, Lower Brazos Basin; four distinct seasonal moisture phases.
8	South Fork of Iowa River	Iowa	788	Mostly D with some B	Majority <2	Mostly 0.28 to 0.32	Upper Mississippi River basin; poor drainage conditions; majority of soils hydric; subsurface tile drains and surface ditches.
9	Upper Big Walnut Creek	Ohio	492	Over 80% D with some C	Mixed with half <2 and one-fourth >4	Nearly all >0.32	Eastern Corn belt; Ohio River basin; moderately to high runoff potential.
10	Upper Choptank watershed	Maryland	1,042 (headwater)	Mostly D with some B	Nearly two-thirds <2	Nearly equal 0.28 to >0.32 and <0.24	Lower Chesapeake Bay; mixture of well and poorly drained soils.
11	Upper Snake Rock	Idaho	1,136	Mostly C with some D	Mostly flat	All >0.32	Pacific Northwest Region, Upper Snake Basin; historic surface irrigation created majority of aquifer; many canals and drains in the area.
12	Walnut Creek	Iowa	51	Majority D with some C and B	Over half <2	Majority >0.28	Upper Mississippi River basin; till prairie; poorly dissected terrain; internally drained potholes; subsurface drainage.
13	WE-38	Pennsylvania	7	Mostly D and then B	Over 80% >6	Mostly >0.32	Upper Chesapeake Bay; restrictive layer underlying permeable layer; subsurface baseflow is 70% of total flow.

Figure 1
Map of selected sites for Soil Vulnerability Index (SVI) evaluation.



are surface drained, with drainage ditches networked across the watershed. The Manila and Leachville sites have K-factor soil erodibility mostly greater than 0.32. Caraway has mostly 0.28 or greater erodibility, Burdette Precision Level has primarily 0.24 to 0.28 erodibility, and Burdette Zero and Marked Tree have K-factor erodibility less than 0.24.

Goodwin Creek. The Goodwin Creek watershed is in north central Mississippi. It covers approximately 21 km² (8 mi²), with mixed land use and cropping systems that influence sediment loss to the streams (Alonso and Bingner 2000). A key characteristic of this watershed is the large sediment loads generated by stream channel erosion. There are more than 20 soil types in the watershed, but only seven soil series, with one soil series covering nearly half of the watershed. Substantial gullying occurs from mostly silty soils, which account for nearly a fourth of the watershed. Over half of the watershed is in hydrologic group D, with nearly equal amounts of groups B and C. There are essentially no group A soils. Nearly half of the watershed has slopes greater than 6%, with nearly equal amounts having slopes between 4% to 6%, 2% to 4%, and less than 2%. The K-factor erodibility is greater than 0.32 for the entire watershed.

Little River Experimental Watershed. The Little River Experimental Watershed is near Ashburn in south central Georgia and covers an area of 334 km^2 (129 mi^2). Outflow from the watershed flows south to its confluence with the Withlacoochee River, eventually joining to the Suwannee River that empties into the Gulf of Mexico west of Gainesville, Florida (Bosch et al. 2007). It has broad floodplains with mostly sandy soils, with little drainage in the watershed. Soils are primarily in hydrologic soil group B, with lesser amounts in group C. An interesting feature is the presence of hydrologic soil group A soils along the east side of most coastal plain streams adjacent to group D soils (Stephenson and Veatch 1915). Nearly three-fourths of the watershed has slopes less than 4%, with nearly one-fifth having slopes between 4% and 6%. The majority of soils have a K-factor erodibility less than 0.24, with some K-factors greater than 0.28 in lower sections of the watershed.

Mark Twain Lake. The Salt River basin/Mark Twain Lake watershed is situated in northeast Missouri and includes nine watersheds (North Fork, Middle Fork, Elk Fork, Long Branch, South Fork, Lick Creek, Black Creek, Crooked Creek, and Otter Creek), ranging in area from 271 to 1,579 km^2 (104.6 to 609.7 mi^2). The Salt River basin drains 6,417 km^2 (2,478 mi^2) at the outlet to the Mark Twain Lake. The basin has predominantly claypan soils, which have characteristically high soil runoff potential. This results in over 90% of the watershed being in hydrologic soil group D. Slopes vary across the watershed, with the majority of slopes less than 4% and the greatest majority of those less than 2%. However, some areas in the watershed have slopes greater than 6%, the majority of those being in grassland and forest. The K-factor erodibility is greater than 0.32 for most of the watershed, with a small area having an erodibility factor between 0.28 and 0.32.

Riesel Experimental Watershed. The Riesel Experimental Watershed, 1.6 km^2 (0.6 mi^2) in area, is in the Blackland Prairies ecoregion of east central Texas. The watershed is characterized by shrink-swell Vertisol clay soils (Harmel et al. 2006). This site has four distinct soil moisture phases that sequence through the year (Harmel et al. 2006). These include the saturated phase (February through May), the transition phase (evapotranspiration exceeds precipitation, June), the dry phase (essentially no runoff or subsurface flow, July through November), and the field capacity phase (precipitation begins to exceed evapotranspiration, December through January). Soils are predominately in the hydrologic soil group D, with small areas in the hydrologic soil group C. There are no group A or B soils within the watershed. More than 70% of the watershed is less than 3% slope, and over 40% is less than 2%. The K-factor erodibility is mostly 0.28 to 0.32.

South Fork of Iowa River. The South Fork of Iowa River watershed covers 788 km^2 (304.2 mi^2) in north central Iowa and lies in the eastern edge of the Des Moines Lobe. The watershed drainage includes tributaries of the South Fork River, Tipton Creek, and Beaver Creek. The lower southeastern portion of the watershed consists of natural stream incisions, while the upper portions of the watershed are dominated by till plains internally drained by prairie potholes (Yan et al. 2010). Agricultural crops are grown in 85% of the watershed, with pasture covering 6%. Approximately 13% of the watershed is rated as highly erodible land (Tomer and James 2004). Soil wetness is problematic, with nearly 54% of the watershed consisting of hydric soils that exhibit poor drainage conditions due to low relief. Artificial subsurface (tile) drainage is prevalent with approximately 80% of the watershed in tile drainage (Green et al. 2006). About 70% of annual stream flow originates from subsurface drainage, mostly occurring during spring and early summer (Schilling et al. 2007). Soils are predominantly in hydrologic soil group D along the summit and backslopes, with lesser amounts in group B in the river valleys. Nearly half of the watershed has slopes less than 2%, with nearly 80% less than 4% slope. The majority of the watershed has K-factor erodibility values between 0.28 and 0.32.

Upper Big Walnut Creek. The Upper Big Walnut Creek (UBWC) watershed is in central Ohio, covering an area approximately 492 km^2 (190 mi^2). Cropland for production agriculture is the dominant land use (73%), followed by urban/farmstead (21%) and woodland (6%) (Williams et al. 2015). The primary crops include corn, soybean (*Glycine max* [L.] Merr.), and wheat (*Triticum aestivum* L.) managed with conservation tillage, fertilizer, and pesticide applications (King et al. 2008). There is an extensive network of subsurface tile drainage, located mostly in the southern portion but some existing over the entire watershed (King et al. 2008). The northern portions of the watershed have smaller, natural surface drainage. There are four experimental subwatersheds: two paired channelized watersheds where streams have been deepened and straightened to improve surface and subsurface discharge capacity, and two paired unchannelized watersheds, where stream channels have developed under natural conditions (King et al. 2008). Over 80% of the watershed is in hydrologic soil group D, with the next greatest being group C. There are essentially no group A soils. Nearly half of the watershed has slopes of 2% or less, with about a fourth of the area having slopes greater than 4%. The K-factor erodibility is mostly greater than 0.32 or less than 0.24.

Upper Choptank. The Upper Choptank watershed consists of two subwatersheds: the Greensboro River watershed in the east and the Tuckahoe River watershed in the west in Maryland (Staver et al. 1996). Total watershed area is 1,042 km^2 (402.3 mi^2). The Choptank River is an estuary and tributary of the Chesapeake Bay, and is affected by excessive nutrient and sediment loads from agricultural lands (McCarty et al. 2008). The headwater section of the watershed has been the primary area of study due to the lower portions being tidal. Land use includes agricultural, forests, and developed areas (Fisher et al. 2006). Most soils are in hydrologic soil group D, with lesser amounts in group B. There are nearly equal amounts of group A and C, which combined make up about a third of the remaining watershed. Slopes are relatively flat, with nearly two-thirds of the watershed having slopes less than 2%. Soil K-factor erodibility is high, greater than 0.32, along the western edge of the Tuchahoe River watershed. The remainder of the watershed is equally divided among K-factors greater than 0.32, between 0.28 and 0.32 , and less than 0.24.

Upper Snake Rock. The Upper Snake Rock watershed is in the Magic Valley region near Twin Falls, Idaho. It covers 1,136 km^2 (438.6 mi^2), and is bounded by the service area of the Twin Falls Canal Company, which operates between Milner Dam and Salmon Falls Creek on the Snake River, and south to the High-Line Canal. The average annual precipitation is low (20 to 40 cm [7.8 to 15.7 in]). The only major tributary in the watershed is Rock Creek. The remaining water entering the area is from diversions from Milner Lake. The aquifer is unique in that it essentially consists of drainage water from irrigation from the canal. The soil is mostly loess deposits with scattered clay lenses that are primarily in the hydrologic soil group C, with about a third in group D. There is a small percentage of group B soils and essentially no group A soils. Overall, the area is mainly flat but there are steep slopes along the river canyons of the irrigation district. Over 50% of the area has slopes less than 2%, with 25% of the area having slopes between 2% and 4%. The K-factor soil erodibility is greater than 0.32 in essentially all of the watershed.

Walnut Creek. The Walnut Creek watershed is in central Iowa, covering approximately 51 km^2 (19.7 mi^2). The watershed has a low relief of rolling topography (0% to 9% slope) containing tiles and potholes. Artificial drainage includes ditches, subsurface pipes and tile lines, and surface water intakes (Tomer et al. 2003) to support row crop production. About 33% of the watershed is classified as well drained, with 10% somewhat poorly drained, 50% poorly drained, and 5% very poorly drained (Douglas et al. 2005). Nitrate-N is a common nutrient loss from the artificial subsurface drainage. The dense, unoxidized till in the upland soils reduce vertical drainage, resulting in more poorly drained soils in the lower elevation areas (Saleh et al. 2007). More than half of the soils are in hydrologic soil group D, with lesser amounts in group B. The remainder are in hydrologic group C with essentially no soils in group A. The majority of slopes are less than 2%, with nearly 80% of the watershed slope less than 4%. The majority of the watershed has a K-factor erodibility greater than 0.28.

WE-38 Experimental Watershed. The WE-38 Experimental Watershed is near Harrisburg, Pennsylvania. It is a relatively small watershed of 7 km^2 (2.7 mi^2), representative of a nonkarst region in the Valley and Ridge Province of central Pennsylvania. Although limestone is a common component of the geology throughout the region, it is absent in this watershed. Rock formations contain acid sedimentary sandstones, siltstones, and shales. The hydrology is variable source, with saturation excess occurring at lower landscape positions. Land use is primarily cropland, but also includes woodlands and pasture, as well as some developed areas. Over two-thirds of the watershed is in hydrologic groups D and B, with slightly more in group D. The remainder are in group C with very small amounts in group A. Slopes in the cultivated portions of the watershed typically range from 0% to 18%, although some hillslopes approach 32%. Slopes on foot slopes and shoulders are often less than 12%, with over 80% of the watershed having slopes greater than 6%. The majority of soils have K-factor erodibility greater than 0.32, with nearly equal areas of erodibility between 0.28 and 0.32 and less than 0.24.

Synthesis of SVI Evaluation

Watershed Characteristics where the SVI Worked Well. The evaluation of the SVI based on hydrologic soil group, slope, and soil erodibility made use of data from all 13 CEAP watershed sites. Because the SVI is an index assigning vulnerability to one of four categorical classifications, reliability was determined using the following means. Where data for watershed model evaluations were available, contingency table land areas classified by the SVI were directly compared to vulnerable areas classified from simulations using SWAT and/or AnnAGNPS model(s) to establish a numerical degree of agreement. Qualitative agreement was assessed through vulnerability comparison with aerial images, historical land use review, and local experts familiar with the watershed. For example, if the SVI classified an area as high vulnerability, a current review of land use could be used to verify if crop selection and production practices were consistent with this risk level. In steeper watersheds, aerial imagery was useful to identify if physical evidence, such as rilling, was present. Finally, consistency between the SVI vulnerability and the processes that take place on the landscape were considered, informed by the accumulated experience and knowledge of local experts in their respective watersheds. This process is explained in greater detail in Baffaut et al. (2020) and Lohani et al. (2020a).

In general, the SVI worked well for those watersheds that had mixed slope topography and a range of hydrologic soil groups (Little River and Cedar Creek). Specifically watersheds having a more evenly distributed range in slope from less than 2% to over 6% (matching the slope threshold classification values for runoff) and a representative distribution of hydrologic soil groups (i.e., more than a single dominant soil group) properly identified SVI vulnerability classifications. In watersheds with flat slopes (<2%), only the hydrologic soil group and K-factor influenced the SVI classification. Often these areas were dominated by hydrologic soil group D soils and K-factor values less than 0.28 resulting in SVI classification of low to moderately low runoff vulnerability (e.g., Mark Twain Lake and Riesel).

Artificial drainage is used to remove water from fields by surface and/or subsurface processes. The SVI does not distinguish the type of artificial drainage, but modifies the leaching vulnerability classification equally for either type. Of the 13 watersheds reviewed, eight sites were identified in which artificial drainage was a major practice necessary to support cropland management and production (Upper Choptank, Upper Big Walnut Creek, Cedar Creek, South Fork of the Iowa River, Walnut Creek, Delta Management Center, Beasley Lake, and Upper Snake Rock). The type of artificial drainage (surface or subsurface) did affect the ability of the SVI to properly identify vulnerability classification. Specifically, results from these watersheds found that the SVI properly identified the leaching vulnerability classification in fields that used subsurface tile drainage, although runoff vulnerability was typically overestimated. However, when surface drainage was used to drain excess water from the fields, the leaching vulnerability was overestimated and the runoff vulnerability was underestimated.

Watershed Characteristics where the SVI Lacked Targeting Power or Misidentified Classification. In watersheds that had a limited range in hydrologic soil groups or had uniform slopes relative to the SVI threshold, the SVI did not have the ability to identify sensitive areas. Most often the vulnerability classification was limited to the same class, such as low vulnerability or high vulnerability. In watersheds where steep slopes were present (slope >6%), the SVI did not consistently locate the most vulnerable areas since the classification was automatically assigned high vulnerability regardless of hydrologic soil group or K-factor, except for soil group A, which was assigned low vulnerability regardless of the K-factor. This resulted in an overestimation of SVI vulnerability classification in runoff and sediment loss for those areas with steeper slopes (Goodwin Creek) and underestimation of vulnerability in areas with flatter slopes (Beasley Lake) when compared to results from AnnAGNPS simulations (Yasarer et al. 2020). Both of these watersheds are in the lower Mississippi basin, known to experience greater average rainfall intensities than the region in which the SVI was developed, which may explain part of the underestimation where flatter slopes exist.

Locations where shallow surface soils had differing properties compared to the subsoil were often misclassified by SVI. This typically occurred where the underlying soils had restrictive layers or much lower infiltration rates. For example, the Upper Snake Rock watershed has well drained shallow topsoil underlain by a basalt hardpan 30 to 45 cm (11.8 to 17.7 in) below the surface that is fissured at random places. This results in dominant hydrologic soil group C throughout the area. Water percolates through this surface profile and accumulates above the basalt, forming a perched water table. In places where the basalt is fissured, there is rapid leaching to groundwater. Historically, large tunnels (1.3 × 2.3 m [4.2 × 7.5 ft]) were dug through the basalt, providing an escape route for the perched water where fractures in the basalt occurred (Carter et al. 1971). The SVI classification of moderate vulnerability to leaching was correct where no cracks exist, but underestimated the leaching risk where cracks or large tunnels occurred. In essence, these tunnels represent a type of artificial drainage, unique to the region and difficult to generalize across the whole watershed.

In regions with claypan soils, such as Mark Twain Lake watershed, the clay layer beneath the shallow surface silt loam layer dominates the infiltration process, resulting in saturated soil above the restrictive layer and greater surface runoff or lateral rather than vertical flow. Even if these fields have minimal slopes (<2%), they may be vulnerable to greater runoff than the SVI would otherwise indicate when the topsoil depth is less than 25 to 30 cm (8.9 to 11.8 in). In such situations, a modified SVI is suggested to better account for these unique soil profiles.

The SVI vulnerability classifications to runoff and leaching were not appropriate in the case of surface drainage or tile drainage with a surface inlet. Actual leaching vulnerabilities were lower than indicated by the SVI, while runoff vulnerabilities were higher than predicted due to the increased runoff amounts compared to the undrained situation. Artificial drainage with surface drainage ditches removes ponded water and water that is present in the topsoil. In effect, drainage ditches increased surface runoff discharged to receiving streams (i.e., Upper Choptank, Delta Management Center, Upper Snake Rock, and Beasley Lake). Surface drainage does not modify leaching or soil water content below the bottom of those ditches, which can vary from fairly shallow (less than 30 cm [11.8 in]) to much deeper (1 or 2 m [3.3 or 6.5 ft]). Artificial drainage with subsurface tiles removes water from the intermediate soil layers, which encourages infiltration from the soil surface to free up water holding capacity (e.g., Walnut Creek, South Fork of the Iowa River, Cedar Creek, and Upper Big Walnut Creek).

Suggested Modifications to Improve SVI Targeting Power. In areas where the hydrologic soil group was uniform and slopes were relatively uniform (0% to 4%), it was important to use a DEM instead of slopes from soil surveys to improve discernment of runoff vulnerability rather than the NRCS definition of the SVI, which uses the representative slope for each soil map unit (Chan et al. 2017). Resolutions of DEM were varied from 30 m (98.4 ft) down to 1 m (3.3 ft), but a single DEM resolution that would work in all applications was not identified. Instead the preferred resolution was dependent on the scale of topographic features of interest. High DEM resolution (3 m [9.8 ft] or less) may cause the SVI to predict high vulnerability in areas that do not cause concern (e.g., road or railway side banks or minimal area in a field). These areas should be excluded by focusing on cropland. Irrigation and drainage ditches should be included since they are part of the agricultural system. High DEM resolution is necessary in very flat land (less than 2% slope) to properly account for the subtle slope differences. Coarser resolutions were acceptable for broader features or landscapes having steeper slopes. Due to the strong dependence of leaching classification on hydrologic soil group (table 2), the specific DEM resolution had no influence on SVI leaching classification. Additional discussion on the effect of DEM resolution can be found in Lohani et al. (2020a). It is suggested that further studies be conducted to standardize the DEM resolution specific to topographic conditions and features of interest.

In the initial definition of the SVI, there was no indication of where to apply the artificially drained conditions other than the presence of artificial drainage. While this is straightforward at field scale, it is more difficult to know where artificial drainage is installed for watersheds greater than 10 to 20 km^2 (3.8 to 7.7 mi^2). Where artificial drainage was present, SVI leaching vulnerability was increased by two classes (low to moderately high, and moderately and moderately high to high). This included all watersheds having flat slopes and poor drainage. In many cases this improved the agreement between the SVI classification and local scientist observation at the site. However, this improvement was not necessarily based on the correct assumptions. For example, porous drain pipe is intended to capture water passing through the soil profile, intercepting the leaching fraction and associated dissolved nutrients. It may also enhance surface runoff in cases where glacial depressions would otherwise remain water filled. Surface drainage ditches do capture surface runoff and likely transport sediments, but have a minimal effect on lowering a perched water table. However, nutrient transport will be different due to the limited time that water would have percolated into the soil. Depending on whether the evaluation is intended for a field or a watershed scale, the leaching component may be better evaluated if SVI considerations were made for both artificial drainage and for no drainage (Baffaut et al. 2020). In addition, consideration should be given to the type of artificial drainage and modifications proposed to runoff and leaching components to better account for the differences. The use of drainage class to determine the need for artificial drainage might be helpful, but in some cases (e.g., shallow soils), the required drainage density would make it prohibitively expensive and impractical to farm. It is suggested that other SSURGO elements may help determine the presence of artificial drainage such as topsoil depth, soil permeability, and dual hydrologic soil group.

When complex soil profiles were encountered, the aggregation method of "dominant condition" was used in selecting the principal hydrologic soil group and K-factor. A more detailed soil analysis may help to better classify the vulnerability where the dominant soil represents less than 50% of the total soil profile or where land-leveling has disturbed the surface soils. In these situations, the SVI may not be effective and SSURGO soil data too coarse a resolution to best identify appropriate soil properties. In the case where shallow soils may exist or to improve identifying their presence, consideration of depth to a restrictive layer, clay content, slope length, and/or landscape position could help identify these areas.

The SVI was developed for conditions of the Upper Mississippi and Ohio-Tennessee River basins, and reflect the respective rainfall characteristics of seasonal and annual depth, and seasonal rainfall intensity associated with that region. Although the significant SVI factors related to hydrologic soil group, slope, and K-factor erodibility would likely be unchanged, the classification thresholds related to runoff and leaching in locations where annual or seasonal rainfall differ both in amount and intensity may need to be modified. There is currently no consideration of rainfall intensity in the SVI, although including some form of annual rainfall energy has been suggested. In areas having lower rainfall intensity, such as in the Upper Big Walnut Creek, vulnerability to runoff tends to be overestimated. For regions where rainfall intensity is greater, SVI classification tended to underestimate runoff vulnerability but to overestimate leaching vulnerability. For areas such as the Mississippi River basin watersheds (Beasley Lake and Goodwin Creek), this tends to give a false sense of safety as even fields with low predicted vulnerability to runoff required some conservation practices to accommodate the greater rainfall intensities. Incorporating a form of rainfall intensity into the SVI process is suggested. A similar recommendation should be considered for areas where irrigation is commonly practiced, such as the Upper Snake Rock watershed. Irrigation increases the average soil moisture content such that both runoff and leaching may be enhanced during rainfall events. Additionally the irrigation method may need to be taken into account since the influence on the soil surface and depth of soil moisture per irrigation can be quite different between surface and sprinkler irrigation.

An alternative means to use SVI classification by incorporating the SVI into a modified crop index was evaluated for the Mark Twain Lake watershed in northeast Missouri (Lohani et al. 2020b). The purpose was to evaluate if spatial distribution of vulnerability to runoff and leaching could be used to explain sediment and nutrient loads measured at the subwatershed level. Using measured data from 2006 to 2010, a crop index was determined relating crop distribution with total land cover fraction of the entire watershed in each year. A modified crop factor index was subsequently proposed where the land cover fraction of the entire watershed in each SVI classification was determined for each respective year and compared to a simple average for the crop factor that did not account for the SVI. Comparisons were made using sediment and nutrient loss estimated using SWAT (10.3) for the Goodwater Creek Experimental Watershed (Chan et al. 2017). Additional description on the development of the modified crop factor index can be found in Lohani et al. (2020b). Based on multiple regression analysis, the frequency of significance (90% level) for both runoff and leaching was greater by accounting for the SVI. Overall, including SVI weighting showed promise to improve management planning, but most relationships were not strongly defined and more work with additional site evaluations is suggested.

Summary and Conclusions

The SVI classification was evaluated over 13 watersheds having various ranges in slope, hydrologic soil group, and soil erodibility K-factor. For those areas having mixed slopes and mixed hydrologic soil groups, the SVI classification agreed well with scientists' knowledge of vulnerability. For watersheds with mixed slopes, hydrologic soil group and K-factor were most important in properly assigning classifications. In areas having steep slopes (>6%), the SVI did not consistently locate the most vulnerable areas and tended to overestimate vulnerability. In flatter areas, the SVI tended to underestimate vulnerability, particularly for hydrologic soil group C and D soils. Often vulnerable areas identified were in drainage ditches or pathways along field boundaries, which although not actual cropland, can still contribute to sediment loss. In areas that had both uniform slopes and uniform hydrologic soil groups, the SVI did not readily distinguish vulnerable areas. In such cases, additional information such as slope length and landscape position would be useful. For regions where rainfall intensities were greater than in the Upper Mississippi and Ohio-Tennessee River basins, the SVI tended to underestimate runoff vulnerability and overestimate leaching. In areas with complex soils, more detailed soil profile analysis would likely improve SVI classification. Increasing the SVI vulnerability classification for artificially drained soils improved the ability to properly identify areas for leaching problems, but it also compressed the ranking to only two categories, either moderately high or high. It is suggested that classification could be improved by separating surface from subsurface drained fields since the mechanisms for water removal and subsequent impact on nutrient and sediment loss are different for each.

Although the development of the SVI was based on soil map unit representative slope, improved classification was observed by using DEM slopes. However, a best DEM resolution was not identified, with the preferred resolution dependent on the scale of topographic feature of interest. It is suggested that further study be conducted to better define the optimum DEM resolution. Because of the strong dependence of leaching on hydrologic soil classification, the DEM resolution did not impact the SVI leaching classification.

The appeal of the SVI is its simplicity and readily available source data, yet rain amount, intensity, and crop management are known to impact runoff and leaching but are not included in the classification. The attempt to incorporate the SVI into a modified crop index to help explain sediment and nutrient loads measured at the subwatershed level showed promise but was inconsistent in identifying vulnerable areas. Further work is encouraged since the SVI has strong potential to improve watershed management.

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Disclaimer

The findings and conclusions in this publication are those of the authors and should not be construed to represent any official USDA or US Government determination or policy.

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