EPA Public Access

Author manuscript

Hydrol Process. Author manuscript; available in PMC 2019 January 01.

About author manuscripts

Submit a manuscript

Published in final edited form as:

Hydrol Process. 2018 ; 32(2): 305–313. doi:10.1002/hyp.11405.

Estimating restorable wetland water storage at landscape scales

Charles Nathan Jones^{1,2}, Grey R. Evenson², Daniel L. McLaughlin², Melanie K. Vanderhoof³, Megan W. Lang⁴, Greg W. McCarty⁵, Heather E. Golden⁶, Charles R. Lane⁶, and Laurie C. Alexander⁷

¹The National Socio-Environmental Synthesis Center, University of Maryland, 1 Park Place, Suite 300, Annapolis, MD 21401, USA

²Department of Forest Resources and Environmental Conservation, Virginia Tech, Cheatham Hall, Rm 313, 310 W Campus Dr, Blacksburg, VA 24061, USA

³U.S. Geological Survey Geosciences and Environmental Change Science Center, P.O. Box 25046, DFC, MS 980, Denver, CO 80225, USA

⁴USFWS National Wetlands Inventory Program, 5275 Leesburg Pike, Falls Church, VA 22041, USA

⁵USDA-ARS Hydrology and Remote Sensing Laboratory, 10300 Baltimore Avenue, BLDG. 007, RM. 104, BARC-WEST, Beltsville, MD 20705, USA

⁶USEPA Office of Research and Development, National Exposure Research Laboratory, 26 West Martin Luther King Drive, Mail Code: 587, Cincinnati, OH 45268, USA

⁷USEPA Office of Research and Development, National Center for Environmental Assessment, William Jefferson Clinton Building, 1200 Pennsylvania Avenue, N. W., Mail Code: 8623P, Washington, DC 20460, USA

Abstract

Globally, hydrologic modifications such as ditching and subsurface drainage have significantly reduced wetland water storage capacity (i.e., volume of surface water a wetland can retain) and consequent wetland functions. While wetland area has been well documented across many landscapes and used to guide restoration efforts, few studies have directly quantified the associated wetland storage capacity. Here, we present a novel raster-based approach to quantify both contemporary and potential (i.e., restorable) storage capacities of individual depressional basins across landscapes. We demonstrate the utility of this method by applying it to the Delmarva Peninsula, a region punctuated by both depressional wetlands and drainage ditches. Across the entire peninsula, we estimated that restoration (i.e., plugging ditches) could increase storage capacity by 80%. Focusing on an individual watershed, we found that over 59% of restorable storage capacity occurs within 20 m of the drainage network, and that 93% occurs within 1 m elevation of the drainage network. Our demonstration highlights widespread ditching in this landscape, spatial patterns of both contemporary and potential storage capacities, and clear opportunities for hydrologic restoration. In Delmarva and more broadly, our novel approach can

inform targeted landscape-scale conservation and restoration efforts to optimize hydrologically mediated wetland functions.

1 LOSS AND RESTORATION OF WETLAND SURFACE WATER STORAGE

Water storage in wetlands enables a suite of hydrologic, biogeochemical, and biological functions (Cohen et al., 2016). While wetland definitions vary widely from broad descriptions that highlight inundation or saturation (e.g., Ramsar Convention, 2016) to more stringent requirements for regulatory purposes (e.g., U.S. Army Corp of Engineers, 1987), all implicitly include wetlands' ability to store water. From a landscape perspective, wetland water storage capacity has been shown to modulate both high and low stream flows (e.g., Evenson, Golden, Lane, & D'Amico, 2016; McLaughlin, Kaplan, & Cohen, 2014), improve downstream water quality through increased water residence times (e.g., via denitrification; Cheng & Basu, 2017), and support critical habitat functions (e.g., provide required inundation for amphibian development; Biggs, von Fumetti, & Kelly-Quinn, 2017). Nonetheless, wetlands (and their storage capacity) remain one of the most vulnerable ecosystems to alteration and loss (Gibbs, 2000), necessitating efforts to restore and conserve wetland water storage capacities and novel approaches to inform those efforts.

Historically, artificial drainage (e.g., ditching and subsurface "tile" drainage) was one of the most common techniques used to convert or otherwise hydrologically alter wetlands for agricultural or urban land uses. In the USA, this tradition can be traced back to colonial agricultural practices (Levy, 1991). Conversion of wetlands for large-scale agriculture continued throughout the 1800s, when Congress encouraged wetland drainage through the Swamp Land Acts, and into the early 1900s with Depression-era Civilian Conservation Corps projects for mosquito control (Bourn & Cottam, 1950). Today, extensive drainage systems are widely used for agricultural production throughout the Midwest and eastern USA (Blann, Anderson, Sands, & Vondracek, 2009), where their prevalent use reduces wetland water storage and subsequent functions at local to landscape scales.

Wetland drainage has resulted in extensive wetland loss and degradation, with attendant and large (but unknown) loss of water storage capacity at landscape scales. Roughly 47.4 million hectares of wetlands, or 53% of estimated wetland area across the continental USA, were lost between European settlement and 1980 (Dahl, 1990); more recent estimates document continued loss (e.g., Davidson, 2014; Dixon et al., 2016). Loss has been most concentrated in the Midwestern and eastern USA, where some states have lost more than 90% of their wetland area. However, these estimates are based on loss of wetland area, and there are no concurrent estimates of large-scale loss of wetland surface water storage. Yet, contemporary restoration practices prioritize wetland water storage volume in design to target a suite of associated wetland functions (e.g., from water quality and stormwater storage to habitat; Millhollon et al., 2009). Going forward, innovative tools are needed to enumerate current and potential (i.e., restorable) water storage and, in doing so, better inform landscape-scale wetland conservation and restoration plans to target priority locations and maximize ecosystem service provision.

With emerging remote sensing datasets and methodological advances, large-scale quantification of wetland water storage capacity is becoming possible. Current tools for quantifying wetland storage capacity include methods using available topographic data and either empirical relationships (e.g., Gamble, Grody, Undercoffer, Mack, & Micacchion, 2007; Haag, Lee, & Herndon, 2005) or contour-based approaches (e.g., Wu & Lane, 2016). High-resolution, airborne light detection and ranging (LiDAR) data are becoming more readily available, enabling catchment and even regional topographic analyses (e.g., Huang et al., 2011; Kessler & Gupta, 2015; Lane & D'Amico, 2010). Taking advantage of this increasingly available technology, here we present a new raster-based approach to quantify both (a) contemporary wetland storage capacities (Figure 1a) and (b) potential wetland storage capacities that could be achieved through hydrologic restoration (i.e., ditch plugging; Figure 1b). We apply this approach to the greater Delmarva Peninsula, a low-gradient landscape in the U.S. mid-Atlantic Coastal Plain, much of which drains to the culturally and ecologically significant Chesapeake Bay. Further highlighting the potential utility of this approach to target restoration and conservation efforts, we also investigate the spatial distribution of wetland storage capacities within a single watershed, an important factor controlling landscape hydrology and associated function (e.g., Babbar-Sebens, Barr, Tedesco, & Anderson, 2013).

2 A NEW APPROACH TO QUANTIFY RESTORABLE WETLAND WATER STORAGE CAPACITIES

2.1 Description of approach

Our approach employs fine spatial resolution, LiDAR-derived digital elevation models (DEMs) to delineate depressional basins and their wetland water storage capacities under both current and potentially restored conditions. Here, we define depressional basins as the small, internally draining (i.e., endorheic) watersheds that punctuate many low-gradient landscapes and that typically contain wetland features where water accumulates (e.g., Wu & Lane, 2017). In this context, we also define wetland storage capacity as the maximum surface water volume each depressional basin can store without spilling to downgradient waters. The identification of the spill threshold, or the inundation depth where surface water discharges out of the depressional basin, is a key component of the presented approach and allows for the delineation of both contemporary and potential storage capacities. Note that our measure of storage capacity represents the maximum volume of possible storage that may or may not be realized via time-varying, actual water storage.

Our approach consists of three major components: (a) identification of depressional basins, (b) estimation of water depth to storage volume relationships, and (c) identification of water depths that result in surface water spillage out of the basin. First, we delineate internally draining basins (i.e., depressional basins; Figure 1c) using standard DEM processing procedures. Briefly, this includes filling sinks in the DEM less than the vertical accuracy of the LiDAR, smoothing the DEM with a Gaussian moving window filter, and identifying internally draining basins using the deterministic 8-flow direction algorithm (e.g., O'Callaghan & Mark, 1984). In order to avoid inclusion of major stream channels, we then remove depressional basins that intersect National Hydrography Dataset flow lines.

Second, we develop relationships among inundation depth, area, and storage volume for each individual depressional basin (Figure 1d). Specifically, we use conditional raster algebra to estimate inundated area (and associated storage volume) by identifying cells at elevations equal to or lower than specific inundation depths; doing so incrementally results in estimates of inundated volume and area as functions of inundation depth (see Jones, Scott, Guth, Hester, & Hession, 2015 for further details). Because LiDAR does not capture topography for areas inundated during data collection, we also account for “below water volume” for such areas utilizing techniques and previously established bathymetric relationships presented in Gleason, Tangen, Laubhan, Kermes, and Euliss (2007), Kessler and Gupta (2015), and Wu and Lane (2016).

Finally, we identify spill thresholds for each delineated depressional basin to estimate contemporary storage capacity, presence/absence of ditching, and, if appropriate, the potential storage capacity that could be achieved via ditch filling. To estimate contemporary storage capacity, we identify the minimum inundation depth and associated volume that generates inundation (and thus spillage) at the basin boundary (Figure 1e). We then determine the presence or absence of a ditch by examining the length of the basin boundary that experiences inundation (i.e., spill boundary length; secondary y-axis in Figure 1d). If the spill boundary length is less than or equal to 3 m (i.e., resolution of available DEM), we assume that the basin is drained through surface ditching (i.e., a narrow, artificial conveyance; Figure 1e). For these ditched basins, we also estimate the potential storage capacity by identifying the minimum inundation depth and associated volume that produces a spill boundary length greater than 3 m, which is assumed to represent more distributed, natural basin spillage (Figure 1f). Here, potential storage capacity represents the maximum storage volume that could be achieved through hydrologic restoration (i.e., plugging the ditch). All analyses are conducted using ESRI ArcGIS Version 10.2 and the RPyGeo (Brenning, 2012), raster (Hijmans, 2015), sp (Pebesma & Bivand, 2005), and rgdal (Bivand & Rundel, 2016) packages within the R Statistical Software environment (R Core Development Team, 2017). Relevant R code can be found in the Supplemental Material.

It is important to highlight specific limitations of our approach. First, it utilizes contemporary topographic data (i.e., representative of a hydrologically altered landscape) to define internally draining basins, and as such, does not directly capture historical distributions of wetlands (e.g., Van Meter & Basu, 2015; Serran & Creed, 2016; Serran, Creed, Ameli, & Aldred, 2017). Instead, our analysis enumerates spatial distributions of contemporary and potentially restorable wetland storage capacities (sensu Gleason et al., 2007). Our approach also does not account for subsurface drainage features (e.g., tile drainage, road culverts), which likely modify contemporary storage capacities for locations where such features occur. Other potential sources of uncertainty include the representation of spill mechanism (e.g., conveyance vs. merging; Leibowitz, Mushet, & Newton, 2016), commission or omission of depressional basins (e.g., Vanderhoof, Distler, Lang, & Alexander, 2017), and uncertainty associated with the LiDAR-derived DEM (e.g., Lang, McDonough, McCarty, Oesterling, & Wilen, 2012). Further, our approach does not directly account for surface volume that was inundated during LiDAR collection, but instead relies on previously developed bathymetric relationships (e.g., Gleason et al., 2007; Kessler & Gupta, 2015; Wu & Lane, 2016).

2.2 Application to the Delmarva Peninsula

The greater Delmarva Peninsula is an ideal landscape to apply and test our new approach for quantifying wetland storage capacity at large spatial scales. The Delmarva Peninsula is roughly 14,000 km² and forms the eastern boundary of the Chesapeake Bay. Delmarva is predominantly a low-gradient landscape where hydrology is defined by both an abundance of wetlands, many of which have a depressional morphology, and agricultural ditches that drain many of those wetlands (Fenstermacher, Rabenhorst, Lang, McCarty, & Needelman, 2014; McDonough, Lang, Hosen, & Palmer, 2014). Wetland features include riparian wetlands, wetland flats, and Delmarva bays (Tiner, 2005). Delmarva bays are of particular interest, as they are often considered geographically isolated (surrounded completely by uplands; Tiner, 2003; Mushet et al., 2015) and are particularly vulnerable to development (Sharitz, 2003). Fenstermacher et al. (2014) estimate that approximately 70% of historical Delmarva bays have been hydrologically impacted by agriculture, often resulting in the loss of wetland water storage within the depressional basin. Consequently, there are growing efforts to restore Delmarva bays across the region through water quality improvement programs associated with the larger Chesapeake Bay Watershed restoration effort (e.g., Shenk & Linker, 2013; Yepsen et al., 2014). Many restoration projects plug or fill-in ditches, essentially re-establishing wetland hydrologic regime and water storage capacity (De Steven & Lowrance, 2011). Quantification of contemporary and potential wetland storage capacities could better inform such large-scale restoration efforts in the Delmarva and other impaired landscapes.

In this demonstration, we (a) estimated contemporary and potential wetland storage capacity for the entire Delmarva Peninsula, and then (b) examined spatial distribution of wetland storage capacity within the Greensboro watershed, a ~290 km² watershed draining to the Chesapeake Bay (Figure 2). The LiDAR data used for both stages of this study were collected during the springs of 2003 and 2006 by the Maryland Department of Natural Resources, with a vertical accuracy of 18 cm root mean square error and horizontal accuracy 50 cm (See Lang et al., 2012 for more details). To describe the spatial distribution of wetland storage capacity in the Greensboro watershed, we focused on variations in position (elevation and distance) of storage capacity relative to the nearest drainage feature. To do so, we used a fine resolution stream dataset that includes the derivation of perennial, intermittent, and ephemeral streams and some agricultural drainage ditches (Vanderhoof et al., 2017), representing a more spatially resolved drainage network compared to the National Hydrography Dataset. With these data representing drainage networks, we first examined variation in wetland storage capacity as a function of height above the nearest drainage feature. Cumulative wetland storage capacity (across the watershed) was quantified incrementally as a function of elevation above the drainage network, where the drainage network elevation was interpolated across the watershed using inverse distance weighting (e.g., Jones, Poole, O'Daniel, Mertes, & Stanford, 2008). Second, we quantified variations in wetland storage capacity as a function of Euclidean distance between each basin's centroid and the nearest drainage feature.

3 CONTEMPORARY AND POTENTIAL WETLAND STORAGE CAPACITY AT VARYING SPATIAL SCALES

Using our new approach, we first quantified contemporary and potential wetland storage capacity for individual depressional basins. Across Delmarva, we identified approximately 102,000 depressional basins, 48% of which were classified as ditched (i.e., their spill boundary length was less than 3 m). We then aggregated storage capacity values to U.S. Geological Survey hydrologic unit subwatersheds (i.e., HUC12s, U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service, 2009) and calculated specific storage capacity by dividing by total watershed area. Contemporary specific storage capacity (for HUC12s) ranged from 0.1 to 11.9 cm (median = 2.8 cm), whereas potential specific storage capacity ranged from 0.15 to 20.4 cm (median = 5.1 cm; Figure 2). When aggregated to the entire Delmarva Peninsula, we estimated cumulative contemporary and potential specific storage capacities of 4.1 (or $8.9 \times 10^8 \text{ m}^3$) and 7.3 cm ($1.6 \times 10^9 \text{ m}^3$), respectively (Figure 2). In short, restoring depressional basins (i.e., filling in the ditches) would potentially increase the landscape's wetland storage capacity by more than 80%.

Here, it is important to reiterate that our approach does not account for possible subsurface drainage features such as tile drains and culverts. While surface ditching (as opposed to tile drainage) is the primary form of drainage across Delmarva (e.g., Fenstermacher et al., 2014), culverts draining road-side ditches likely impact surface water storage in certain locations. To assess possible effects of these road-side drainage features on wetland storage capacity across Delmarva, we identified depressional basins that intersected roads (defined by U.S. Department of Commerce, 2015). Of the over 102,000 delineated depressional basins, approximately 45% intersect roads, and 17% accumulate possible water storage within 3 m of a road. The latter accounts for 28% of contemporary wetland storage capacity, some of which is likely altered through subsurface infrastructure (e.g., culverts). This highlights a limitation of our approach, but also the likely impact road networks have on wetland ecosystems and function.

To further demonstrate the approach's utility, we examined spatial variation in wetland storage capacity within a single watershed using the Greensboro watershed as a case study (Figures 2, 3). We delineated 2,400 depressional basins in the Greensboro watershed, 87% of which coincided with wetlands delineated via an alternative approach by Vanderhoof et al. (2017), suggesting our approach produced an adequate representation of wetland distribution. These delineated basins contribute approximately 1.6% and 2.2% of the contemporary and potential wetland storage capacity for the entire Delmarva Peninsula, respectively. We found that 93% of contemporary storage capacity (vs. 73% of land surface across the entire watershed area) is 1 m or less above drainage feature elevation (Figure 3c), highlighting the likely interaction of water storage and surficial aquifer dynamics that regulate stream baseflow (e.g., McLaughlin et al., 2014). Notably, that volume could be increased by over 250% if potential storage volume was realized (Figure 3c). We also examined the distribution of wetland storage capacity as Euclidean distance from drainage features. All depressional basins were within 400 m of a drainage feature, and 32% and 59%

of contemporary and potential wetland storage capacities, respectively, were found within 20 m of a drainage feature (Figure 3d). In other words, most wetland water storage occurs proximally to the drainage network, where ditches have preferentially and substantially reduced storage capacities.

4 A NEW TOOL TO INFORM LANDSCAPE-SCALE WETLAND CONSERVATION AND RESTORATION

Quantifying wetland storage capacity provides valuable information for managing and restoring hydrologically driven functions such as stormflow mitigation, water quality improvements, and support of aquatic habitat (Lane & D'Amico, 2010). Many studies have examined wetland area and its loss at regional (e.g., Sofaer et al., 2016; Van Meter & Basu, 2015) and even continental scales (e.g., Dahl, 2011), helping to guide wetland restoration and conservation programs; however, no studies have directly examined coincident loss of wetland water storage capacity. Our work provides an approach that both approximates loss of wetland storage capacity (contemporary vis-à-vis restorable) and more directly informs restoration and conservation efforts.

Wetland storage capacity is a common design parameter for local wetland restoration projects, as well as an emerging parameter now being used in watershed-scale modelling and management. Storage capacity regulates water residence times and is thus optimized in restoration and construction projects aimed at decreasing peak stormflow and improving water quality (Millhollon et al., 2009). Similarly, restored wetland storage capacities are often designed to adjust hydrologic regime (e.g., inundation depth and duration) to target specific aquatic habitat conditions (e.g., dry season inundation for salamanders; Chandler et al., 2017). For similar reasons, innovative modelling tools for watershed-scale management (Golden et al., 2017) are beginning to utilize spatially explicit wetland storage capacity data to evaluate cumulative effects of wetlands on watershed inundation patterns, streamflow, and downstream water quality (e.g., Evenson et al., 2016; Fossey & Rousseau, 2016; Golden et al., 2016). Currently, these modelling efforts rely on empirical relationships that estimate storage capacity using wetland area (e.g., Brooks & Hayashi, 2002; Gamble et al., 2007; Gleason et al., 2007). While these empirical relationships are efficient and useful where fine spatial resolution LiDAR data are not available, methods presented here provide direct accounting of wetland storage capacity. Further, our approach quantifies potential wetland storage capacities, allowing managers and scientists to design restoration efforts and predict resultant improvements.

Enumerated spatial distributions of wetland storage capacity will help target efforts for wetland conservation (e.g., existing locations with high wetland storage capacity) and restoration (e.g., locations with high potential). Currently, wetland restoration practices are largely completed on an ad hoc basis, where site selection is more locally driven versus in the context of watershed-scale patterns and processes. However, recent efforts have focused on optimizing restoration site location to improve effectiveness at larger spatial scales (e.g., Babbar-Sebens et al., 2013). Using Delmarva as an example, we demonstrated how quantified wetland storage capacities could help prioritize wetland restoration at the

landscape scale, where specific watersheds (HUC 12; Figure 2) with high potential capacities could be targeted. Further, at the watershed scale, examining spatial distributions of both contemporary and potential wetland storage capacities provides insights into patterns of historical drainage to inform restoration. For example, Figure 3d highlights preferential loss of wetland storage capacity proximate to drainage features (e.g., the largest amount of potential wetland storage capacity was found within 20 m of a drainage feature), highlighting likely priority areas for conservation and restoration.

Known spatial variations in wetland storage capacities will also advance hydrological process understanding, further informing watershed management. For example, Euclidean distance has been used as a proxy for wetland-stream connectivity (e.g., Christensen, Nash, Chaloud, & Pitchford, 2016; Cohen et al., 2016; Van Meter & Basu, 2015). However, this metric and ones similar to it do not always accurately represent downstream effects, particularly subsurface interactions (Ameli & Creed, 2017). To that end, McLaughlin et al. (2014) demonstrate the effect of wetland-groundwater interactions on downstream flows, and specific to the Delmarva Peninsula, Phillips and Shedlock (1993) highlight the tight linkage between variation in wetland water volumes and surficial aquifer water levels. As such, we propose that the combination of both Euclidean distance and vertical distributions of wetland storage capacity in relation to stream networks (and their supporting aquifers) provide useful indicators of wetland effects on downstream waters. Across the Greensboro watershed, over 59% of restorable storage capacity occurs within 20 m of the drainage network, and 93% occurs within 1 m elevation of the drainage network, highlighting areas with the greatest potential for restoration efforts aimed at downstream improvements (e.g., to water quality and streamflow).

As fine spatial resolution LiDAR data become more available, the ability to determine wetland storage capacities across different regions will become a reality, advancing our ability to represent and quantify key wetland functions at varying spatial scales. The gains from more accurate wetland representation will not only increase fundamental understanding of landscape spatial patterns (Figure 3) and associated hydrologic processes, but will also better link wetland storage capacity to the local and landscape-scale functions that it mediates. For example, habitat suitability and wetland biogeochemistry models often rely on inundation depth and area to drive predictions of population success, greenhouse gas emissions, and water quality improvements (e.g., Jones, McLaughlin, Henson, Haas, & Kaplan, 2017). Coupling such models with enumerated wetland storage capacities and hydrologic models will greatly increase the scale and resolution at which we can simulate such emergent functions. Across the Delmarva and other depressional wetland-rich landscapes, spatial representation of wetland storage capacity will better enable landscape-scale conservation and restoration to optimize hydrologically mediated wetland functions.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

Acknowledgments

The work of CNJ, GRE, and DLM was supported by USDA-ARS and USEPA. The work of DLM, MWL, LCA, HEG, and CRL was supported by the John Wesley Powell Center for Analysis and Synthesis in their support of the “North American Analysis and Synthesis on the Connectivity of Geographically Isolated Wetlands to Downstream Waters.” The work of GWM and MWL was supported in part by the USDA NRCS Wetlands Conservation Effects Assessment Project (Wetlands CEAP). Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the USFWS, USDA, or USEPA, but do represent the views of the U.S. Geological Survey.

References

- Ameli AA, Creed IF. Quantifying hydrologic connectivity of wetlands to surface water systems. *Hydrology and Earth System Sciences*. 2017; 21(3):1791–1808. <https://doi.org/10.5194/hess-21-1791-2017>.
- Babbar-Sebens M, Barr RC, Tedesco LP, Anderson M. Spatial identification and optimization of upland wetlands in agricultural watersheds. *Ecological Engineering*. 2013; 52:130–142. <https://doi.org/10.1016/j.ecoleng.2012.12.085>.
- Biggs J, von Fumetti S, Kelly-Quinn M. The importance of small waterbodies for biodiversity and ecosystem services: Implications for policy makers. *Hydrobiologia*. 2017; 793(1):3–39. <https://doi.org/10.1007/s10750-016-3007-0>.
- Bivand, R., Rundel, C. rgeos: Interface to geometry engine - open source (GEOS). R package version 0.3-17. 2016. Available at: <https://cran.rproject.org/package=rgeos>
- Blann KL, Anderson JL, Sands GR, Vondracek B. Effects of agricultural drainage on aquatic ecosystems: A review. *Critical Reviews in Environmental Science and Technology*. 2009; 39(11): 909–1001. <https://doi.org/10.1080/10643380801977966>.
- Bourn, WS., Cottam, C. Some biological effects of ditching tide water marshes. DC, USA: Washington; 1950.
- Brenning, A. RPyGeo: ArcGIS geoprocessing in R via python. R package version 0.9–3. 2012. <https://CRAN.R-project.org/package=RPGeo>
- Brooks RT, Hayashi M. Depharea-volume and hydroperiod relationships of ephemeral (vernal) forest ools in southern New England. *Wetlands*. 2002; 22(20):247–255.
- Chandler HC, McLaughlin DL, Gorman TA, McGuire KJ, Feaga JB, Haas CA. Drying rates of ephemeral wetlands: Implications for breeding amphibians. *Wetlands*. 2017; 37(3):545–557. <https://doi.org/10.1007/s13157-017-0889-1>.
- Cheng, FY., Basu, NB. Biogeochemical hotspots: Role of small water bodies in landscape nutrient processing. *Water Resources Research*. 2017. <https://doi.org/10.1002/2016WR020102>
- Christensen J, Nash M, Chaloud D, Pitchford A. Spatial distributions of small water body types in modified landscapes: Lessons from Indiana, USA. *Ecohydrology*. 2016; 9(1):122–137. <https://doi.org/10.1002/eco.1618>.
- Cohen MJ, Creed IF, Alexander L, Basu NB, Calhoun AJK, Craft C, ... Walls SC. Do geographically isolated wetlands influence landscape functions? *Proceedings of the National Academy of Sciences of the United States of America*. 2016; 113(8):1978–1986. <https://doi.org/10.1073/pnas.1512650113>. [PubMed: 26858425]
- Dahl, TE. Wetlands losses in the United States, 1780's to 1980's Report to the Congress. St. Petersburg, FL: 1990.
- Dahl, TE. Status and trends of wetlands in the conterminous United States 2004 to 2009. U.S. Washington, D.C: Department of the Interior; Fish and Wildlife Service; 2011. p. 108
- Davidson NC. How much wetland has the world lost? Long-term and recent trends in global wetland area. *Marine and Freshwater Research*. 2014; 65(10):934–941. <https://doi.org/10.1071/MF14173>.
- De Steven D, Lowrance R. Agricultural conservation practices and wetland ecosystem services in the wetland-rich piedmont-coastal plain region. *Ecological Applications*. 2011; 21(3 SUPPL) <https://doi.org/10.1890/09-0231.1>.

- Dixon MJR, Loh J, Davidson NC, Beltrame C, Freeman R, Walpole M. Tracking global change in ecosystem area: The wetland extent trends index. *Biological Conservation*. 2016; 193:27–35. <https://doi.org/10.1016/j.biocon.2015.10.023>.
- Evenson GR, Golden HE, Lane CR, D'Amico E. An improved representation of geographically isolated wetlands in a watershed-scale hydrologic model. *Hydrological Processes*. 2016; 30(22): 4168–4184. <https://doi.org/10.1002/hyp.10930>.
- Fenstermacher DE, Rabenhorst MC, Lang MW, McCarty GW, Needelman BA. Distribution, morphometry, and land use of Delmarva bays. *Wetlands*. 2014; 34(6):1219–1228. <https://doi.org/10.1007/s13157-014-0583-5>.
- Fossey M, Rousseau AN. Can isolated and riparian wetlands mitigate the impact of climate change on watershed hydrology? A case study approach. *Journal of Environmental Management*. 2016; 184:327–339. <https://doi.org/10.1016/j.jenvman.2016.09.043>. [PubMed: 27745769]
- Gamble, DE., Grody, E., Undercoffer, J., Mack, J., Micacchion, M. An Ecological and Functional Assessment of Urban Wetlands in Central Ohio. Vol. 2. Columbus, OH: Ohio EPA Technical Report WET/2007-3b, Ohio Environmental Protection Agency; 2007. Morphometric surveys, depth-area-volume relationships and flood storage function.
- Gibbs JP. Wetland loss and biodiversity conservation. *Conservation Biology*. 2000; 14(1):314–317. <https://doi.org/10.1046/j.1523-1739.2000.98608.x>.
- Gleason, R., Tangen, B., Laubhan, MK., Kermes, KE., Euliss, NH. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. 2007. Available at: <http://digitalcommons.unl.edu/usgsnpwrc/89/>
- Golden HE, Creed IF, Ali G, Basu NB, Neff BP, Rains MC, ... Lang M. Integrating geographically isolated wetlands into land management decisions. *Frontiers in Ecology and the Environment*. 2017; 15:319–327. <https://doi.org/10.1002/fee.1504>.
- Golden HE, Sander HA, Lane CR, Zhao C, Price K, D'Amico E, Christensen JR. Relative effects of geographically isolated wetlands on streamflow: A watershed-scale analysis. *Ecohydrology*. 2016; 9(1):21–38. <https://doi.org/10.1002/eco.1608>.
- Haag, KH., Lee, TM., Herndon, DC. Bathymetry and vegetation in isolated marsh and cypress wetlands in the northern Tampa Bay. Area, 2000–2004. 2005.
- Hijmans, R. Geographic data analysis and modeling. R package version 2.3-40. 2015. Available at: <http://cran.univ-lyon1.fr/web/packages/raster/>
- Huang S, Young C, Feng M, Heidemann K, Cushing M, Mushet DM, Liu S. Demonstration of a conceptual model for using LiDAR to improve the estimation of floodwater mitigation potential of prairie pothole region wetlands. *Journal of Hydrology*. 2011; 405(3–4):417–426. <https://doi.org/10.1016/j.jhydrol.2011.05.040>.
- Jones CN, McLaughlin DL, Henson K, Haas CA, Kaplan DA. From salamanders to greenhouse gases: Does upland management affect wetland function? *Frontiers in Ecology and the Environment*. 2017 In press.
- Jones CN, Scott DT, Guth C, Hester ET, Hession WC. Seasonal variation in floodplain biogeochemical processing in a restored headwater stream. *Environmental Science & Technology*. 2015; 49(22): 13190–13198. <https://doi.org/10.1021/acs.est.5b02426>. [PubMed: 26463837]
- Jones KL, Poole GC, O'Daniel SJ, Mertes LAK, Stanford JA. Surface hydrology of low-relief landscapes: Assessing surface water flow impedance using LIDAR-derived digital elevation models. *Remote Sensing of Environment*. 2008; 112(11):4148–4158. <https://doi.org/10.1016/j.rse.2008.01.024>.
- Kessler, AC., Gupta, SC. Drainage impacts on surficial water retention capacity of a prairie pothole watershed; *Journal of the American Water Resources Association (JAWRA)*. 2015. p. 1-13. <https://doi.org/10.1111/jawr.12288>
- Lane CR, D'Amico E. Calculating the ecosystem service of water storage in isolated wetlands using LiDAR in north central Florida, USA. *Wetlands*. 2010; 30(5):967–977. <https://doi.org/10.1007/s13157-010-0085-z>.
- Lang M, McDonough O, McCarty G, Oesterling R, Wilen B. Enhanced detection of wetland-stream connectivity using lidar. *Wetlands*. 2012; 32(3):461–473. <https://doi.org/10.1007/s13157-012-0279-7>.

- Leibowitz SG, Mushet DM, Newton WE. Intermittent surface water connectivity: Fill and spill vs. fill and merge dynamics. *Wetlands*. 2016; 36:323–342. <https://doi.org/10.1007/s13157-016-0830-z>.
- Levy GF. The Vegetation of the Great Dismal Swamp. *Virginia Journal of Science*. 1991; 42(4):411–417.
- McDonough OT, Lang MW, Hosen JD, Palmer MA. Surface hydrologic connectivity between Delmarva Bay wetlands and nearby streams along a gradient of agricultural alteration. *Wetlands*. 2014; 35(1):41–53. <https://doi.org/10.1007/s13157-014-0591-5>.
- McLaughlin DL, Kaplan DA, Cohen MJ. A significant nexus: Geographically isolated wetlands influence landscape hydrology. *Water Resources Research*. 2014; 50(9):7153–7166. <https://doi.org/10.1002/2013WR015002>.
- Millhollon EP, Rodrigue PB, Rabb JL, Martin DF, Anderson RA, Dans DR. Designing a constructed wetland for the detention of agricultural runoff for water quality improvement. *Journal of Environmental Quality*. 2009; 38(6):2458–2467. <https://doi.org/10.2134/jeq2008.0526>. [PubMed: 19875802]
- Mushet DM, Calhoun AJK, Alexander LC, Cohen MJ, DeKeyser ES, Fowler L, ... Walls SC. Geographically isolated wetlands: Rethinking a misnomer. *Wetlands*. 2015; 35(3):423–431. <https://doi.org/10.1007/s13157-015-0631-9>.
- O’Callaghan JF, Mark DM. The extraction of drainage networks from digital elevation data. *Computer Vision, Graphics, and Image Processing*. 1984; 27(2):247. [https://doi.org/10.1016/S0734-189x\(84\)80011-0](https://doi.org/10.1016/S0734-189x(84)80011-0).
- Pebesma, EJ., Bivand, RS. Classes and methods for spatial data in R. 2005. Available at: <http://cran.r-project.org/doc/Rnews/>
- Phillips PJ, Shedlock RJ. Hydrology and chemistry of groundwater and seasonal ponds in the Atlantic coastal plain in Delaware, USA. *Journal of Hydrology*. 1993; 141(1–4):157–178. [https://doi.org/10.1016/0022-1694\(93\)90048-E](https://doi.org/10.1016/0022-1694(93)90048-E).
- R Core Development Team. R: A language and environment for statistical computing. R Foundation for Statistical Computing; Vienna Austria: 2017. <https://doi.org/10.1038/sj.hdy.6800737>
- Ramsar Convention. An introduction to the Ramsar convention on wetlands (previously the Ramsar convention manual). 5. Gland, Switzerland: Ramsar Convention Secretariat; 2016. International cooperation on wetlands. Handbook 1; p. 110
- Serran JN, Creed IF. New mapping techniques to estimate the preferential loss of small wetlands on prairie landscapes. *Hydrological Processes*. 2016; 30(3):396–409. <https://doi.org/10.1002/hyp.10582>.
- Serran, JN., Creed, IF., Ameli, AA., Aldred, DA. Estimating rates of wetland loss using power-law functions. *Wetlands*. 2017. <https://doi.org/10.1007/s13157-017-0960-y>
- Sharitz RR. Carolina Bay wetlands: Unique habitats of the southeastern United States. *Wetlands*. 2003; 23(3):550–562. <https://doi.org/10.1672/02775212%282003%29023%5b0550%3acbwuho%5d2.0.co%3b2>.
- Shenk GW, Linker LC. Development and application of the 2010 Chesapeake Bay watershed total maximum daily load model. *Journal of the American Water Resources Association*. 2013; 49(5): 1042–1056. <https://doi.org/10.1111/jawr.12109>.
- Sofaer HR, Skagen SK, Barsugli JJ, Rashford BS, Reese GC, Hoeting JA, ... Noon BR. Projected wetland densities under climate change: Habitat loss but little geographic shift in conservation strategy. *Ecological Applications*. 2016; 26(6):1677–1692. <https://doi.org/10.1890/15-0750.1>. [PubMed: 27755694]
- Tiner RW. Estimated extent of geographically isolated wetlands in selected areas of the United States. *Wetlands*. 2003; 23(3):636–652. [https://doi.org/10.1672/0277-5212\(2003\)023%5B0636:EEOGIW%5D2.0.CO;2](https://doi.org/10.1672/0277-5212(2003)023%5B0636:EEOGIW%5D2.0.CO;2).
- Tiner RW. Assessing cumulative loss of wetland functions in the Nanticoke River watershed using enhanced National Wetlands Inventory data. *Wetlands*. 2005; 25(2):405–419. <https://doi.org/10.1672/15>.
- U.S. Army Corp of Engineers. Wetlands Delineation Manual. Wetlands Research Program Technical Report. 1987; 1(January):92. pages et annexes Available at: <http://el.erdc.usace.army.mil/wetlands/pdfs/wlman87.pdf>.

- U.S. Department of Commerce, U.S. Census Bureau, Geography Division. Census Tract national-based. 2015. TIGER/Line 2015 Census.
- U.S. Geological Survey and U.S. Department of Agriculture, Natural Resources Conservation Service. Federal guidelines, requirements, and procedures for the national Watershed Boundary Dataset. U.S. Geological Survey Techniques and Methods 11–A3. U.S. Geological Survey; Reston, Virginia, USA: 2009.
- Van Meter KJ, Basu NB. Signatures of human impact: Size distributions and spatial organization of wetlands in the prairie pothole landscape. *Ecological Applications*. 2015; 25(2):451–465. <https://doi.org/10.5061/dryad.7fc8c>. [PubMed: 26263667]
- Vanderhoof, MK., Distler, HE., Lang, MW., Alexander, LC. The influence of data characteristics on detecting wetland/stream surface-water connections in the Delmarva Peninsula, Maryland and Delaware. *Wetlands Ecology and Management*. 2017. <https://doi.org/10.1007/s11273-017-9554-y>
- Wu Q, Lane CR. Delineation and quantification of wetland depressions in the prairie pothole region of North Dakota. *Wetlands*. 2016; 36(2):215–227. <https://doi.org/10.1007/s13157-015-0731-6>.
- Wu Q, Lane CR. Delineating wetland catchments and modeling hydrologic connectivity using lidar data and aerial imagery. *Hydrology and Earth System Sciences*. 2017; 21:3579–2595.
- Yepsen M, Baldwin AH, Whigham DF, McFarland E, LaForgia M, Lang M. Agricultural wetland restorations on the USA Atlantic coastal plain achieve diverse native wetland plant communities but differ from natural wetlands. *Agriculture, Ecosystems and Environment*. 2014; 197:11–20. <https://doi.org/10.1016/j.agee.2014.07.007>.

FIGURE 1.

Conceptual diagram of a (a) drained and (b) restored depressional basin. (c) Digital elevation model delineation with individual internally draining basins (black lines), where ditch networks are evident (white lines). (d) Wetland storage volume and spill boundary length versus inundation depth for the highlighted depressional basin. Vertical lines correspond to estimated contemporary (orange) and potential (blue) storage capacities. (e–f) Orange and blue areas represent estimated current and potential surface inundation, respectively, corresponding to vertical lines in d

FIGURE 2.

(Top left) Palustrine wetland coverage across the eastern USA taken from the U.S. Fish and Wildlife Service National Wetland Inventory (www.fws.gov/wetlands/), highlighting the abundance of wetlands across the coastal plain physiographic region; Delmarva Peninsula is denoted with rectangle. (Middle) Estimated contemporary and potential specific storage capacity across the Delmarva Peninsula aggregated by HUC12 watersheds. The Greensboro watershed is outlined in orange. (Bottom) Histograms highlighting contemporary and potential specific storage capacity of HUC12 watersheds. Note, specific storage capacity is area-normalized wetland storage capacity (i.e., wetland storage capacity divided by the respective HUC12 watershed area). Cumulative storage capacities are also given as both volumes and area-normalized volumes for the entire Delmarva

FIGURE 3.

Spatial distribution of (a) contemporary and (b) potential specific storage capacity across the Greensboro watershed. (c) Vertical distribution of specific storage capacity relative to drainage feature elevation across Greensboro watershed. (d) Distribution of storage capacity as Euclidean distance to the closest drainage feature. Light and dark blue bars represent contemporary and potential wetland storage volumes, respectively. Note, specific storage capacity is area-normalized wetland storage capacity (i.e., wetland storage capacity divided by the area of Greensboro watershed)