Received: 10 October 2019 | Accepted: 15 November 2019

DOI: 10.1002/ael2.20001

Agricultural & Environmental Letters OPEN ACCESS

RESEARCH LETTER

Phosphorus runoff risk assessment in karstic regions of the United States

Andrew N. Sharpley[1] | **Phillip D. Hays**[2] | **Karl W. VanDevender**[3] | **Mike B. Daniels**[4]

[1]Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, 115 Plant Sciences Building, Fayetteville, AR 72701, USA

[2]U.S. Geological Survey, Lower Mississippi-Gulf Water Science Center and Dep. of Geosciences, Univ. of Arkansas, 216 Ozark Hall, Fayetteville, AR 72701, USA

[3]Dep. of Biological and Agricultural Engineering, Cooperative Extension, Univ. of Arkansas, 2301 South University Ave., Little Rock, AR 72204, USA

[4]Dep. of Crop, Soil, and Environmental Sciences, Cooperative Extension, Univ. of Arkansas, 2301 South University Ave., Little Rock, AR 72204, USA

Correspondence
A.N. Sharpley, Dep. of Crop, Soil, and Environmental Sciences, Univ. of Arkansas, 115 Plant Sciences Building, Fayetteville, AR 72701, USA.
Email: sharpley@uark.edu

Abstract

The Phosphorus (P) Index risk assessment tool has been widely adopted across the United States to identify and rank site vulnerability to P runoff as part of the Natural Resources Conservation Service nutrient management planning (NMP) process. However, limited success has been achieved in addressing the risk of P loss by subsurface flow pathways, despite its relative importance in certain areas of the United States, particularly in those U.S. states dominated by karst terrain. Here we review how states with varying land areas classified as having karst features address the risk of P runoff during the NMP process. Indices adopted in Illinois and Indiana require setbacks (widths 15–72 m) around surface karst features. The remaining states with karst address the risk of P loss in NMP development rather than the application of a P Index. Given the spatially variable hydrogeologic properties of karst, technically rigorous field-scale factors are unlikely to be developed in the near future.

1 | INTRODUCTION

The Phosphorus (P) loss risk-assessment tool (P Index) has been widely adopted across the United States as part of the USDA-NRCS nutrient management planning (NMP) process (i.e., 590 Conservation Practice; USDA-NRCS, 2011). Adaptations and refinements of the P-Index framework have occurred across U.S. state boundaries to account for factors that influence the potential for P runoff types, such as varying landscape, geology, hydrology, land management, and dominant soil type (Osmond et al., 2017; Sharpley et al., 2003). While the P Index is an important part of the NMP process, planning is not complete without consideration of other factors, such as source of nutrients, available nutrients, target crop's production information, available crop acres, and other environmental and application limiting information not addressed by the P Index.

The P Index was developed to identify and rank the risk of P loss in surface runoff from a given field (Lemunyon & Gilbert, 1993). However, limited success has been achieved in incorporating subsurface risk factors into P Indices, particularly in areas where subsurface flow can be an important contributor to P loss and where sandy and organic soils have limited P retention capacities (Sharpley et al., 2017). Areas exemplifying these characteristics include parts of Delaware,

Abbreviations: NMP, nutrient management planning.

Florida, Maryland, Michigan, Minnesota, North Carolina, and Virginia. Radcliffe et al. (2015), for example, found that models describing subsurface transport of P were critically inaccurate with respect to P movement via macropore flow, which bypasses P sorption sites in the soil matrix. They recognized that these model deficiencies were also problematic to the accurate representation of subsurface P transport by P Indices.

Core Ideas

- P loss via karst fissures and sinkholes can bypass the soil regolith and enter groundwater.
- Only Illinois and Indiana have P Indices with explicit setbacks around karst features.
- Coupling P Index assessment and nutrient management planning can address P runoff risk in karst terrain.
- Most U.S. states address the risk of accelerated P loss in nutrient management planning.
- Determining P loss risk in karst is challenging due to its spatially variable hydrogeologic properties.

2 | KARST HYDROGEOLOGY AND PHOSPHORUS TRANSFERS

A geological survey and review conducted by Weary and Doctor (2015), determined that about 25% of the United States is underlain by rocks and sediments having karst or pseudokarst features or a potential for these features (Figure 1). Soluble rocks are exposed at or lie near the surface for about 18% of the United States; carbonate rocks constitute 16% of these soluble rocks and evaporite rocks constitute the remaining 2%.

Karst hydrologic systems are defined by the heterogeneous distribution of high-permeability solution channels that have developed in soluble, usually carbonate rock and the connectivity of these channels with the land surface (Figure 2). This connectivity results in rapid transport of surface water, as well as surface-derived nutrients, into the groundwater environment, bypassing soils, regolith, and granular rock strata, where any nutrient attenuation may occur. Karst groundwater flowpaths commonly cross surface topographic divides and are dynamic, frequently changing dominant conduits and flow direction and with variable recharge-area boundaries and hydrologic conditions. Karst terrain is often typified by karst features representing locations on these solution-channel paths, such as sinkholes, springs, caves, and losing streams. These characteristics render the hydrologic system vulnerable to nutrient enrichment and impart additional complexities, which can challenge effective management and

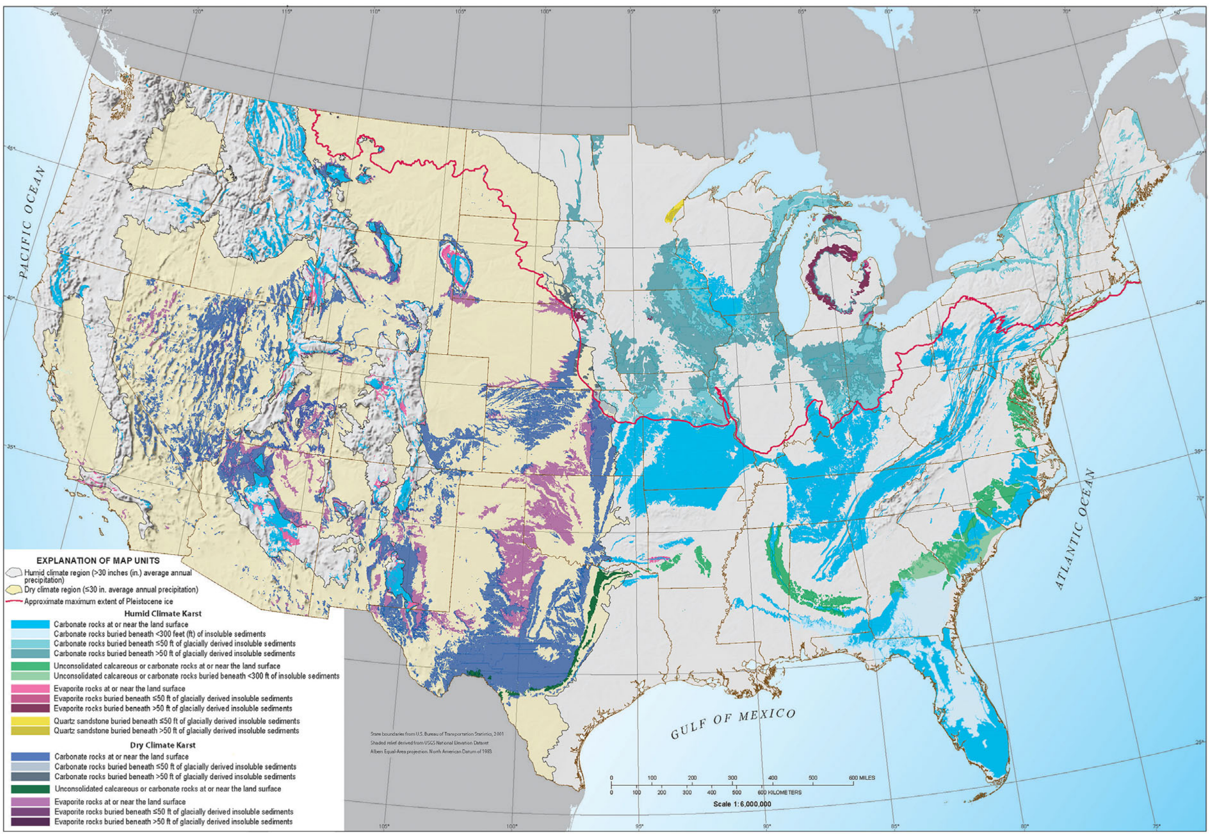

FIGURE 1 Karst and potential karst areas in soluble rocks of the contiguous United States (adapted from Weary & Doctor, 2015)

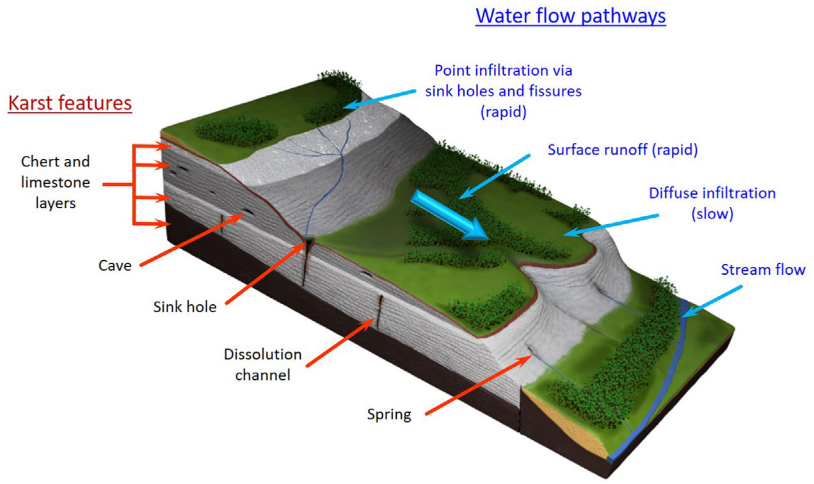

FIGURE 2 Schematic representation of karst features that influence the fate and transport of nutrients in the landscape and which can increase the speed and unpredictability of nutrient flows (adapted from Jarvie et al., 2014)

protection of water resources (Leh, Chaubey, Murdoch, Brahana, & Haggard, 2008).

Recent concerns have been expressed on the reliability of P Indices to address the risk of P loss in karst topography, where features such as dissolution fissures and sinkholes may provide rapid flow pathways, which can bypass the soil matrix and lead to an increased potential for P to enter streams and rivers (Alloush, Boyer, Belesky, & Halvorson, 2003; Brahana et al., 2014). For instance, studies of various agricultural land uses, including concentrated animal feeding operations in karst terrain, have shown that waste lagoons and manure application fields can be sources of nitrogen (N), P, and bacteria in groundwater (Brahana et al., 2016; Hutchins, White, & Mravik, 2012; Kelly et al., 2009).

Mellander et al. (2012), investigating the transfer of P from agricultural soils of elevated P status (>8.0 mg L^{-1} as Morgan's extractable soil P) to a karstified aquifer in County Mayo, Ireland, found concentrations of total P in groundwater were <0.025 mg L^{-1}. While total P concentrations were higher during episodic storm runoff events (0.05 mg L^{-1}), predominant flows and P transfer (75%) occurred during lateral flows within the epikarst (glacial till soils overlying the 3- to 5-m-deep karstic bedrock), where P attenuation and flow diffusion exist (Mellander et al., 2012).

Jarvie et al. (2014) used hydrochemical tracers (conservative tracers and end-member mixing analysis (Jarvie et al., 2011, 2013; Neal et al., 2010) to account for dilution of P, and to quantify net P retention, along transport pathways between agricultural fields and springs in the karst-dominated Ozark Plateau, in northwest Arkansas. They found 90% of the annual dissolved P flux was retained in the surface 2 to 3 m of epikarst, which has the potential to reduce the risk of acute episodic storm-driven losses of agricultural P (Jarvie et al., 2014). However, subsequent remobilization and transfer of retained P may provide a long-term source of "legacy" P transported via springs to surface waters P (Sharpley et al., 2013).

This paper presents a review of how the risk of P loss in subsurface flows in karst landscapes are addressed by P Indices for U.S. states with karst terrain.

3 | RESULTS AND DISCUSSION

The NMP process addresses the enhanced risk of nutrient loss in all U.S. states having karst by requiring a setback or permanent vegetated buffer between the zone of P application and karst features. The width of the setback or buffer generally defaults to NRCS Conservation Practices standards (USDA-NRCS, 2011), ranging from 9 to 91 m (30 to 300 ft) as a function of application timing and field slope (Table 1).

A review of P Indices adopted state by state is given in Table 1, along with the area and percentage of karst terrain in each state. States with more than half the land area classified as karst terrain or having the potential for karst development (Florida, Georgia, Iowa, and Missouri) have not explicitly included or assigned risk factors to any karst features or degree of karst development that may accelerate the loss of P from fields to streams (Table 1). Of 16 states with more than 25% land area exhibiting the potential for karst features, only Illinois and Indiana (26.7 and 46.3%, respectively; Weary & Doctor, 2015) include provision for a setback between karst feature and land application, in lieu of a permanent vegetative cover (Table 1). Illinois requires a 61-m (200-ft) setback, in the absence of a permanent vegetative buffer, which ranges from 11 m (36 ft) for 0.5% field slope to 72 m (235 ft) for >5% slope, while Indiana requires a permanent 15-m (49-ft) buffer.

Numerous U.S. states have generated and used vulnerability maps in the NMP process (McCarty, Matlock, Scott, & Haggard, 2018; Niraula, Kalin, Srivastava, & Anderson, 2013; Walter et al., 2000). Potential issues in vulnerability map use arise from problems of scale due to the heterogeneity of transport factors and subsurface flowpaths, in addition to a lack of state or national-scale databases or maps of surface

TABLE 1 Consideration of karst features in U.S. state P-runoff risk assessment indices

State	Potential karst land area[a] (km²)	Percentage karst area (%)	Management of karst within an applied P Index	Reference
Alabama	35,420	26.5	Not considered. Setbacks around permanent transport conduit/feature as part of NMP[b] process.	Alabama NRCS 2014; Osmond, Crouse, Hardy, & Spencer, 2014
Arkansas	24,675	17.9	Karst features visual from surface that indicate potential of direct contact with groundwater (i.e., sinkholes, rock outcroppings, springs) addressed in NMP process with application setbacks of 15 m (50 ft) for solid and 30 m (100 ft) for liquid manures.	Sharpley, Moore, et al., 2010; Sharpley, Daniels, et al., 2010; Arkansas Pollution Control and Ecology Commission, 2015
Delaware	4	0.1	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Shober & Sims, 2013; Univ. Delaware Extension, 2018
Florida	135,445	92.5	Not considered. Setbacks around karst features as part of NMP process.	Hurt, Mylavarapu, & Boetger, 2012
Georgia	78,402	51.5	Not considered. Setbacks around karst features as part of NMP process.	Butler et al., 2010; Georgia NRCS 2012
Idaho	14,195	6.6	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Leytem, Bjorneberg, & Tarkalson, 2017
Illinois	38,869	26.7	61-m (200-ft) setback in lieu of permanent vegetative buffer ranging from 11 m (36 ft) for 0.5% field slope to 72 m (235 ft) for >5% field slope.	Roberts and Goodrich, 2013
Indiana	43,380	46.3	Minimum buffer of 15 m (50 ft) via permanent filter strip (CP 393), riparian forest buffer (CP 391), use exclusion (CP 472), or fence (CP 382).	Indiana NRCS, 2004
Iowa	81,320	55.8	Karst considered for nitrate leaching but not for P.	Mallarino et al., 2002
Kansas	74,952	35.2	Setbacks around karst features as part of NMP process.	Kansas NRCS, 2003; Sonmez et al., 2009.
Kentucky	35,287	33.7	Not considered. Setbacks around karst features as part of NMP process.	Bolster, 2011
Louisiana	0.6	0.0005	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Felicien, 2007
Maryland	3,051	11.9	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	University of Maryland Extension, 2015; Beegle, Coale, Kleinman, Sexton, & Simpson, 2015
Michigan	42,053	28.0	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Michigan NRCS, 2014
Minnesota	28,389	13.0	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Minnesota Extension, 2018
Mississippi	14,593	11.8	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Mississippi NRCS, 2007
Missouri	122,444	67.8	Setbacks around karst features as part of NMP process.	Lory, Miller, Davis, Steen, & Li, 2007
Nebraska	26,399	13.2	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Al-Wadaey, C.S, Shapiro, Franti, & Eisenhauer, 2010; Eghball & Gilley, 2001; Wortmann, Shapiro, Johnson, & Hancock, 2012

(Continues)

TABLE 1 (Continued)

State	Potential karst land area[a] (km^2)	Percentage karst area (%)	Management of karst within an applied P Index	Reference
New Mexico	57,043	18.1	Not considered. As part of NMP, no application can be made closer than 30 m (100 ft) to any down gradient sinkholes or other conduits to surface or groundwater.	New Mexico NRCS, 2014
New York	18,042	14.4	9-m (30-ft) vegetative buffer and 30-m (100-ft) P application setback.	Czymmek et al., 2011, 2015; Ketterings & Czymmek, 2012; Ketterings, Cela, Collick, Crittenden, & Czymmek, 2017
North Carolina	33,165	25.9	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Osmond et al., 2014
Ohio	44,839	42.0	Not considered. Edge-of-field vegetated buffers not considered.	Williams, King, LaBarge, Confesor, & Fausey, 2016
Oklahoma	38,869	21.5	Oklahoma does not use a P Index as part of its 590 Nutrient Management Planning	DeLaune, Haggard, Daniel, Chaubey, & Cochran, 2006
Oregon	2,919	1.2	Not considered.	Oregon State University Extension, 2003; Raney and Troxell, 2008.
Pennsylvania	18,174	15.5	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Beegle et al., 2007 and 2015
South Carolina	39,400	49.3	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	South Carolina NRCS, 2004
Tennessee	47,757	43.8	Not considered. Buffers around surface water conveyances; width based on P Index risk rating and NRCS standards.	Walker and Hawkins, 2016
Texas	168,743	24.6	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Texas NRCS, 2012; White, Harmel, & Haney, 2012
Vermont	6,500	26.1	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	University of Vermont Extension, 2017
Virginia	18,572	17.9	Not considered. 15-m (50-ft) setback around sinkholes and limestone rock outcrops.	Beegle et al., 2015
Washington	398	0.2	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	Oregon State University Extension, 2003;
West Virginia	5,837	9.3	Not considered. Setbacks around permanent transport conduit/feature as part of NMP process.	McDonald et al., 2012
Wisconsin	44,308	30.6	Not considered. 15- to 30-m (50- to 100-ft) buffer from karst features and 91-m (30-ft) buffer for surface (or winter) applications as part of NMP process.	Good, 2018; Good, Vadas, Panuska, Bonilla, & Jokela, 2012

[a]Potential karst land area in a given U.S. state (see Weary and Doctor, 2014).
[b]NMP, nutrient management planning.

karst features. For example, the vulnerability map created for Arkansas listed the entire Ozarks of northern Arkansas at the highest vulnerability index (Scott, 1993). However, the scientific community recognizes that the distribution of karst features and the variable thickness and composition of soils, spatial distribution of karst features, and differing degrees of karst development result in variable vulnerability across the Ozarks (Adamski, Petersen, Freiwald, & Davis, 1995; Alley, Healy, LaBaugh, & Thomas, 2002; Healy & Scanlon, 2010). Such problems highlight the importance of farm-scale and field-scale data in the NMP process.

In the risk management setting, NMP is the farm- and field-level process by which available nutrients from manure and inorganic fertilizers, available soil fertility levels, crop nutrient needs, P Index-mandated maximum application limits, and other factors determine application rates and locations. Nutrient management planning is largely an agronomic, economic, and land manager's preferences process, which is constrained by the P-Index assessment along with nonapplication areas and setbacks to address concerns not appropriately addressed by the P-Index assessment.

4 | CONCLUSIONS

Accounting for subsurface flow and transport from agricultural fields in P Indices remains a challenge due to the large spatial and temporal variability of factors controlling these flows. Additionally, an inability to reliably quantify subsurface P fluxes from any given field hinders calibration and verification of P-Index risk factors. Karst landscapes impart an additional layer of complexity to subsurface flows.

In practice, the resulting risk potential is used as guidance to help balance the risk of P runoff with other important factors such as soil fertility, crop production, manure utilization, and farm economics. This balance usually results in a per hectare upper limit for manure applied to specific fields. The designation of areas where manure is not to be applied is not the function of a P Index alone: rather that designation is the function of various additional criteria specified by the NMP process.

Distances between P application areas and adjacent properties or residences is one example that illustrates setbacks or vegetative buffer are beyond the scope of the P-Index assessment is. Another example is the prohibiting of applications within specified distances of karst features, such as sinkholes and rock outcrops that indicate the potential for karst-associated P flows through the epikarst to groundwater. As a result, only the coupling of the P-Index assessment and a NMP process addresses both surface and subsurface transport of P to receiving waters. Certainly, there is a need for further research in characterizing subsurface flow and transport of P in karstic regions, along with developing practices to P runoff risk that can be incorporated practically into the nutrient management process.

Although on-farm NMP occurs at the field scale, there is a lack of consistent and well-maintained geographical information system databases of karst features and geologic mapping at this scale. As an example, in Arkansas, the Arkansas Geological Survey topographic-scale geologic mapping (which includes an inventory of karst features) usually maps one to three quads a year; other states map at a similar rate. Thus, NMP development and risk assessment at a state level, where policy is made, would be aided by consistent karst feature databases and geologic mapping.

ACKNOWLEDGMENTS

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Andrew N. Sharpley https://orcid.org/0000-0003-1667-2971
Phillip D. Hays https://orcid.org/0000-0001-5491-9272

REFERENCES

Adamski, J. C., Petersen, J. C., Freiwald, D. A., & Davis, J. V. (1995). Environmental and hydrologic setting of the Ozark Plateaus study unit, Arkansas, Kansas, Missouri, and Oklahoma (USGS Water-Resources Investigation Report 94-4022). Reston, VA: USGS.

Alabama NRCS. (2014). *Phosphorus Index for Alabama: A planning tool to assess and manage P movement* (Agronomy Technical Note AL-71). Washington, DC: USDA-NRCS.

Alley, W., Healy, R. W., LaBaugh, J. W., & Thomas, E. R. (2002). Flow and storage in groundwater systems. *Science*, *296*, 1985–1990.

Alloush, G. A., Boyer, D. G., Belesky, D. P., & Halvorson, J. J. (2003). Phosphorus mobility in a karst landscape under pasture grazing system. *Agronomie*, *23*, 593–600.

Al-Wadaey, A., C. S, Wortmann, Shapiro, C. A., Franti, G. T., & Eisenhauer, E. D. (2010). Manure application setback effect on phosphorus and sediment in runoff. *Journal of Soil Science and Environmental Management*, *1*(5), 92–98.

Arkansas Pollution Control and Ecology Commission. (2015). *Liquid animal waste management systems*. Little Rock: Arkansas Pollution Control and Ecology Commission.

Beegle, D., Coale, F., Kleinman, P., Sexton, T., & Simpson, T. (2015). *Phosphorus management tools in Virginia, Maryland, and Pennsylvania*. Annapolis, MD: Chesapeake Bay Commission.

Beegle, D., Bryant, R., Gburek, W., Kleinman, P., Sharpley, A., & Weld, J. (2007). *The Pennsylvania Phosphorus Index, version 2*. University Park: Pennsylvania State University. Retrieved from https://extension.psu.edu/programs/nutrient-management/tools/phosphorus-index

Bolster, C. H. (2011). A critical evaluation of the Kentucky Phosphorus Index. *Journal of the Kentucky Academy of Science*, *72*(1), 46–58.

Brahana, V., Nix, J., Bitting, C., Bitting, C., Quick, R., Murdoch, J., … North, V. (2014). CAFOs on karst: Meaningful data collection to adequately define environmental risk, with specific application from the southern Ozarks of northern Arkansas. In E. L. Kuniansky & L. E. Spangler (Eds.), *U.S. Geological Survey Karst Interest Group Proceedings* (U.S. Geological Survey Scientific Investigations Report *2014-5035*, pp. 87–96). Reston, VA: USGS.

Brahana, J. V., Nix, J., Kuyper, C., Turk, T., Usrey, F., Hodges, S., … Murdoch, J. (2016). Geochemical processes and controls affecting water quality of the karst area of Big Creek near Mt. Judea, Arkansas. *Journal of the Arkansas Academy of Science*, *70*, 1–14.

Butler, D. M., Franklin, D. H., Cabrera, M. L., Risse, L. M., Radcliffe, D. E., West, L. T., & Gaskin, J. W. (2010). Assessment of the Georgia Phosphorus Index on farm at the field scale for grassland management. *Journal of Soil and Water Conservation*, *63*(3), 200–210.

Czymmek, K., Geohring, L., Lendrum, J., Wright, P., Albrecht, G., Brower, B., & Ketterings, Q. (2011). *Manure management guidelines for limestone bedrock/karst areas of Genesee*

County, New York: Practices for risk reduction. Ithaca, NY: Cornell University Animal Science. Retrieved from http://nmsp.cals.cornell.edu/NYOnFarmResearchPartnership/PI_Eval_NE.html

Czymmek, K. J., Geohring, L., Ketterings, Q. M., Wright, P., Walter, T., Albrecht, G., … Eaton, A. (2015). *Revised winter and wet weather manure spreading guidelines to reduce water contamination risk*. Ithaca, NY: Cornell University Animal Science.

DeLaune, P. B., Haggard, B. E., Daniel, T. C., Chaubey, I., & Cochran, M. J. (2006). The Eucha/Spavinaw phosphorus index: A court mandated index for litter management. *Journal of Soil and Water Conservation*, *61*(2), 96–105.

Eghball, B., & Gilley, J. (2001). Phosphorus risk assessment index evaluation using runoff measurements. Biological Systems Engineering. Retrieved from https://digitalcommons.unl.edu/biosysengfacpub/142

Felicien, W. L. (2007). *Assessment of the phosphorus index for Louisiana* (Master's thesis, Louisiana State University). Retrieved from https://digitalcommons.lsu.edu/gradschool_theses/2464/

Georgia NRCS. 2012. *The Georgia Phosphorus Index* (Agronomy Technical Note). Washington, DC: USDA-NRCS.

Good, L. W. (2018). *Wisconsin Phosphorus Index*. Retrieved from https://wpindex.soils.wisc.edu/

Good, L. W., Vadas, P., Panuska, J. C., Bonilla, C. A., & Jokela, W. E. (2012). Testing the Wisconsin Phosphorus Index with year-round, field-scale runoff monitoring. *Journal of Environmental Quality*, *41*, 1730–1740. https://doi.org/10.2134/jeq2012.0001

Healy, R., & Scanlon, B. R. (2010). Groundwater recharge. In *Estimating groundwater recharge* (pp. 1–14). Cambridge, U.K.: Cambridge University Press. https://doi.org/10.1017/CBO9780511780745.002

Hurt, G. W., Mylavarapu, R. S., & Boetger, S. P. (2012). UF/IFAS nutrient management series: Computational tools for field implementation of the Florida Phosphorus Index. Retrieved from https://edis.ifas.ufl.edu/topic_series_florida_phosphorous_index

Hutchins, S. R., White, M. V., & Mravik, S. C. (2012). *Case studies on the impact of concentrated animal feeding operations (CAFOs) on groundwater quality* (EPA 600/R-12/052. QA ID #G-10033). Ada, OK: USEPA, Office of Research and Development, National Risk Management Research Laboratory.

Indiana NRCS. (2004). *Indiana nutrient and sediment loss risk assessment tool*. Washington, DC: Indiana NRCS. Retrieved from https://efotg.sc.egov.usda.gov/references/public/IN/590_Offsite_Risk_Index.pdf

Jarvie, H., Neal, C., Withers, P. J. A., Baker, D. B., Richards, P. R., & Sharpley, A. N. (2011). Quantifying phosphorus retention and release in rivers and watersheds using extended end-member mixing analysis (EEMMA). *Journal of Environmental Quality*, *40*, 492–504. https://doi.org/10.2134/jeq2010.0298

Jarvie, H. P., Sharpley, A. N., Scott, T., Haggard, B., Bowes, M., & Massey, L. (2013). Within-river phosphorus retention: Accounting for a missing piece in the watershed phosphorus puzzle. *Environmental Science & Technology*, *46*(24), 13284–13292.

Jarvie, H. P., Sharpley, A. N., Brahana, J. V., Simmons, T., Price, A., Neal, C., … Haggard, B. (2014). Phosphorus retention and remobilization along hydrological pathways in karst terrain. *Environmental Science & Technology 48*, 4860–4868.

Kansas NRCS. (2003). *The Kansas Phosphorus Index*. Washington, DC: Kansas NRCS.

Kelly, W. R., Panno, S. V., Hackley, K. C., Martinsek, A. T., Krapac, I. G., Weibel, C. P., & Storment, E. C. (2009). Bacteria contamination of groundwater in a mixed land-use karst region. *Water Quality, Exposure and Health*, *1*(2), 69–78.

Ketterings, Q., Cela, S., Collick, A. S., Crittenden, S. J., & Czymmek, K. J. (2017). Restructuring the P Index to better address p management in New York. *Journal of Environmental Quality*, *46*, 1372–1379. https://doi.org/10.2134/jeq2016.05.0185

Ketterings, Q. M., & Czymmek, K. J. (2012). Phosphorus index as a phosphorus awareness tool: Documented phosphorus use reduction in New York State. *Journal of Environmental Quality*, *41*, 1767–1773. https://doi.org/10.2134/jeq2012.0050

Leh, M. D., Chaubey, I., Murdoch, J., Brahana, J. V., & Haggard, B. E. (2008). Delineating runoff process and critical runoff source areas in a pasture hillslope of the Ozark Highlands. *Hydrological Processes*, *22*, 4190–4204.

Lemunyon, J. L., & Gilbert, R. G. (1993). The concept and need for a phosphorus assessment tool. *Journal of Production Agriculture*, *6*(4), 483–486.

Leytem, A., Bjorneberg, D., & Tarkalson, D. (2017). The Phosphorus Site Index: A systematic approach to assess the risk of nonpoint source pollution of Idaho waters by agricultural phosphorus. Retrieved from https://agri.idaho.gov/main/wp-content/uploads/2018/12/Phosphorus-Site-Index-reference-2017-revised.pdf

Lory, J. A., Miller, R., Davis, G., Steen, D., & Li, B. (2007). *The Missouri Phosphorus Index* (G9184). Missouri University Extension, University of Missouri-Columbia, Division of Plant Sciences and Commercial Agriculture Program. Retrieved from https://extension2.missouri.edu/g9184

Mallarino, A. P., Stewart, B. M., Baker, J., Downing, J. D., & Sawyer, J. E. (2002). Phosphorus indexing for cropland: Overview and basic concepts of the Iowa Phosphorus Index. *Journal of Soil and Water Conservation*, *57*, 440–447.

McCarty, J. A., Matlock, M. D., Scott, J. T., & Haggard, B. E. (2018). Risk indicators for identifying critical source areas in five Arkansas watersheds. *Transactions of the American Society of Agricultural and Biological Engineers*, *61*(3), 1025–1032. https://doi.org/10.13031/trans.12699

McDonald, L., Faulkner, J., Basden, T., Thompson, J., Gorman, J., Harman, M., & Rayburn, E. (2012). *The revised West Virginia Phosphorus Index* (version 2.0; NRCS Technical Note WV_CPA_WS_590_3). Washington, DC: USDA.

Mellander, P. E., Jordan, P., Wall, D. P., Melland, A. R., Meehan, R., Kelly, C., & Shortle, G. (2012). Delivery and impact bypass in a karst aquifer with high phosphorus source and pathway potential. *Water Research*, *46*, 2225–2236.

Michigan NRCS. (2014). *Michigan phosphorus risk assessment tool* (Technical Note Agronomy No. 60, Revised 2014). Washington, DC: Michigan NRCS.

Minnesota Extension. (2018). The Minnesota Phosphorus Index: Assessing risk of phosphorus loss from cropland. Retrieved from https://extension.umn.edu/phosphorus-and-potassium/minnesota-phosphorus-index-assessing-risk-phosphorus-loss-cropland#state-regulations-616410

Mississippi NRCS. (2007). *Phosphorus Index for Mississippi* (Agronomy Technical Note MS-05). Washington, DC: USDA-NRCS.

Neal, C., Jarvie, H. P., Williams, R., Love, A., Neal, M., Wickham, H., … Armstrong, L. (2010). Declines in phosphorus concentration in the upper River Thames (UK): Links to sewage effluent cleanup and extended end-member mixing analysis. *Science of the Total Environment*, *408*(6), 1315–1330.

New Mexico NRCS. (2014). *Comprehensive nutrient management planning guidelines for New Mexico*. Washington, DC: USDA-NRCS. Retrieved from https://www.nrcs.usda.gov/wps/PA_NRCSConsumption/download?cid=stelprdb1260046&ext=pdf

Niraula, R., Kalin, L., Srivastava, P., & Anderson, J. J. (2013). Identifying critical source areas of nonpoint source pollution with SWAT and GWLF. *Ecological Modelling*, *268*, 123–133. https://doi.org/10.1016/j.ecolmodel.2013.08.007

Oregon State University Extension. (2003). *Agricultural phosphorus management using the Oregon/Washington Phosphorus Indexes* (EM 8848-E). Corvallis: Oregon State University Extension Service.

Osmond, D., Crouse, D., Hardy, D., & Spencer, J. (2014). The North Carolina phosphorus loss assessment tool (PLAT): A guide for technical specialists. North Carolina State Extension. Retrieved from https://content.ces.ncsu.edu/the-north-carolina-phosphorus-loss-assessment-tool-plat-a-guide-for-technical-specialists

Osmond, D., Bolster, C., Sharpley, A. N., Cabrera, M., Feagley, S., Forsberg, A., … Zhang, H. (2017). Southern Phosphorus Indices, water quality data, and modeling (APEX, APLE, and TBET) results: A comparison. *Journal of Environmental Quality*, *46*, 1296–1305. https://doi.org/10.2134/jeq2016.05.0200

Radcliffe, D. E., Reid, D. K., Blomback, K., Bolster, C. H., Collick, A. S., Easton, Z. M., … Smith, D. R. (2015). Applicability of models to predict phosphorus losses in drainage fields: A review. *Journal of Environmental Quality*, *44*(2), 614–628. https://doi.org/10.2134/jeq2014.05.0220

Raney, R., & Troxell, D. (2008). *The Phosphorus Index* (Agronomy Technical Note No. 26). Washington, DC: USDA-NRCS.

Roberts, B., & Goodrich, K. (2013). *The Illinois Phosphorus Index* (IPI 1.2). Washington, DC: Illinois NRCS.

Scott, H. D. (1993). Determination of areas vulnerable to pesticide contamination of groundwater by GIS and satellite remote sensing. Retrieved from https://arkansas-water-center.uark.edu/publications/msc/MSC134.pdf

Sharpley, A. N., Daniels, M., VanDevender, K., Haggard, B., Slaton, N., & West, C. (2010). *Using the 2010 Arkansas Phosphorus Index*. Cooperative Extension Service, Division of Agriculture. Retrieved from http://www.uaex.edu/Other_Areas/publications/PDF/MP487

Sharpley, A. N., Jarvie, H. P., Buda, A., May, L., Spears, B., & Kleinman, P. (2013). Phosphorus legacy: Overcoming the effects of past management practices to mitigate future water quality impairment. *Journal of Environmental Quality*, *42*, 1308–1326. https://doi.org/10.2134/jeq2013.03.0098

Sharpley, A. N., Kleinman, P. J. A., Baffaut, C., Beegle, D., Bolster, C., Collick, A., … Weld, J. (2017). Evaluation of phosphorus site assessment tools: Lessons from the U.S.A. *Journal of Environmental Quality*, *46*, 1250–1256. https://doi.org/10.2134/jeq2016.11.0427

Sharpley, A. N., Moore, P., VanDevender, K., Daniels, M., Delp, W., Haggard, B., … Baber, A. (2010). *Arkansas Phosphorus Index*. Cooperative Extension Service, Division of Agriculture, University of Arkansas. Retrieved from http://www.uaex.edu/Other_Areas/publications/PDF/FSA-9531.pdf

Sharpley, A. N., Weld, J. L., Beegle, D. B., Kleinman, P. J. A., Gburek, W. J., Moore, P. A., & Mullins, G. (2003). Development of phosphorus indices for nutrient management planning strategies in the U.S. *Journal of Soil and Water Conservation*, *58*, 137–152.

Shober, A. L., & Sims, J. T. (2013). *Management strategies for Delaware's agricultural soils: The Phosphorus Site Index*. University of Delaware Extension. Retrieved from http://extension.udel.edu/factsheets/phosphorus-management-strategies-for-delawares-agricultural-soils-the-phosphorus-site-index/

Sonmez, O., Pierzynski, G. M., Frees, L., Davis, B., Leikam, D., Sweeney, D. W., & Janssen, K. A. (2009). A field-based assessment tool for phosphorus losses in runoff in Kansas. *Journal of Soil and Water Conservation*, *64*(3), 212–222.

South Carolina NRCS. (2004). Waste utilization: Phosphorus Index, version 6. In *Part 651: Agricultural waste management field handbook* (Chapter 11, South Carolina Supplement 2.). Washington, DC: USDA.

Texas NRCS. (2012). *Phosphorus assessment tool for Texas* (Technical Note No 15). Washington, DC: USDA.

University of Delaware Extension. (2018). *The Delaware Phosphorus Site Index technical guidance manual*. Retrieved from http://extension.udel.edu/factsheets/de-phosphorus-site-index-technical-guidance-manual/

University of Maryland Extension. (2015). *Soil fertility management: The Maryland Phosphorus Site Index technical uses guide*. University of Maryland Extension. Retrieved from https://extension.umd.edu/anmp/phosphorus-site-index-psi

University of Vermont Extension. (2017). *Vermont Phosphorus Index user guide, version 6.0*. Burlington: University of Vermont Extension. Retrieved from https://www.uvm.edu/extension/agriculture/vermont-phosphorous-index

USDA-NRCS. (2011). *Conservation practice standard, Nutrient Management 590*. Washington, DC: USDA-NRCS. Retrieved from http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1046177.pdf

Walker, F., & Hawkins, S. (2016). *Guidelines for using the revised Tennessee Phosphorus Risk Index*. Knoxville: University of Tennessee Institute of Agriculture.

Walter, M. T., Walter, M. F., Brooks, E. S., Steenhuis, T. S., Boll, J., & Weiler, K. (2000). Hydrologically sensitive areas: Variable source area hydrology implications for water quality risk assessment. *Journal of Soil and Water Conservation*, *55*, 277–284.

Weary, D. J., & Doctor, D. H. (2015). Karst mapping in the United States: Past, present, and future. In J. Feinberg, Y. Gao, & E. C. Alexander, Jr. eds., *Caves and karst across time* (pp. 35–48). Boulder, CO: Geological Society of America. https://doi.org/10.1130/2015.2516(04)

White, M. W., Harmel, R. D., & Haney, R. L. (2012). Development and validation of the TX Best Management Practice Evaluation Tool (TBET). *Journal of Soil and Water Conservation*, *67*(6), 525–535.

Williams, M. R., King, K. W., LaBarge, G. A., Confesor, R. B. Jr., & Fausey, N. R. (2016). Edge-of-field evaluation of the Ohio Phosphorus Risk Index. *Journal of Environmental Quality*, *46*, 1306–1313. https://doi.org/10.2134/jeq2016.05.0198

Wortmann, C. S., Shapiro, C. A., Johnson, L. J., & Hancock, R. F. (2012). *The Nebraska Phosphorus Index (2012): Background and users guide*. University of Nebraska-Lincoln Extension. Retrieved from http://extensionpubs.unl.edu/publication/9000016362921/the-nebraska-phosphorus-index-2012/

How to cite this article: Sharpley AN, Hays PD, VanDevender KW, Daniels MB. Phosphorus runoff risk assessment in karstic regions of the United States. *Agric Environ Lett*. 2020;5:e20001. https://doi.org/10.1002/ael2.20001