Wetlands
DOI 10.1007/s13157-017-0887-3

SHORT COMMUNICATION

The Significant Surface-Water Connectivity of "Geographically Isolated Wetlands"

Aram J. K. Calhoun[1] · **David M. Mushet**[2] · **Laurie C. Alexander**[3] · **Edward S. DeKeyser**[4] · **Laurie Fowler**[5] · **Charles R. Lane**[6] · **Megan W. Lang**[7] · **Mark C. Rains**[8] · **Stephen C. Richter**[9] · **Susan C. Walls**[10]

Received: 22 December 2016 / Accepted: 6 February 2017

Abstract We evaluated the current literature, coupled with our collective research expertise, on surface-water connectivity of wetlands considered to be "geographically isolated" (*sensu* Tiner Wetlands 23:494–516, 2003a) to critically assess the scientific foundation of grouping wetlands based on the singular condition of being surrounded by uplands. The most recent research on wetlands considered to be "geographically isolated" shows the difficulties in grouping an ecological resource that does not reliably indicate lack of surface water connectivity in order to meet legal, regulatory, or scientific needs. Additionally, the practice of identifying "geographically isolated wetlands" based on distance from a stream can result in gross overestimates of the number of wetlands lacking ecologically important surface-water connections. Our findings do not support use of the overly simplistic label of "geographically isolated wetlands". Wetlands surrounded by uplands vary in function and surface-water connections based on wetland landscape setting, context, climate, and geographic region and should be evaluated as such. We found that the "geographically isolated" grouping does not reflect our understanding of the hydrologic variability of these wetlands and hence does not benefit conservation of the Nation's diverse wetland resources. Therefore, we strongly discourage use of categorizations that provide overly simplistic views of surface-water connectivity of wetlands fully embedded in upland landscapes.

Keywords Clean Water Act · Connectivity · Geographic isolation · Hydrology · Streams · Upland embedded wetlands · Waters of the U.S.

Introduction

Throughout the world, small wetlands with seasonal hydrology are at great risk of loss or degradation and effective approaches to conserving their functions lag behind the increase in threats (Calhoun et al. 2017). For this reason, researchers and managers need to improve the understanding of vulnerable wetland functions and this includes both continuing research and clarifying regulations that do exist while considering alternative

✉ Aram J. K. Calhoun
calhoun@maine.edu

[1] Department of Wildlife, Fisheries, and Conservation Biology, University of Maine, Orono, ME 04469, USA

[2] Northern Prairie Wildlife Research Center, US Geological Survey, 8711 37th Street SE, Jamestown, ND 58401, USA

[3] Office of Research and Development, US Environmental Protection Agency, 1200 Pennsylvania Ave NW (8623-P), Washington, DC 20460, USA

[4] School of Natural Resource Sciences, North Dakota State University, Fargo, ND 58108, USA

[5] School of Law, University of Georgia, Athens, GA 30602, USA

[6] Office of Research and Development, US Environmental Protection Agency, Cincinnati, OH 45268, USA

[7] National Wetland Inventory, US Fish and Wildlife Service, Falls Church, VA 22041, USA

[8] School of Geosciences, University of South Florida, Tampa, FL 33620, USA

[9] Department of Biological Sciences and Division of Natural Areas, Eastern Kentucky University, Richmond, KY 40475, USA

[10] Wetland and Aquatic Research Center, US Geological Survey, 7920 NW 71st Street, Gainesville, FL 32653, USA

approaches. In this paper, we give one example of addressing this issue that has relevance to wetland managers globally. In a recent issue of *WETLANDS*, we published an essay entitled "Geographically Isolated Wetlands: Rethinking a Misnomer" (Mushet et al. 2015). In our paper, we described the declining relevance and confusing nature of the "geographically isolated wetlands" (GIWs) categorization as currently used in wetland science and policy in the United States. Leibowitz (2015) published a thoughtful response to our review in which he defended the use of the categorization and argued that there are important scientific, legal, and regulatory needs for identifying wetlands that are completely surrounded by uplands (i.e., GIWs, sensu Tiner 2003a). We have found that scientific responses to the legacies of the last decade's court actions and policy needs for wetland regulation under the Clean Water Act (CWA; 33 U.S.C. Chapter 26) have improved our understandings of the complexity of wetland hydrology, functions, and nexuses that transcend simple assessments of degree of upland embeddedness. Grouping wetlands by whether they are surrounded by uplands does not indicate a lack of a "significant nexus," and therefore does not provide a useful separation for meeting legal and regulatory information needs (Cohen et al. 2016).

We provide a brief review of key scientific findings to instantiate our thesis that having a static category based on upland embeddedness is no longer beneficial and, in fact, may be detrimental to conservation of these wetland resources and their influence on downgradient systems. The GIW term, or any term that implies that wetlands surrounded by uplands are in fact functionally isolated, is difficult to justify scientifically, difficult to apply pragmatically, subject to misuse and misinterpretation, and maps poorly onto the regulatory landscape. In this paper, we use the term upland-embedded wetland to describe a geospatial setting with no assumptions about connectivity or lack thereof and with no intent to replace the GIW term with "upland-embedded wetland". We focus on surface-water connections, as the GIW categorization has not been promoted as providing meaningful insights into other forms of connectivity (e.g., groundwater, biogeochemical, biotic) that clearly transcend degrees of upland embeddedness. We define surface water connectivity as flow of surface water (episodic, seasonal, or semi-permanent) between two unique landscape elements that may or may not be linked by an aquatic feature with a bed and bank (i.e., channel or other indicators of flow permanence).

Dynamic Surface-Water Connections

Upland-embedded wetlands occur along continuous spatial and temporal gradients, from highly connected to highly disconnected (Cohen et al. 2016). Research on upland-embedded wetlands demonstrates that many have surface-water connections to other aquatic landscape components (e.g., rivers, streams, lakes, other wetlands; Vanderhoof et al. 2016). A brief synthesis of key findings in the literature follows.

A conceptual model for thinking about how upland-embedded wetlands function at broader ecosystem scales is provided by Rains et al. (2016). They describe upland embedded wetlands as nodes in hydrological networks and state that these wetlands are "…integrally connected to uplands, other wetlands, and downgradient waters." The authors further describe complex lag, sink, and source functions of these wetlands and their resultant influences on surface-water and shallow-groundwater flows to downgradient waters (also see Golden et al. 2016). Rains et al. (2016) describe a wide range of surface-water connectivity displayed by wetlands, with wetlands identified as GIWs ranging from "infrequent/absent surface connectivity" (i.e., isolated) to "intermittent surface connectivity" (i.e., clearly not isolated). Likewise, Leibowitz (2015) describes GIWs that range from a wetland connected to a river by surface flow through a non-channelized swale to a geographically isolated wetland that is hydrologically isolated from a river. The key feature of the continuous range of surface-water connectivity described by both Leibowitz (2015) and Rains et al. (2016) is magnitude and timing, not the degree to which a wetland is surrounded by upland. While the "isolated" term has been used to describe the surface connections of all upland-embedded wetlands, the term describes only a subset of GIWs.

Consider work in the Prairie Pothole Region (PPR) of the Midwestern USA. Wetlands in this region have long been iconic examples of "geographically isolated" wetlands (Tiner 2003a) yet current research has documented high levels of hydrologic, biologic, and biogeochemical connectivity (Marton et al. 2015; Mushet et al. 2015; Cohen et al. 2016; Leibowitz et al. 2016; McLean et al. 2016). For example, Leibowitz et al. (2016) described the complex spill-and-fill and spill-and-merge surface-water connectivity of eight prairie pothole wetlands over a 26-year period (1979–2015). Their findings suggest that research exploring the effects of surface-water connections needs to address the specific types of connections and not broader categories. Further, in a detailed analysis of wetland hydrology, Hayashi et al. (2016) demonstrated how Midwestern USA prairie pothole wetlands and their upland catchments function as integrated units whose existence depends on the lateral movement of both subsurface and surface runoff water. Furthermore, they found that differences in surface-water connectivity among individual wetlands controlled ponded-water permanence, leading to a diversity of wetland functional types within wetland complexes.

The importance of surface-water connections to many wetlands considered to be "geographically isolated" is also supported by research that has documented high levels of hydrologic, biologic, and biogeochemical connectivity among vernal pools in California, USA (Golden et al. 2016; Rains et al. 2016). Western vernal pools are small depressional wetlands commonly connected by swales to one another and downgradient waters.

The climate of this landscape is Mediterranean with pronounced wet and dry seasons. In the dry season, the variable source area from which streamflow is derived contracts and vernal pools may present as upland or upland- embedded wetlands. However, in the wet season, these vernal pools and swales become part of the river network system. These surface-water connections are not speculative or insubstantial, with measured surface-water connections for as many as 150–200 days being reported (Rains et al. 2006; Rains et al. 2008).

The condition of being wholly embedded within an upland matrix does not reliably indicate lack of surface water connectivity to other aquatic ecosystems. In short, there is a continuum of connectivity that applies to an individual wetland, complexes of wetlands, and wetlands within an ecoregion. Furthermore, abiotic factors including soil type, precipitation patterns and geomorphology are often significant factors influencing degrees and nature of surface water connections, but these factors are not accounted for by the label "geographically isolated" (Fig. 1).

Distance as a Surrogate for Isolation

A reexamination of the commonly used practice of identifying upland-embedded wetlands based on distance from a stream or large water body reveals that this methodology may result in a gross overestimate of the number of wetlands lacking significant surface flows to downstream waters (i.e., the condition that the GIW designation is assumed to identify). Vanderhoof et al. (2016) found notable variation among ecoregions in empirically measured distances at which wetlands connected via surface water to mapped streams, making it problematic to identify surface-water connected wetlands based on distance alone. For example, in the Des Moines Lobe ecoregion of the PPR, the authors found that 78% of surface-water connected wetlands were located within 400 m of a mapped stream. However, in the Drift Plains ecoregion of the PPR, only 52% of the connected wetlands were located within that same stream-buffer distance. Relative to these findings, most buffer distances previously used to identify upland-embedded wetlands (e.g., 76 m, Levin et al. 2002; 20–40 m, Tiner et al. 2002 and Tiner 2003b; 10 m, Frohn et al. 2009; 10 m, Reif et al. 2009; 20 or 40 m buffer for small streams and 300 m for large streams, Vance 2009; 10 m, Lane et al. 2012; 10 m, Lane and D'Amico 2016) are likely insufficient to judge surface water connectivity within some landscapes. As a result, numerous surface-water connected wetlands located beyond the threshold buffer distance are being grouped with wetlands lacking such connections. Not surprisingly, Lane and D'Amico (2016) found that increasing their 10-m buffer distance to 300 m resulted in a significant decrease in the number of putative GIWs in multiple ecoregions across the US. Further, Golden et al. (2016) found in their modeling assessment of the influence of GIWs on downgradient streamflow in the lower Neuse River Basin, North Carolina, USA, that the farther upland-embedded wetlands were located from downgradient streams, the greater their potential contributions to streamflow across long time scales (i.e., seasonally and annually). With the inclusion of all wetlands in the analyses, this effect disappeared. Therefore, many quantifications of upland-embedded wetlands likely have overestimated occurrence of non-connected wetlands

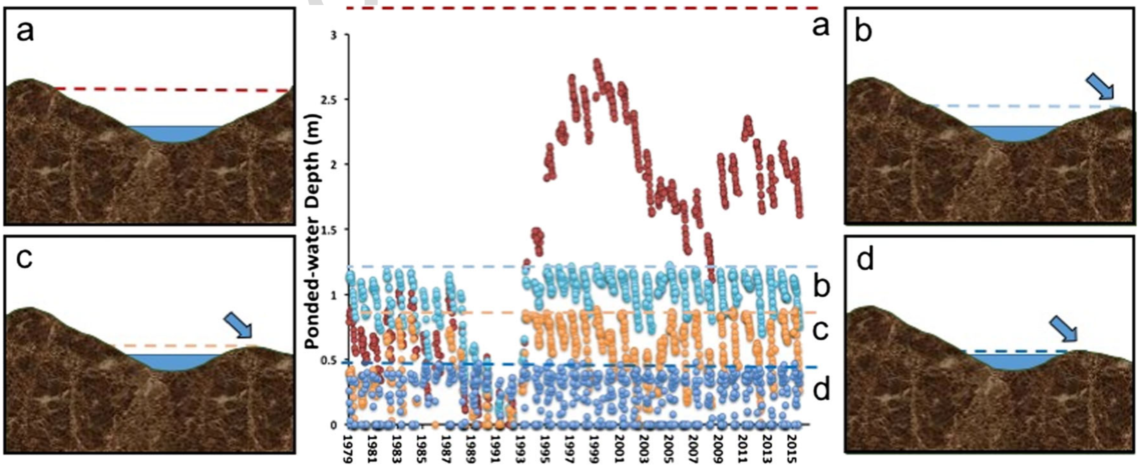

Fig. 1 Little knowledge about magnitude and timing of surface-water connectivity is gained by knowing that a wetland is surrounded by upland, i.e., is "geographically isolated." The above hydrograph displays water levels of four "geographically isolated" prairie-pothole wetlands (labeled a–d) at the Cottonwood Lake Study Area in Stutsman County, North Dakota, over a 36-year period (1979–2015). The drawings on the left and right of the hydrograph characterize the upland-embedded basins of the wetlands. External spill points (arrows), as defined by Leibowitz et al. (2016), set limits (color-coded dashed lines) to water storage and thus the magnitude of water losses from these wetland basins. Wetland P1 (**a**) is situated within a deep basin that does not have a realized external spill-point and thus does not contribute (i.e., spill) to down-gradient surface-water flows. By contrast, wetlands P8 (**b**), P3 (**c**), and T6 (**d**) each, to varying degrees, contribute to down-gradient flows when water levels reach an external spill point. The magnitude and timing of these surface-water flows vary greatly with similarly variable hydrological, geochemical and ecological effects

since the multitude of connected wetlands outside the buffer distance are identified as isolated. Furthermore, Lang et al. (2012) found that commonly available stream vector datasets (e.g., the US Geological Survey National Hydrography Dataset [NHD]) used to quantify wetland–stream connections underestimate stream length, at least in relatively wet regions like the eastern US. This is partially explained by the fact that the NHD dataset was not designed to map ephemeral streams or streams < 1.6 km in length. Lang et al. (2012) concluded that these factors would lead many wetlands to be incorrectly considered to be disconnected from the stream network. This is counter to arguments that quantifications derived using buffers are conservative estimates of the numbers of upland-embedded wetlands (Leibowitz 2015).

Direct pre-identification of upland-embedded wetlands will continue to lessen the guesswork currently employed in establishing regulatory connectivity. For example, Wu and Lane (2016) developed a new approach to identifying wetland depressions in the PPR that accounts for dynamic filling, spilling and merging hydrological processes not considered in previous algorithms designed to identify such depressions (Leibowitz et al. 2016). Even low-tech methods involving using local knowledge and ground-truthing involving citizen-scientists can produce important information on current pools and past occurrences of connectivity. Levesque et al. (2016) describe a vernal pool conservation initiative in New England, USA, that recognizes the landscape-scale functions of vernal pools and encourages conservation of "poolscapes" in partnership with land trusts and other conservation groups who recognize the value of conserving ecosystem connections—work all driven by community based collaboration.

Proximity to mapped streams and other drainage features have been used as proxies for surface water connectivity (see above) because of the difficulty inherent in quantifying surface-water connectivity (Lane and D'Amico 2016). More advanced technologies and approaches provide promising solutions to better characterize connectivity. For example, other methods that could be examined include direct monitoring of inundation patterns using lidar intensity, multispectral and synthetic aperture radar data, predicting flow based on slope derived from lidar-based digital elevation models, and using process-based hydrologic models parameterized using geospatial data. Methodologies that move away from a categorical definition of geographically isolated wetlands and more closely approximate the adjacent versus non-adjacent definition will be better aligned with current legal/regulatory needs.

Legal/Regulatory Considerations

In the years immediately following the U.S. Supreme Court's 2001 decision in *SWANCC* (*Solid Waste Agency of Northern Cook County* [*SWANCC*] vs. *US Army Corps of Engineers*, *531 US 159*), there was a great deal of confusion regarding the concept of an "isolated" wetland. In scientific literature, this term was commonly used to describe various types of depressional wetlands (e.g., Damman and French 1987; Semlitsch and Bodie 1998; Bailey 1999). Following scientific usage, the Corps of Engineers promulgated a regulatory definition of "isolated wetland" for administration of their Nationwide Permit Program (NWP) 26 (33 CFR 330.2(e)). Prior to *SWANCC*, neither usage was relevant to Clean Water Act (CWA) jurisdiction (Downing et al. 2003). Following the *SWANCC* and later *Rapanos* (*Rapanos* vs. *United States*, *547 U.S. 715*,*2006* decisions), existing definitions were muddied by case law that misinterpreted scientific and regulatory concepts of "isolation" and "adjacency" as end-members of waterbody functional connectivity. At its inception, the term "geographically isolated wetland" was meant to correct this misinterpretation and avoid further error (e.g., Tiner et al. 2002; Leibowitz 2003; Tiner 2003a). Unfortunately, the clarification presented in those seminal publications warning that geographic isolation should not be used to infer functional isolation did not communicate well to other communities of practice. For example, in genetics, "geographic isolation" has a long-used and well-defined functional definition (Mushet et al. 2015). The science now shows that the degree of wetland surface-water connectivity cannot be assessed in a meaningful way by a simple determination of upland embeddedness (USEPA 2015; Rains et al. 2016; Cohen et al. 2016).

The recent Clean Water Rule (CWR, 80 FR 37054), which is currently stayed, does not use the GIW term, suggesting that federal agencies have moved beyond consideration of "geographic isolation" as a factor for determining CWA jurisdiction. Instead, the rule recognizes the best-available science by establishing five subcategories of wetlands (prairie potholes, Carolina and Delmarva bays, pocosins, western vernal pools in California, and Texas coastal prairie wetlands) that must be considered as "similarly situated" (that is, functioning as systems at the watershed scale) rather than as individual wetland basins, when determining their influence on navigable waters (CWR, 80 FR 37054). This consideration of the watershed-scale cumulative effects of wetlands and wetland complexes rather than individual basins is a large step forward from the localized, basin-scale assessments inherent in GIW categorization (Tiner 2003a; and Leibowitz 2015).

Conclusions

Recent research findings show that wetlands surrounded by uplands vary greatly in occurrence, type, as well as frequency, timing, and importance of surface-water connections to other aquatic systems (Rains et al. 2016; Cohen et al. 2016). Ambiguous generalizations about degrees of connectivity and isolation between upland-embedded wetlands and other wetlands and downstream waters are illogical (Mushet et al. 2015). The single condition of being surrounded by uplands currently used by wetland scientists to define "geographic isolation" does not provide a useful separation between wetlands that have a significant surface-water connection and those that do not. Upland embeddedness does not necessarily provide any indication that these wetlands are functionally "isolated."

Current research on connectivity of wetlands to downstream waters clearly shows that scientific needs are best met when gradients of surface-water connectivity are considered rather than through the use of a grouping defined by a threshold that does not reliably separate surface water connected/isolated wetlands, yet alone functionally connected/isolate wetlands. Embracing this knowledge requires a rethinking of our use of the "geographically isolated wetlands" misnomer and opens up advanced avenues to conserving wetland landscapes. Fully embracing the scientific knowledge gained since inception of the GIW grouping, knowledge that has identified the inherent connectedness of these "isolated" wetlands individually and as complexes, is needed to facilitate the long-term conservation of these important, and increasingly threatened, wetland resources. Conservation decisions cannot be made based on a broad category that, while created to help alleviate confusion over the term "isolated," has instead further muddied the waters. Recognizing the diverse functions supported by gradients of wetland connectivity will lead to better conservation of all wetland resources.

Acknowledgements We thank Heather Golden and two anonymous reviewers for providing their critical reviews of an earlier draft of this manuscript. We also thank participants of a "Geographically Isolated Wetlands Research Workshop" convened and co-hosted by the U.S. Environmental Protection Agency Office of Research and Development and the Joseph W. Jones Ecological Research Center and held in Newton, GA, November 18–21, 2013, for contributing to the ideas and discussions within which this and our previous manuscript originated. We also thank Scott Leibowitz for providing the impetus needed to encourage our further explorations into the use and misuse of the GIW terminology. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. USGS Cottonwood Lake Study Area water-level data used in Fig. 1 is available at: http://dx.doi.org/10.5066/F7707ZJ6. The findings and conclusions in this article are those of the authors and USGS and do not necessarily represent the views of the U.S. Fish and Wildlife Service.

This is Maine Agricultural and Forest Experiment Station Publication # 3517.

References

Bailey MA (1999) Small isolated wetlands: vital to diversity. Alabama Wildlife Federation, Montgomery, AL. Alabama Wildlife Magazine Archives. (www.alawild.org/wetland.htm)

Q3 Calhoun AJK, Mushet DM, Bell KP, Boix D, Fizsimons JA, Isselin-Nondedeu F (2017) Temporary wetlands: challenges and solutions for protecting a "disappearing" ecosystem. Biological Conservation

Cohen MJ, Creed IF, Alexander L, Basu NB, Calhoun AJK, Craft C, D'Amico E, DeKeyser E, Fowler L, Golden HE, Jawitz JW, Kalla P, Kirkman LK, Lane CR, Lang M, Leibowitz SG, Lewis DB, Marton J, McLaughlin DL, Mushet DM, Raanan-Kiperwas H, Rains MC, Smith L, Walls SC (2016) Do geographically isolated wetlands influence landscape functions? Proceedings of the National Academy of Sciences 113:1978–1986

Damman AWH, French TW (1987) The ecology of peat bogs of the glaciated northeastern United States: a community profile. U.S. Fish and Wildlife Service, Washington, DC, USA. Biological Report 85(7.16)

Downing DM, Winer C, Wodd LD (2003) Navigating through Clean Water Act jurisdiction: a legal review. Wetlands 23:475–493

Frohn RC, Reif M, Lane C, Autrey B (2009) Satellite remote sensing of isolated wetlands using object-oriented classification of Landsat-7 data. Wetlands 29:931–941

Golden HE, Sander HA, Lane CR, Zhao C, Price K, D'Amico E, Christensen JR (2016) Relative effects of geographically isolated wetlands on streamflow: a watershed-scale analysis. Ecohydrology 9:21–38

Hayashi M, van der Kamp G, Rosenberry DO (2016) Hydrology of prairie wetlands: understanding the integrated surface-water and groundwater processes. Wetlands. doi:10.1007/s13157-016-0797-9

Lane CR, D'Amico E (2016) Identification of putative geographically isolated wetlands of the conterminous United States. Journal of the American Water Research Association 52:701–722

Lane CR, D'Amico E, Autrey B (2012) Isolated wetlands of the southeastern United States: abundance and expected condition. Wetlands 32:753–767

Lang M, McDonough O, McCarty G, Oesterling R, Wilen B (2012) Enhanced detection of wetland-stream connectivity using LiDAR. Wetlands 32:461–473

Leibowitz SG (2003) Isolated wetlands and their functions: an ecological perspective. Wetlands 23:517–531

Leibowitz SG (2015) Geographically isolated wetlands: why we should keep the term. Wetlands 35:997–1003

Leibowitz SG, Mushet DM, Newton WE (2016) Intermittent surface water connectivity: fill and spill vs. fill and merge dynamics. Wetlands. doi:10.1007/s13157-016-0830-z

Levin GA, Suloway L, Plocher AE, Hutto FR, Miner JJ, Phillips CA, Agarwal J, Lin Y (2002) Status and function of isolated wetlands in Illinois. Illinois Natural History Survey, Champaign, **Special Publication 23**

Levesque V, Calhoun AJK, Bell KP (2016) Turning contention into collaboration: engaging power, trust, and learning in collaborative networks. Society and Natural Resources. doi:10.1080/08941920.2016.1180726

Marton JM, Creed IF, Lewis DB, Lane CR, Basu NB, Cohen MJ, Craft CB (2015) Geographically isolated wetlands are important biogeochemical reactors on the landscape. BioScience 65:408–418

McLean K, Mushet DM, Stockwell CA (2016) From "duck factory" to "fish factory": climate induced changes in vertebrate communities of prairie pothole wetlands and small lakes. Wetlands. doi:10.1007/s13157-016-0766-3

Mushet DM, Calhoun AJK, Alexander LC, Cohen MJ, DeKeyser ES, Fowler L, Lane CR, Lang MW, Rains MC, Walls SC (2015) Geographically isolated wetlands: rethinking a misnomer. Wetlands 35:423–431. doi:10.1007/s13157-015-0631-9

Rains MC, Dahlgren RA, Williamson RJ, Fogg GE, Harter T (2008) Geological control of physical and chemical hydrology in vernal pools, Central Valley, California. Wetlands 28:347–362

Rains MC, Leibowitz SG, Cohen MJ, Creed IF, Golden HE, Jawitz JW, Kalla P, Lane CR, Lang MW, McLaughlin DL (2016) Geographically isolated wetlands are part of the hydrological landscape. Hydrological Processes 30:153–160

Rains MC, Fogg GE, Harter T, Dahlgren RA, Williamson RJ (2006) The role of perched aquifers in hydrological connectivity and biogeochemical processes in vernal pool landscapes, Central Valley, California. Hydrological Processes 20:1157–1175

Reif M, Frohn RC, Lane CR, Autrey B (2009) Mapping isolated wetlands in a karst landscape: GIS and remote sensing methods. GIScience & Remote Sensing 46:187–211

Semlitsch RD, Bodie JR (1998) Are small, isolated wetlands expendable? Conservation Biology 12:1129–1133

Tiner RW (2003a) Geographically isolated wetlands of the United States. Wetlands 23:494–516

Tiner RW (2003b) Estimated extent of geographically isolated wetlands in selected areas of the United States. Wetlands 23:636–652

Tiner RW, Bergquist HC, DeAlessio GP, Starr MJ (2002) Geographically isolated wetlands: A preliminary assessment of their characteristics and status in selected areas of the United States. U.S. Department of the Interior, Fish and Wildlife Service, Northeast Region, Hadley

U.S. Environmental Protection Agency (USEPA) (2015) Connectivity of Streams & Wetlands to Downstream Waters: A Review & Synthesis of the Scientific Evidence. EPA/600/R-14/475F. U.S. Environmental Protection Agency, Washington, DC

Vance LK (2009) Geographically isolated wetlands and intermittent/ephemeral streams in Montana: extent, distribution, and function. Report to the Montana Department of Environmental Quality and the U.S. EPA. Montana Heritage Program, Helena

Vanderhoof MK, Christensen JR, Alexander LC (2016) Patterns and drivers for wetland consolidation in the Prairie Pothole Region, United States. Wetlands Ecology and Management. doi:10.1007/s11273-016-9516-9

Wu Q, Lane CR (2016) Delineation and quantification of wetland depressions in the Prairie Pothole Region of North Dakota. Wetlands 36:215–227