Our Response to Anonymous Referee #1

General Comments

This manuscript addresses an important area of research, improving our ability to model and map hydrological interactions between wetlands and streams. It is well written and creative in its integration of methods, however the paper becomes a little confusing and muddled in interpreting whether theoretical or actual connectivity was modeled. In addition the inundation map does not appear to be validated. General and specific comments are below.

RESPONSE: We thank the reviewer for his/her thorough review and very helpful comments/suggestions. The positive feedback encourages us to continue working on this subject in the future.

1) The Introduction provides a strong background of the PPR, but could be strengthened by clarifying the novelty of the approach. Right now this is limited to stating that few studies of prairie wetlands have treated wetlands and catchments as integrated units and lidar is rarely used at broad scale but no citations are offered. Has this approach been used in other wetland landscapes, just not in the PPR? Or is this approach actually quite novel? What about related studies that have mapped wetland depressions and/or delineated wetland catchments? How does this approach fit in with those studies? Adding just a few sentences to discuss this would help contextualize the work presented.

RESPONSE: We thank the reviewer for the useful comments. We have revised this section and added appropriate references to justify the novelty of our approach.

"To our knowledge, little work has been done to delineate potential flow paths between wetlands and stream networks and use flow paths to characterize hydrologic connectivity in the PPR. In addition, previous remote sensing-based work on the hydrology of prairie wetlands mainly focused on mapping wetland inundation areas (e.g., Huang et al., 2014; Vanderhoof et al., 2017) or wetland depressions (e.g., McCauley and Anteau, 2014; Wu and Lane, 2016), few studies have treated wetlands and catchments as integrated hydrological units. Therefore, there is a call for treating prairie wetlands and catchments as highly integrated hydrological units because the existence of prairie wetlands depends on lateral inputs of runoff water from their catchments in addition to direct precipitation (Hayashi et al., 2016). Furthermore, hydrologic models for the PPR were commonly developed using coarse-resolution DEMs, such as the 30-m National Elevation Dataset (see Chu, 2015; Evenson et al., 2015; Evenson et al., 2016). High-resolution light detection and ranging (LiDAR) data have rarely been used in broad-scale (e.g., basin- or subbasin-scale) studies to delineate wetland catchments and model wetland connectivity in the PPR."

2) Right now the last paragraph of the introduction is essentially a summary of what the paper did, but it would be stronger if the authors added what the goals, objectives, or research questions were. . .for example, our goal was to demonstrate a method to map potential hydrologic connections between wetlands and the river networks. . .

RESPONSE: Good suggestion. We have revised this paragraph and made our research objectives clear.

"In this paper, we present a semi-automated framework for delineating nested hierarchical wetland depressions and their corresponding catchments as well as simulating wetland connectivity using high-resolution LiDAR data. Our goal was to demonstrate a method to characterize fill-spill wetland hydrology and map potential hydrological connections between wetlands and stream networks. The hierarchical structure of wetland depressions and catchments was identified and quantified using a localized contour tree method (Wu et al., 2015). The potential hydrologic connectivity between wetlands and streams was characterized using the least-cost path algorithm. We also utilized high-resolution LiDAR intensity data to delineate wetland inundation areas, which were compared against the National Wetlands Inventory (NWI) to demonstrate the hydrological dynamics of prairie wetlands. Our ultimate goal is to build on our proposed framework to improve overland flow simulation and hydrologic connectivity analysis, which subsequently may improve the understanding of wetland hydrological dynamics at watershed scales."

3) In calculating flow paths it is sometimes acknowledged that these are potential and sometimes stated that temporary and intermittent flowpaths have been identified. It should be made clear that these are potential hydrologic connections that are identified via the flowpaths, as it is not shown currently in the paper how or if active flowpaths are or could be distinguished from inactive flowpaths. However, the authors also mapped inundation and depressions, couldn't these be used to determine which depressions were connected? It isn't entirely clear if this is what is presented partially in Figure 10 or not.

RESPONSE: In the revised version, we have made it clear that the derived flow paths are potential hydrologic connections. We tried to distinguish active flow paths from inactive flow paths by visually assessing the derived flow paths overlaid on aerial photographs. Although we were not able to conduct quantitative assessments, we did find that the many potential flow paths were collocated with vegetated areas, which indicates that flow paths are likely located in high soil moisture areas that are directly or indirectly related to surface water or groundwater connectivity. The inundation areas were derived from the LiDAR intensity data, whereas the depressions were derived from the LiDAR DEM. Theoretically, the inundation areas are a subset of the depressions. In other words, the depressions represent the maximum ponded extents for the inundation areas. Since the LiDAR data were acquired during an extremely wet period, many wetlands already coalesced with adjacent wetlands to form larger wetland complexes. We could use dry-period aerial photographs to determine which depressions were connected. The LiDAR data can be used to show which depressions might potentially connect, but it cannot tell which depressions were actually connected.

4) It does not appear that the inundation map has been validated. Because of a lack of date match between the NAIP imagery and the LiDAR collection date, the NAIP imagery, appropriately, is primarily used to show that surface water changes over time. I realize it is challenging to validate maps classified from high resolution imagery but given the nearby Cottonwood site which monitors water levels at multiple ponds, are there field-measured water levels collected at a close date that could be used to help validate the inundation map?

RESPONSE: We thank the reviewer for this good suggestion. We have looked into the in-situ water-level data of the Cottonwood Lake Study Area retrieved from the USGS website (Mushet et al. 2016). We chose the field-measured water levels collected on October 27, 2011, which was the closest date to the LiDAR data acquisition date used in this study. The water levels of eight semi-permanent wetlands numbered through P1-P8 were used to compare the water elevation of wetland inundation areas derived using LiDAR data. The water level difference between the field measurement and LiDAR-derived measurement for these eight wetlands ranged from -5 cm to 11 cm, with an average

elevation difference of 0.5 cm, which falls within the vertical accuracy of the LiDAR DEM (15.0 cm). We have also made the inundation map available online at http://wetlands.io/maps/inundation.html.

Wetland ID	P01	P02	P03	P04	P06	P07	P08	Average
Field-measured (m)	560.30	561.01	557.86	561.01	562.55	562.76	556.66	NA
LiDAR-derived (m)	560.22	561.12	557.91	561.12	562.50	562.71	556.61	NA
Water-level difference (m)	-0.08	0.11	0.05	0.11	-0.05	-0.05	-0.05	0.0057

David M. Mushet, Donald O. Rosenberry, Ned H. Euliss, Jr., and Matthew J. Solensky, 2016, Cottonwood Lake Study Area - Water Surface Elevations. U.S. Geological Survey Data Release, http://dx.doi.org/10.5066/F7707ZJ6

5) I think the conclusion that dry NWI wetlands are likely no longer wetlands is a bit of a stretch. The PHDI does not consider snowmelt and is just based on rainfall and temperature, as the LiDAR collection was in October it is entirely possible that a large number of these wetlands are temporarily wet for few weeks in the spring following snowmelt. I don't think you can assume that these NWI wetlands no longer function as wetlands given just 1 fall date of inundation, even if in a wet year.

RESPONSE: We thank the reviewer for this concern. In the revised version, we have removed the statement that those 'dry' NWI wetlands are no longer wetlands. We have added more explanations about the discrepancy between NWI wetlands and our results derived by the LiDAR data.

"It is worth noting that most of these 'dried' NWI wetlands were relatively small with a median size of 1.2×10^3 m^2 (Table 2). The LiDAR intensity data were acquired in late October 2011, an extremely wet month according to the Palmer Hydrological Drought Index (Fig. 6). During this wet season, most wetlands would be expected to have abundant standing water. If no standing water could be detected in a wetland patch during this extremely wet period, it is possible that some of these small wetlands might have dried out during the past weeks to months. It is possible that land use change surrounding the 'dried' wetlands (e.g., row-cropping replacing pasture lands) may have affected their hydrology (Wright and Wimberly, 2013); water diversion via drainage or ditches could also be responsible for the lack of inundation, though we did not explore either of these potential drivers of change in this study. However, it is also likely that some of the 'dried' wetland might become wet again in the spring following snowmelt. The 'dried' NWI wetlands could also be attributed to the source of error in the original NWI data, which has a minimum mapping unit (i.e., the minimum sized wetland that can be consistently mapped) of 0.1 ha for the PPR (Tiner, 1997). Figure 5(b) shows that 37% of the 'dried' NWI polygons are smaller than the minimum mapping unit (1000 m^2). This implies that these small 'dried' NWI polygons could be due to the NWI mapping error."

Minor Comments

Line 27 – grammatical error, change "highly" to "most" and modify sentence to avoid using "as" twice.

RESPONSE: We have revised the sentence as suggested.

Line 32 – awkward sentence, change to "the potholes range in size from"

RESPONSE: We have revised the sentence as suggested.

Line 34 – the term ephemeral is more commonly used for streams, the term "temporary" is more commonly used for wetlands.

RESPONSE: We have changed "ephemeral" to "temporary"

Line 37 – remove the word "as"

RESPONSE: We have removed "as".

Line 39 – conterminous is misspelled

RESPONSE: We have corrected the typo.

Line 94 – change to "collected in late October"

RESPONSE: We have revised the sentence as suggested.

Line 97 – add space between in and 15.0 cm.

RESPONSE: Space added.

2.2. LiDAR Data – I realize you mention this in the Discussion, but it would be helpful to also add quick comment here regarding how wet October 2011 was and how this may have influenced the resulting DEM.

RESPONSE: We thank the author for the good suggestion. We have added the following sentences to the end of this section: "It is worth noting that October 2011 was an extreme wet period according to the Palmer Hydrological Drought Index. Consequently, small individual wetland depressions nested within larger inundated wetland complexes might not be detectable from the resulting LiDAR DEM."

Line 126 – change "these" to "the"

RESPONSE: We have changed "these" to "the".

Comment - In the Methodology section change from present tense to past tense.

RESPONSE: We have revised the Methodology section as suggested. For specific data processing steps we performed, we used the past tense. When describing diagrams not tied to specific data processing steps we performed, we used the present tense.

Line 215 – add the word "of" between number and upslope.

RESPONSE: We have added the word "of".

Section 3.2 – I'm assuming to use the contour approach you need to convert the DEM to vectors. . .is any information lost in this process? why not just use a raster-based approach to find depressions?

RESPONSE: To the best of our knowledge, there is no raster-based approach available to delineate and characterize the nested hierarchical structure of depressions. The traditional sink-filling method can delineate the maximum extent of a composite depression. However, it cannot distinguish or delineate the individual depressions (if any) nested within the composite depression. Moreover, the topological relationship between nested depressions cannot be derived from the raster-based approach. The vector-based contour-tree approach used in this study can not only identify nested depressions but also characterize their topological relationships, which are crucial for studying the filling-merging-spilling hydrology. In this study, we set the contour interval as 20 cm, which was chosen based on the LiDAR vertical accuracy (15 cm) and consideration of computational time. Like any other vector-raster data conversion process, there might be some information lost in this process. Nevertheless, we believe that the contour interval of 20 cm is sufficient to minimize the information loss based on our experiments. An in-depth discussion about the contour interval selection is available in the Wu et al. (2015) paper.

Section 3.4 – In calculating ponding time, are you assuming no infiltration? If so, add this as an assumption to the text.

RESPONSE: We have added the following sentences to this section: "For the sake of simplicity, we made two assumptions. First, we assumed that the rainfall was temporally and spatially consistent and uniformly distributed throughout the landscape and all surfaces were impervious. Second, we assumed no soil infiltration."

Section 3.4 – Does the water storage capacity, and in turn the ponding time equations assume the depression is dry to start with? How is the pre-existing water in the depressions dealt with? This is particularly an issue for permanent wetlands.

RESPONSE: We did not assume the depression is dry to start with. The ponding time of a depression was calculated based on the potential water storage and its corresponding catchment area. In other words, we don't need the existing water storage to calculate the ponding time. It does not matter whether a depression is dry or has existing water. If a depression is completely dry without any existing water, the potential water storage refers to the storage volume between the lowest point and the spilling point of the depression. If a depression has existing water in it, the potential water storage refers to the potential water volume the depression can hold between the water surface and the spilling point. The potential water storage capacity of each wetland depression was computed through statistical analysis of the LiDAR DEM grid cells that fall within the depression. The calculation of existing water storage is not the focus of this study. Since the near-infrared LiDAR sensors generally could not penetrate water, the depression morphology beneath the water surface could not be derived from LiDAR data. Therefore, it is not possible to calculate the exact storage volume of an existing waterbody. However, many studies have showed that there is a strong statistical relationship between

storage volume and surface area in a depression (e.g., see Gleason, et al. (2007), Wu and Lane (2016)). Therefore, existing water storage can be estimated using empirical equations if needed.

1) Gleason, R. A., B. A. Tangen, M. K. Laubhan, K. E. Kermes and N. H. Euliss Jr. 2007. Estimating water storage capacity of existing and potentially restorable wetland depressions in a subbasin of the Red River of the North. p. 36. U.S. Geological Survey Open-File Report 2007-1159.
2) Wu, Q. and C. R. Lane. 2016. Delineation and Quantification of Wetland Depressions in the Prairie Pothole Region of North Dakota. Wetlands, 36:215-227.

Comment – what was the range of rainfall intensities that were added to derive the ponding time estimates?

RESPONSE: For this study, we used a uniform steady rainfall with an intensity of 5.0 cm/h based on the literature (e.g., see Chu (2015)). The rainfall intensity can be easily adapted in other study areas to derive the ponding time estimates.

1) Chu, X. 2015. Delineation of Pothole-Dominated Wetlands and Modeling of Their Threshold Behaviors. Journal of Hydrologic Engineering: D5015003.

Line 287-310 This paragraph is methods and should be moved to the Methods section accordingly.

RESPONSE: We have moved this paragraph to the Methodology section as suggested.

Line 303-304 – What about inundation in streams that may not have been mapped as depressions, would these inundation objects be lost given this filtering step?

RESPONSE: Based on our visual assessments, no major inundation areas along streams were missed during the filtering step. In other others, all major inundation areas along streams were mapped as depressions. The inundation mapping results overlaid on the LiDAR intensity imagery are available for viewing at http://wetlands.io/maps/inundation.html.

Section 4.2 How common was it for wetland depressions to be nested within a larger catchments? Is there a way this nested hierarchy could be quantified or showed?

RESPONSE: The fill-and-spill hydrology in the Prairie Pothole Region is well documented in the literature. It is very common for wetland depression to be nested within a larger catchment. In our study, the nested hierarchy was quantified and characterized using the localized contour tree approach. A conceptual diagram of the approach is shown in Figure 4. Real-world examples demonstrating the fill-spill process and nested hierarchy can be seen from the time-series aerial images shown in Figure 2.

Line 362-363 – Although the findings are based on a much larger sample size, they are also all derived from a single watershed, so the results may also be site specific.

RESPONSE: It is true that our results are also site-specific. We have modified the sentence and stated that the results are "for the study area" only. Nevertheless, we believe that our results regarding the proportion of depression area to catchment area are statistically more reliable than that

reported in previous studies, which were calculated based on a very limited number (<20) of depressions. In contrast, our results were computed from more than 30,000 wetland depressions and catchments.

Section 4.3 – The flow paths are potential flow paths, however, right? Water may not have flowed along a fraction of them to date. This should be made clear in the text.

RESPONSE: We thank the reviewer for pointing this out. We have modified the text accordingly and made it clear that the flow paths derived in this study are potential flow paths.

Line 384 – remove "the" before late October

RESPONSE: We have removed "the".

Line 385 – add "a" after such.

RESPONSE: We have added "a" after such.

Line 388-389 - revise sentence to "A substantial number of inundated NWI wetlands were found to coalesce with adjacent wetlands. . .."

RESPONSE: We have revised the sentence as suggested.

Line 402 – Do you mean you "could" use it if a dry-period LiDAR was available?

RESPONSE: Yes, this is what we meant. We have changed "can" to "could".

Line 384-406 – This is a good discussion of an important issue but it is not entirely clear how this issue affected your findings in this case. I would guess that you likely under-estimated the number of depressions that coalesced?

RESPONSE: We thank the reviewer for the encouraging comment. We have to admit that our findings were inevitably affected by the LiDAR data used in this study. Since the LiDAR data were acquired during an extreme wet period, many wetlands already coalesced with adjacent wetlands to form larger wetland complexes. Therefore, it is not possible delineate the individual wetlands before they coalesced unless we had another LiDAR dataset acquired during a dry period. Our methods focused on the potential coalescence between adjacent wetlands when water levels in wetlands continued to increase rather than the coalescence that already took place. In an ideal situation, i.e., the LiDAR data is acquired during an extremely dry period, our methods can simulate the filling-merging-spilling processes and project the coalescences between wetlands. The results can then be validated using the wet-period LiDAR data and aerial photographs.

Line 404-405 – As far as I can tell, however, in this case you did not use the time-series or wet inundation to evaluate or summarize fill-and-spill patterns. Is this correct?

RESPONSE: It is correct that we were not able to use the wet-period LiDAR data to evaluate the fill-and-spill patterns. This is partly due to the limitation of the LiDAR data. As noted in the paper, the LiDAR data used in this study were acquired in late October 2011, which was an extremely wet period according to the Palmer Hydrological Drought Index. During such a wet period, a substantial number of inundated wetlands were found to coalesce with adjacent wetlands and form larger wetland complexes. As a result, we were not able to obtain the information of basin morphology of individual depressions before they merged into large wetland complexes. Ideally, using multiple LiDAR datasets acquired in both dry and deluge conditions in conjunction with time-series aerial photographs would be essential for studying the fill-and-spill mechanism of prairie wetlands. In this case, we could use the dry-period LiDAR data to delineate and characterize the morphology of individual wetland depressions before the fill-and-spill processes occur. Furthermore, we can derive the potential flow paths and project the coalescing of wetland depressions after the fill-and-spill processes initiate. The wet-period LiDAR data and time-series aerial photographs can serve as validation datasets to evaluate the fill-and-spill patterns. We plan to further investigate this issue when a dry-period LiDAR data for our study area becomes available.

Line 425 – Can't use the word "accurately" if no validation was done.

RESPONSE: We have removed the word "accurately".

Line 433 – Add "potential" before hydrological connectivity.

RESPONSE: We have added the word "potential" before hydrological connectivity.

Line 435 – I am struggling with this statement which is used several times throughout the manuscript. Although temporary or seasonal flow paths were likely identified, flowpaths were also likely identified that never actually carry water. How can we distinguish between these or can we?

RESPONSE: We thank the reviewer for this concern. We have made changes throughout the manuscript and made it clear that all flow paths identified in this study are potential flow paths. By examining the potential flow paths overlaid on the color infrared aerial photograph, we found that many potential flow paths appeared to be collocated with vegetated areas (see Fig. 9(b)). This indicates that flow paths are likely located in high soil moisture areas that are directly or indirectly related to surface water or groundwater connectivity. We agree with the reviewer that some potential flow paths might never actually carry water. We plan to further investigate this issue in a follow-up study to categorize and validate potential flow paths.

Line 439 –Add what the specific limiting factors have been with traditional remote sensing methods.

RESPONSE: We have modified the sentence as suggested: "Broad-scale prairie wetland hydrology has been difficult to study with traditional remote sensing methods using multi-spectral satellite data due to the limited spatial resolution and the interference of tree canopy (Klemas, 2011; Gallant, 2015)."

1) Klemas, V.: Remote sensing of wetlands: case studies comparing practical techniques, Journal of Coastal Research, 27, 418-427, 2011.
2) Gallant, A.: The Challenges of Remote Monitoring of Wetlands, Remote Sensing, 7, 10938, 2015.

Table 1 – remove extra spaces between Freshwater and Emergent.

RESPONSE: We have removed the extra spaces.

Figure 5, 8 and 10 – I would add a basic color to the histograms, maybe light gray? To improve the aesthetics.

RESPONSE: We have modified all histograms as suggested.

Figure 6 – Modify x-axis to just show year

RESPONSE: We have modified the x-axis as suggested.

Figure 7 – the yellow and blue lines are hard to see, maybe making them a little thicker might make them more visible.

RESPONSE: We have made the lines thicker. In addition, we switched the line colors to make them consistent with those shown in Figure 9. Yellow line and blue line represent NWI wetlands and LiDAR-derived inundation areas, respectively.

Figure 10 – This figure gets at several questions I had. Was connectivity calculated so that all wetlands connected to each other and eventually to a stream? And this is then the length distribution of those flowpath lines? If so it should be indicated that these are potential connectivity. What does connected wetlands mean here? Are these just the coalesced wetlands?

RESPONSE: We have modified the figure and corresponding text to indicate the potential wetland connectivity. Figure 10a shows the distribution of potential flow path lengths. Figure 10b shows the distribution of elevation differences between wetlands connected through the potential flow paths.

Our Response to Anonymous Referee #2

General Comments

This manuscript was well thought out, well organized and well written. In the United States the regulatory status of wetlands is currently linked to connectivity to streams so the topic of this manuscript is important. The conceptual model presented for wetland fill and spill seems very useful. The approach used in the reported study is sound and findings support the conclusions reached.

RESPONSE: We thank the reviewer for the encouraging comments.

Specific comments:

The last paragraph of the introduction is a summary of the study findings. It should be modified to reflect study goals instead.

RESPONSE: We thank the reviewer for the good suggestion. We have revised this paragraph and made our research objectives more clear.

"In this paper, we present a semi-automated framework for delineating nested hierarchical wetland depressions and their corresponding catchments as well as simulating wetland connectivity using high-resolution LiDAR data. Our goal was to demonstrate a method to characterize fill-spill wetland hydrology and map potential hydrological connections between wetlands and stream networks. The hierarchical structure of wetland depressions and catchments was identified and quantified using a localized contour tree method (Wu et al., 2015). The potential hydrologic connectivity between wetlands and streams was characterized using the least-cost path algorithm. We also utilized high-resolution LiDAR intensity data to delineate wetland inundation areas, which were compared against the National Wetlands Inventory (NWI) to demonstrate the hydrological dynamics of prairie wetlands. Our ultimate goal is to build on our proposed framework to improve overland flow simulation and hydrologic connectivity analysis, which subsequently may improve the understanding of wetland hydrological dynamics at watershed scales."

Flow routing was performed using D8 algorithm (line 213) but often it has been found that D-infinity algorithms provide more realistic flow characteristics.

RESPONSE: We agree with the reviewer that D-infinity algorithms might provide more realistic flow characteristics. In our study, the flow direction raster was generated and used as an intermediate dataset to derive wetland catchments. For delineating catchments/watersheds, we tried the ArcGIS Hydrology Toolbox (https://goo.gl/GhmFId) and the open-source Whitebox Geospatial Analysis Tools (https://goo.gl/dqV4cE). Both software packages use D8 algorithm for watershed delineation. Since our data processing flow was built on the ArcGIS Hydrology Toolbox, for the sake of simplicity, we used the D8 algorithm available in ArcGIS to derive flow directions. Nevertheless, we believe that both flow direction algorithms should lead to the same watershed delineation results.

When reporting numerical results consider the errors associated with the underlying model used to produce the values. The number of nonzero digits should generally reflect the uncertainty. For example see lines 347 and 348 with values reported with 4 significant figures whereas it is known that

these estimates have substantial uncertainty. Also in tables with data reported with up to 8 significant digits (Tables 1 to 4).

RESPONSE: We appreciate this concern. In the revised manuscript, we have reduced the number of significant digits to no more than three throughout the manuscript.

Figure 7 needs to be reworked. Labels on figure are very difficult to read

RESPONSE: We have revised Figure 7. We made the lines thicker. In addition, we switched the line colors to make them consistent with those shown in Figure 9. Yellow line and blue line represent NWI wetlands and LiDAR-derived inundation areas, respectively.

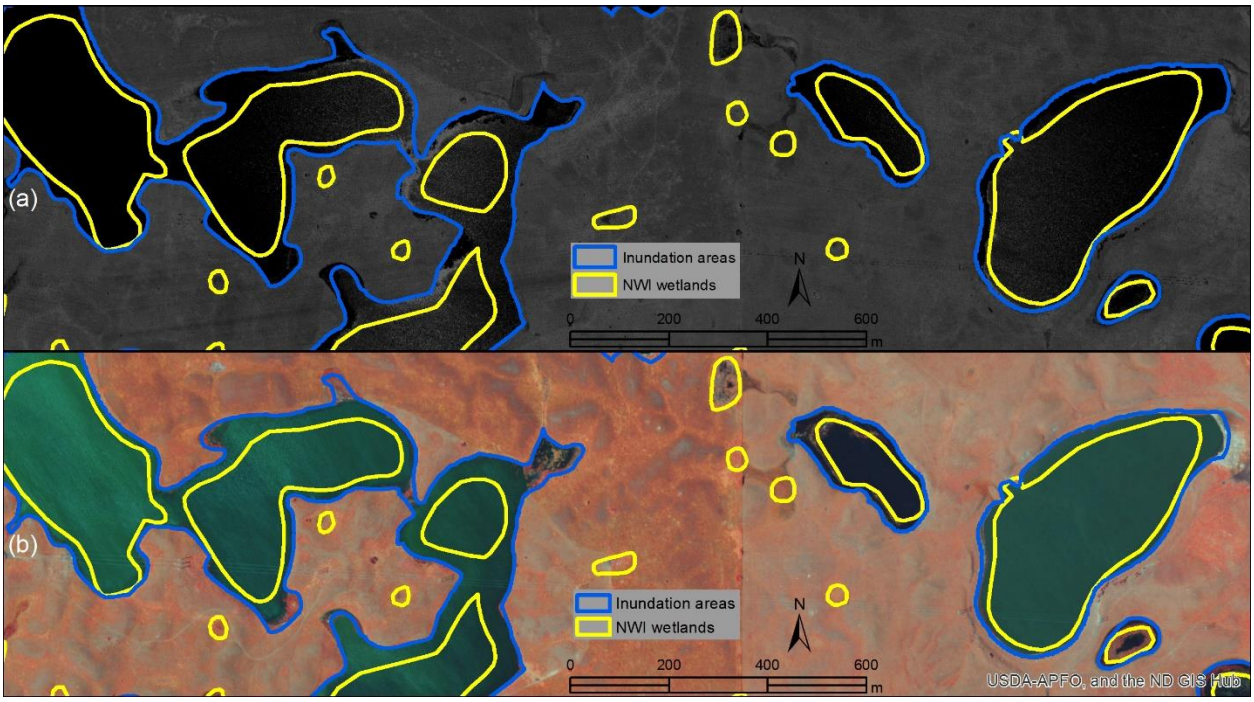

Figure 7. Comparison between inundation areas (derived from LiDAR intensity data) and NWI wetland polygons

Delineating wetland catchments and modeling hydrologic connectivity using LiDAR data and aerial imagery

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Abstract: In traditional watershed delineation and topographic modeling, surface depressions are generally treated as spurious features and simply removed from a digital elevation model (DEM) to enforce flow continuity of water across the topographic surface to the watershed outlets. In reality, however, many depressions in the DEM are actual wetland landscape features with seasonal to permanent inundation patterning characterized by nested hierarchical structures and dynamic filling-spilling-merging surface-water hydrological processes ~~that are seldom fully filled with water~~. Differentiating and appropriately processing such ecohydrologically meaningful features remains a major technical terrain-processing challenge, particularly as high-resolution spatial data are increasingly used to support modeling and geographic analysis needs. ~~For instance, wetland depressions in the Prairie Pothole Region (PPR) are seasonally to permanently flooded wetlands characterized by nested hierarchical structures with dynamic filling spilling merging surface water hydrological processes.~~ The objectives of this study were to delineate hierarchical wetland catchments and model their hydrologic connectivity using high-resolution LiDAR data and aerial imagery. The graph theory-based contour tree method was used to delineate the hierarchical wetland catchments and characterize their geometric and topological properties. Potential hydrologic connectivity between wetlands and streams were simulated using the least-cost path algorithm. The resulting flow network delineated ~~putative temporary or seasonal~~potential flow paths connecting wetland depressions to each other or to the river network at scales finer than available through the National Hydrography Dataset. The results demonstrated that our proposed framework is promising for improving overland flow simulation and hydrologic connectivity analysis.

Keywords: flow path, geographically isolated wetlands, hydrologic connectivity, LiDAR, prairie pothole, wetland depressions~~, geographically isolated wetlands, flow path, LiDAR~~

1 Introduction

The Prairie Pothole Region (PPR) of North America extends from the north-central United States (U.S.) to south-central Canada, encompassing a vast area of approximately 720,000 km^2. The landscape of the PPR is dotted with millions of wetland depressions formed by the glacial retreat that happened during the Pleistocene Epoch (Winter, 1989). The PPR is considered as one of the largest and ~~highly~~ most productive wetland areas in the world, which ~~as it~~ serves as a primary breeding habitat for much of North America's waterfowl population (Keddy, 2010; Steen et

al., 2014; Rover and Mushet, 2015). The wetland depressions, commonly known as potholes, possess important hydrological and ecological functions, such as providing critical habitat for many migrating and breeding waterbirds (Minke, 2009), acting as nutrient sinks (Oslund et al., 2010), and storing surface water that can attenuate peak runoff during a flood event (Huang et al., 2011b). The potholes ~~size ranges~~ in size from a relatively small area of less than 100 m^2 to as large as 30,000 m^2, with an estimated median size of 1600 m^2 (Zhang et al., 2009; Huang et al., 2011a). Most potholes have a water depth of less than 1 m with varying water permanency, ranging from ~~ephemeral~~ temporary to permanent (Sloan, 1972). Due to their small size and shallow depth, these wetlands are highly sensitive to climate variability and are vulnerable to ecological, hydrological, and anthropogenic changes. Wetland depressions have been extensively drained and filled due to agricultural expansion, which is considered ~~as~~ the greatest source of wetland loss in the PPR (Johnston, 2013). In a report to the ~~United States (~~U.S.~~)~~ Congress on the status of wetland resources, Dahl (1990) estimated that the conterminous U.S. lost more than 50 percent of ~~their~~ its original wetland acreage~~s~~ over a period of 200 years between the 1780s and the 1980s. More recently, Dahl (2014) reported that the total wetland area in the PPR declined by approximately 300 km^2 between 1997 and 2009. This represents an average annual net loss of 25 km^2. Regarding the number of depressions, it was estimated that the wetland depressions declined by over 107,000 or four percent between 1997 and 2009 (Dahl, 2014).

The extensive wetland drainage and removal have increased precipitation runoff into regional river basins, which is partially responsible for the increasing frequency and intensity of flooding events in the PPR (Miller and Nudds, 1996; Bengtson and Padmanabhan, 1999; Todhunter and Rundquist, 2004). Concerns over flooding along rivers in the PPR have stimulated the development of hydrologic models to simulate the effects of depression storage on peak river flows (Hubbard and Linder, 1986; Gleason et al., 2007; Gleason et al., 2008; Huang et al., 2011b). Since most of these prairie wetlands do not have surface outlets or well-defined surface water connections, they are generally considered as geographically isolated wetlands (GIWs) or upland-embedded wetlands (Tiner, 2003; Mushet et al., 2015; Cohen et al., 2016; Lane and D'Amico, 2016). Recently, the U.S. Environmental Protection Agency conducted a comprehensive review of over 1350 peer-reviewed papers with the aim to synthesize existing scientific understanding of how wetlands and streams affect the physical, chemical, and biological integrity of downstream waters (U.S. EPA, 2015). The report concludes that additional research focused on the frequency, magnitude, timing, duration, and rate of fluxes from GIWs to downstream waters is needed to better identify wetlands with hydrological connections or functions that ~~significantly~~ substantially affect other waters and maintain the long-term sustainability and resiliency of valued water resources.

In addition to the comprehensive review by the U.S. EPA (2015), a number of recent studies focusing on the hydrologic connectivity of prairie wetlands have been reported in the literature. For example, Chu (2015) proposed a ~~puddle-to-puddle~~ modeling framework to delineate prairie wetlands and characterize their dynamic hydro-topographic properties in a small North Dakota research area ~~the Cottonwood Lake area~~ (2.55 km^2) using a 10-m resolution digital elevation model (DEM). Vanderhoof et al. (2016) examined the effects of wetland expansion and contraction on surface water connectivity in the PPR using time series Landsat imagery. Ameli and Creed (2017) developed a physically-based hydrologic model to characterize surface and groundwater hydrologic connectivity of prairie wetlands. These reported studies represent some of the latest research developments on hydrologic

connectivity in the PPR. To our knowledge, little work has been done to delineate potential flow paths between wetlands and stream networks and use flow paths to characterize hydrologic connectivity in the PPR. In addition, previous remote sensing-based work on the hydrology of prairie wetlands mainly focused on mapping wetland inundation areas (e.g., Huang et al., 2014; Vanderhoof et al., 2017) or wetland depressions (e.g., McCauley and Anteau, 2014; Wu and Lane, 2016), few studies have treated wetlands and catchments as integrated hydrological units. Therefore, there is a call for treating ~~In a comprehensive overview of wetland hydrology in the PPR, Hayashi et al. (2016) highlighted that~~ prairie wetlands and catchments ~~should be considered~~ as highly integrated hydrological units because the existence of prairie wetlands depends on lateral inputs of runoff water from their catchments in addition to direct precipitation (Hayashi et al., 2016). ~~To our knowledge, however, few studies on the hydrology of prairie wetlands have treated wetlands and catchments as integrated hydrological units(McCauley and Anteau, 2014; Wu and Lane, 2016).~~ Furthermore, hydrologic models for the PPR were commonly developed using ~~course~~coarse-resolution DEMs, such as the 30-m National Elevation Dataset ~~high-resolution light detection and ranging (LiDAR) data have rarely been used in broad-scale (e.g., basin- or subbasin-scale) studies to delineate wetland catchments and model wetland connectivity in the PPR~~(see Chu, 2015; Evenson et al., 2015; Evenson et al., 2016). ~~h~~High-resolution light detection and ranging (LiDAR) data have rarely been used in broad-scale (e.g., basin- or subbasin-scale) studies to delineate wetland catchments and model wetland connectivity in the PPR.

In this paper, we present a semi-automated framework for delineating nested hierarchical wetland depressions and their corresponding catchments as well as simulating wetland connectivity using high-resolution LiDAR data. Our goal was to demonstrate a method to characterize fill-spill wetland hydrology and map potential hydrological connections between wetlands and stream networks. The hierarchical structure of wetland depressions and catchments was identified and quantified using ~~the~~ a localized contour tree method (Wu et al., 2015). The potential hydrologic connectivity between wetlands and streams was characterized using the least-cost path algorithm. We also utilized high-resolution LiDAR intensity data to delineate wetland inundation areas, which were compared against the National Wetlands Inventory (NWI) to demonstrate the hydrological dynamics of prairie wetlands. ~~The resulting flow network delineated putative temporary or seasonal flow paths connecting wetland depressions to each other or to the river network at scales finer than available through the National Hydrography Dataset. The results demonstrated that our proposed framework is promising for improving~~ Our ultimate goal is to build on our proposed framework to improve overland flow simulation and hydrologic connectivity analysis, which subsequently may improve the understanding of wetland hydrological dynamics at watershed scales.

2 Study area and datasets

2.1 Study area

~~Our study~~The work ~~area~~ focused on the Pipestem River subbasin in the Prairie Pothole Region of North Dakota (Fig. 1). The subbasin is an 8-digit Hydrologic Unit Code (#10160002) with a total area of approximately 2,770 km^2, covering four counties in North Dakota (see Fig. 1). The climate of the subbasin is characterized by long, cold, dry winters and short, mild, variably wet summers (Winter and Rosenberry, 1995). Average annual precipitation is

approximately 440 mm with substantial seasonal and annual variations (Huang et al., 2011a). The land cover of the Pipestem subbasin is dominated by cultivated crops (44.1%), herbaceous vegetation (25.9%), and ~~pay~~hay/pasture (13.1%), with a substantial amount of open water (7.1%) and emergent herbaceous wetlands (5.6%) (Jin et al., 2013). The Cottonwood Lake area (see the blue rectangle in Fig. 1), a long-term field research site established by the U.S. Geological Survey (USGS) and the U.S. Fish and Wildlife Service (USFWS) in 1977 for wetland ecosystem monitoring, has been a very active area of research for several decades (e.g., Sloan, 1972; Winter and Rosenberry, 1995; Huang et al., 2011a; Mushet and Euliss, 2012; Hayashi et al., 2016).

2.2 LiDAR data

The LiDAR elevation data for the Pipestem subbasin were collected in ~~the~~ late October ~~of~~ 2011 and distributed through the North Dakota GIS Hub Data Portal (https://gis.nd.gov/, accessed December 30, 2016). The bare-earth digital elevation models (DEMs) derived from LiDAR point clouds are freely available as 1-m resolution image tiles (2 km × 2 km). The vertical accuracy of the LiDAR DEM is 15.0 cm. ~~In total, the Pipestem Subbasin consists of 786 DEM tiles with an aggregated file size of 22.66 GB.~~ We created a seamless LiDAR DEM (see Fig. 1) for the Pipestem subbasin by mosaicking 786 DEM tiles and used it for all subsequent data analyses (approximately 22.66 GB ~~file size~~). The elevation of the subbasin ranges from 422 m to 666 m, with relatively high-elevation areas in the west and low-elevation areas in the east.

The LiDAR intensity data for the Pipestem subbasin were also collected at 1-m resolution coincident with the LiDAR elevation data collection. In general, the return signal intensities of water areas are relatively weak due to water absorption of the near-infrared spectrum (Lang and McCarty, 2009; McCauley and Anteau, 2014). As a result, waterbodies typically appear as dark features whereas non-water areas appear as relatively bright features in the LiDAR intensity image. Thresholding techniques have been commonly used to distinguish water pixels from non-water pixels (Huang et al., 2011b; Huang et al., 2014; Wu and Lane, 2016). In this study, the LiDAR intensity data were primarily used to extract standing-water areas (i.e., inundation areas) while the LiDAR DEMs were used to derive nested wetland depressions and their corresponding catchments above the standing-water surface. It is worth noting that October 2011 was an extreme wet period according to the Palmer Hydrological Drought Index (Huang et al., 2011a). Consequently, small individual wetland depressions nested within larger inundated wetland complexes might not be detectable from the resulting LiDAR DEM.

2.3 Ancillary data

In addition to the LiDAR datasets, we used three ancillary datasets, including the 1-m resolution aerial imagery from the National Agriculture Imagery Program (NAIP) of the U.S. Department of Agriculture (USDA), the National Wetlands Inventory (NWI) from the USFWS, and the National Hydrography Dataset (NHD) from the USGS.

The NAIP imagery products were also acquired from the North Dakota GIS Hub Data Portal. The default spectral resolution of the NAIP imagery in North Dakota is natural color (Red, Green, and Blue, or RGB). Beginning in 2007, however, the state data ~~has~~ have been delivered with four bands of data: RGB and Near Infrared. We downloaded and processed six years of NAIP imagery for the Pipestem subbasin, including 2003, 2004, 2006,

2009, 2012, and 2014. A small portion of the study area with the NAIP imagery is shown in Fig. 2. These time-series NAIP imagery clearly demonstrate the dynamic nature of prairie pothole wetlands under various dry and wet conditions. In particular, the extremely wet year of 2014 resulted in many individual wetlands to coalesce and form larger wetland complexes (see the yellow arrows in Fig. 2). It should be noted that all the NAIP imagery were collected during the summer growing season of agricultural crops. Since no coincident aerial photographs were collected during the LiDAR data acquisition campaign in 2011, these NAIP imagery can serve as valuable data sources for validating the LiDAR-derived wetlands catchments and hydrological pathways in this study.

The NWI data for our study area were downloaded from https://www.fws.gov/wetlands/ (accessed December 30, 2016). ~~These~~ The wetland~~s~~ inventory data in this region were created by manually interpreting aerial photographs acquired in the 1980s with additional support from soil surveys and field checking (Cowardin et al., 1979; Huang et al., 2011b; Wu and Lane, 2016). Tiner (1997) reported that the target mapping unit, the size class of the smallest group of NWI wetlands that can be consistently mapped, was between 1000 m^2 and 4000 m^2 in the Prairie Pothole Region. It should be noted that the target mapping unit is not the minimum wetland size of the NWI. In fact, there are a considerable amount of NWI wetland polygons smaller than the target mapping unit (1000 m^2). In this study, we focused on the prairie wetlands that are greater than 500 m^2. Therefore, 5644 small NWI wetland polygons (< 500 m^2) were eliminated from further analysis. In total, there were 32,016 NWI wetland polygons (≥ 500 m^2) across the Pipestem subbasin (Table 1). The total size of these NWI wetlands was approximately 279.5 km^2, covering 10.1% of the Pipestem subbasin. The areal composition of NWI wetlands were freshwater emergent wetlands (86.5%), lakes (7.5%), freshwater ponds (5.3%), freshwater forested/shrub wetland (0.4%), and riverine systems (0.3%). The median size of wetlands (≥ 500 m^2) in our study area was ~~1778~~ 1.8×10^3 m^2. Although the NWI data is the only spatially comprehensive wetland inventory for our study area, it is now considerably out-of-date, as it was developed 30 years ago and it does not reflect the wetland temporal change (Johnston, 2013). The wetland extent and type for many wetland patches have changed since its original delineation (e.g., Fig. 2). Nevertheless, NWI does provide valuable information about wetland locations (Tiner, 1997; Huang et al., 2011b). Furthermore, the NWI definition of wetlands requires only one of three wetland indicators (soils, hydrology, or plants) whereas regulatory delineation requires all three [33 Code of Federal Regulations 328.3(b)]. In our study, the NWI polygons were primarily used to compare with the wetland depressions delineated from the LiDAR DEM.

The high-resolution NHD data were downloaded from http://nhd.usgs.gov (accessed December 30, 2016). There were 1840 polyline features in the NHD flowline layer for the Pipestem subbasin, with a total length of ~~1402.2~~ 1.4×10^3 km and an average length of 762 ~~.1~~ m. The NHD flowlines overlaid on top of the LiDAR DEM ~~with is~~are shown in Fig. 1. It is worth noting that the majority of the NHD flowline features were found in the low-elevation areas in the east. The high-elevation areas in the west where most NWI wetland polygons are located have very few NHD flowlines, except for the Little Pipestem Creek. This ~~implies~~ suggests that a large number of temporary and seasonal flow paths were not captured in the NHD dataset, perhaps due to the fact that ~~. It is also worth noting that~~ the NHD does not try to systematically measure stream lines <1.6 km (Stanislawski, 2009; Lane and D'Amico, 2016). In this study, the NHD flowlines were used to compare the LiDAR-derived potential flow paths using our proposed methodology.

3 Methodology

3.1 Outline

Our methodology for delineating nested wetland catchments and flow paths is a semi-automated approach consisting of several key steps: (a) extraction of hierarchical wetland depressions using the localized contour tree method (Wu et al., 2015); (b) delineation of nested wetland catchments; (c) calculation of potential water storage; and (d) derivation of potential flow paths using the least-cost path search algorithm. The LiDAR DEM ~~is~~ was used to delineate hierarchical wetland depressions and nested wetland catchments. The LiDAR intensity imagery ~~is~~ was used to extract wetland inundation areas. The potential water storage of each individual wetland depression ~~is~~ was calculated as the volume between the standing water surface and the maximum water boundary where water ~~may~~ might overspill into downstream wetlands or waters. The potential flow paths representing surface water connectivity ~~can~~ were ~~then be~~ derived according to the potential water storage and simulated rainfall intensity. The flowchart in Fig. 3 shows the detailed procedures of the methodology for delineating wetland catchments and potential flow paths.

3.2 Extraction of hierarchical wetland depressions

The fill-and-spill hydrology of prairie wetland depressions have received considerable attention in recent years (Shaw et al., 2012; Shaw et al., 2013; Golden et al., 2014; Chu, 2015; Hayashi et al., 2016; Wu and Lane, 2016). It is generally acknowledged that the fill-and-spill mechanism of wetland depressions results in intermittent hydrologic connectivity between wetlands in the ~~Prairie Pothole Region of North America~~PPR. In this study, wetland depressions were categorized into two groups based on their hierarchical structure: simple depressions and composite depressions. A simple depression is a depression that does not have any other depressions embedded in it, whereas a composite depression is composed of two or more simple depressions (Wu and Lane, 2016). As shown in Fig. 4(a), for example, depressions A, B, C, D and E are all simple depressions. As water level gradually increases in these simple depressions, they will eventually begin to spill and merge to form composite depressions. For instance, the two ~~adjacent~~ adjoining simple depressions A and B can form a composite depression F (see Fig. 4(b)). Continuously, composite depression F and simple depression C can further coalesce to form an even larger composite depression G. Similarly, the two adjoining ~~adjacent~~ simple depressions D and E can coalesce to form a composite depression H.

It is worth noting that the flow direction of surface waters resulting from the fill-and-spill mechanism between adjoining ~~adjacent~~ wetland depressions can be bidirectional, depending on the antecedent water level and potential water storage capability of the depressions. Most previous studies simply assumed that water always flows unidirectionally from an upper waterbody to a lower one. This assumption, however, does not apply when two adjoining ~~adjacent~~ depressions share the same spilling elevation or when there is a groundwater hydraulic head preventing the flow from one to another. For example, in Fig. 4(a), the water flow direction resulting from fill-and-spill between depressions A and B can be bidirectional. If depression B fills up more quickly than depression A, then water will flow from depression B to depression A through the spilling point, and vice versa. Depression with a

high elevation of antecedent water level does not necessarily spill to an adjoining ~~adjacent~~ depression with a lower elevation of antecedent water level. The key factors affecting the initialization of spilling process leading to flow direction are the depression ponding time and catchment precipitation conditions. If the rain or runoff comes from the east and that is where depression B is, then it might fill more quickly than if the runoff comes from the west where depression A is. The wetland depression whichever takes less time to fill up will spill to the adjoining ~~adjacent~~ depression and eventually coalesce to form a larger composite depression. If no ~~adjacent~~ adjoining depression with the same spilling elevation is available, the upstream wetland depression will directly spill to downstream wetlands or ~~river~~ streams. For example, the largest fully-filled composite depression G will spill to the simple depression D or the composite depression H, if available.

To identify and delineate the nested hierarchical structure of potential wetland depressions, we utilized the localized contour tree method proposed by Wu et al. (2015). The concept of contour tree was initially proposed to extract key topographic features (e.g., peaks, pits, ravines, and ridges) from contour maps (Kweon and Kanade, 1994). The contour tree is a tree data structure that can represent the nesting of contour lines on a continuous topographic surface. Wu et al. (2015) improved and implemented the contour tree algorithm, making it a locally adaptive version. In other words, the localized contour tree algorithm builds a series of trees rather than a single global contour tree for the entire area. Each localized contour tree represents one disjointed depression (simple or composite), and the number of trees represents the total number of disjointed depressions for the entire area. When a disjointed depression is fully flooded, the water in it will spill to the downstream wetlands or waters through overland flow. For example, Fig. 4(c) and (d) show the corresponding contour tree graphs for the composite depressions in Fig. 4(b). Once the composition G is fully filled, water will spill into simple depression D or composite depression H.

3.3 Delineation of nested wetland catchments

After the identification and extraction of hierarchical wetland depressions from the contour maps, various hydrologically relevant terrain attributes can be derived based on the DEM, including flow direction, flow accumulation, catchment boundary, flow path, flow length, etc. The calculation of flow direction is essential in hydrological analysis because it frequently serves as the first step to derive other hydrologically important terrain attributes. On a topographic surface represented in a DEM, flow direction is the direction of flow from each grid cell to its steepest downslope neighbor. One of the widely used flow direction algorithms is the eight-direction flow model known as the D8 algorithm (O'Callaghan and Mark, 1984), which is available in most GIS software packages. Flow accumulation is computed based on flow direction. Each cell value in the flow accumulation raster represents the number of upslope cells that flow into it. In general, cells with high flow accumulation values correspond to areas of concentrated flow (e.g. stream channels), while cells with a flow accumulation value of zero correspond to the pattern of ridges (Zhu, 2016). Therefore, flow accumulation provides a basis for identifying ridgelines and delineating catchment boundaries.

A catchment is the upslope area that drains water to a common outlet. It is also known as the watershed, drainage basin, or contributing area. Catchment boundaries can be delineated from a DEM by identifying ridgelines

between catchments based on a specific set of catchment outlets (i.e., spilling points). In traditional hydrological modeling, topographic depressions are commonly treated as spurious ~~depressions (or is it "~~features~~")~~ and simply removed to create a hydrologically correct DEM, which enforces water to flow continuously across the landscape to the catchment outlets (e.g., stream gauges, dams). In the PPR, however, most topographic depressions in the DEM are real features that represent wetland depressions, which are rarely under fully-filled condition (see Hayashi et al., 2016; Lane and D'Amico, 2016; Vanderhoof et al., 2016). As illustrated above, we used the localized contour tree algorithm to delineate the hierarchical wetland depressions, which ~~can be~~were used as the source locations for delineating wetland catchments. Each wetland depression (simple or composite) has a corresponding wetland catchment. As shown in Fig. 4(b), the corresponding wetland catchment of each wetland depression is bounded by the vertical lines surrounding that depression. For example, the wetland catchment of simple depression A is $Catchment_{lm}$, and the wetland catchment of simple depression B is $Catchment_{mn}$. Similarly, the wetland catchment of composite depression F is $Catchment_{ln}$, which is an aggregated area of $Catchment_{lm}$ and $Catchment_{mn}$, resulting from the coalesce ~~from~~ of simple depressions A and B.

3.4 Calculation of potential water storage and ponding time

The potential water storage capacity (V [m^3]) of each wetland depression ~~can be~~was computed through statistical analysis of the grid cells that fall within the depression (Wu and Lane, 2016):

$$V = \sum_{i=1}^{n} (C - Z_i) \cdot R^2 \qquad (1)$$

where C is the spilling elevation (m), i.e., the elevation of the grid cell where water spills out of the depression; Z_i is the elevation of the grid cell i (m); R is the spatial resolution (m); and n is the total number of grid cells that fall within the depression.

The ponding time of a depression ~~can be~~was calculated as follows:

$$T = V / (A_c \cdot I) \cdot 1000 \qquad (2)$$

where V is the potential water storage capacity of the depression (m^3); A_c is the catchment area of the corresponding depression (m^2); and I is the rainfall intensity (mm/h). For the sake of simplicity, we made two assumptions. First, we assumed that the rainfall ~~is~~ was temporally and spatially consistent and uniformly distributed throughout the landscape (e.g., 50 mm/h) and all surfaces ~~are~~ were impervious. Second, we assumed no soil infiltration.

The proportion of wetland depression area (A_w) to catchment area (A_c) ~~is~~ was calculated by:

$$P_{wc} = A_w / A_c \qquad (3)$$

The wetland depression area (A_w) refers to the maximum ponding extent of the depression. The proportion (P_{wc}) can serve as a good indicator for percent inundation of the study area under extremely wet conditions (e.g., Vanderhoof et al., 2016).

3.5 Derivation of surface-water flow paths

Based on the computed ponding time of each depression under a specific rainfall intensity, the most probable sequence of the overland flow path ~~can be~~were constructed. The depression with the least ponding time will first fill and start to overspill down-gradient. In hydrology, the path which water takes to travel from the spilling point to the downstream surface outlet or channel is commonly known as flow path. The distance it takes for water to travel is known as flow length. In this study, we adopted and adapted the least-cost path search algorithm (Wang and Liu, 2006; Metz et al., 2011; Stein et al., 2011) to derive the potential flow paths. The least cost path algorithm requires two input datasets: the DEM and the depression polygons. Given the fact that topographic depressions in high-resolution LiDAR DEM are frequently a combination of artifacts and actual landscape features (Lindsay and Creed, 2006), the user can set a minimum size threshold for depressions to be treated as actual landscape features. In other words, depressions with a size smaller than the threshold will be treated as artifacts, and thus removed from the DEM. This results in a partially-filled DEM in which depressions smaller than the chosen threshold are filled to enforce hydrologic flow while larger depressions are kept for further analysis. Based on the partially-filled DEM, flow direction for each grid cell can be calculated using the D8 flow direction algorithm (O'Callaghan and Mark, 1984). The least cost path minimizes the cumulative cost (i.e., elevation) along its length. Flow paths are computed by tracing down gradient, from higher to lower cells, following assigned flow directions. With the simulated overland flow path, flow length can be calculated, which is defined as the distance between the spilling point of an upslope wetland and the inlet of a downslope wetland or stream. In our study, hydrologic connectivity refers to the water movement between wetland-wetland and wetland-stream via hydrologic pathways of surface water.

3.6 Wetland Hydrology Analyst

To facilitate automated delineation of wetland catchments and flow paths, we ~~have~~ implemented the proposed framework as an ArcGIS toolbox – Wetland Hydrology Analyst, which is freely available for download at https://GISTools.github.io/ (accessed December 30, 2016). The core algorithms of the toolbox were implemented using the Python programming language. The toolbox consists of three tools: Wetland Depression Tool, Wetland Catchment Tool, and Flow Path Tool. The Wetland Depression Tool asks the user to select a DEM grid, and then executes the localized contour tree algorithm with user-defined parameters (e.g., base contour elevation, contour interval, min. depression size, min. ponding depth) automatically to delineate hierarchical wetland depressions. The depressional wetland polygons can be stored as ESRI Shapefiles or a Feature Dataset in a Geodatabase. Various morphometric properties (e.g., width, length, size, perimeter, max. depth, mean depth, volume, elongatedness, compactness) are computed and included in the attribute table of the wetland polygon layers. The Wetland Catchment Tool uses the DEM grid and the wetland polygon layers resulted from the Wetland Depression Tool as

input, and exports wetland catchment layers in both vector and raster format. The Flow Path Tool can be used to derive potential overland flow paths of surface water based on the DEM grid and the wetland polygon layers.

3.7 Wetland inundation mapping

The LiDAR intensity image was primarily used to map inundation areas. Before inundation mapping, we applied a median filter to smooth the LiDAR intensity image. The median filter is considered as an edge-preserving filter that can effectively remove data noise while preserving boundaries between image objects (Wu et al., 2014). Subsequently, a simple thresholding method was used to separate inundated and non-inundated classes. Similar thresholding techniques have been used in previous studies to extract water areas from LiDAR intensity imagery (Lang and McCarty, 2009; Huang et al., 2011b). By examining typical inundation areas and the histogram of the LiDAR intensity imagery used in our study, we chose an intensity threshold value of 20. Grid cells with an intensity value between 0 and 20 were classified as an inundated class while grid cells with an intensity value greater than 20 as a non-inundated class, which resulted in a binary image. In the binary image, each region composed of inundated pixels that were spatially connected (8-neighbor) was referred to as a potential inundation object. The "boundary clean" and "region group" functions in ArcGIS Spatial Analyst were then used to clean ragged edges of the potential inundation objects and assign a unique number to each object. It should be noted that water and live trees might both appear as dark features in the LiDAR intensity imagery and have similar intensity values, although trees are not particularly common in this region. As a result, some trees were misclassified as inundation objects. To correct the misclassifications and obtain reliable inundation objects, we further refined the potential inundation objects using additional criteria with the aid of the LiDAR DEM. First ~~of all~~, we assumed that each inundation object must occur within a topographic depression in order to retain water. In other words, all inundation objects must intersect with depression objects derived using the "sink" function in ArcGIS Spatial Analyst. Secondly, given the relatively flat and level surface of inundated regions, the standard deviation of pixel elevations within the same inundation object should be very small. By examining the standard deviation of pixel elevations of some typical inundation objects and tree objects, we chose a threshold of 0.25 m, which is slightly larger than the vertical accuracy of the LiDAR data (0.15 m). This step can be achieved using the "zonal statistics as table" in ArcGIS Spatial Analyst. Thirdly, we only focused on wetlands greater than 500 m^2. Therefore, inundation objects with areas smaller than 500 m^2 were eliminated from further analysis.

4 Results

4.1 Inundation mapping results

~~The LiDAR intensity image was primarily used to map inundation areas. Before inundation mapping, we applied a median filter to smooth the LiDAR intensity image. The median filter is considered as an edge-preserving filter that can effectively remove data noise while preserving boundaries between image objects (Wu et al., 2014). Subsequently, a simple thresholding method was used to separate inundated and non-inundated classes. Similar thresholding techniques have been used in previous studies to extract water areas from LiDAR intensity imagery~~

~~(Lang and McCarty, 2009; Huang et al., 2011b). By examining typical inundation areas and the histogram of the LiDAR intensity imagery used in our study, we chose an intensity threshold value of 20. Grid cells with an intensity value between 0 and 20 were classified as an inundated class while grid cells with an intensity value greater than 20 as a non-inundated class, which resulted in a binary image. In the binary image, each region composed of inundated pixels that were spatially connected (8-neighbor) was referred to as a potential inundation object. The "boundary clean" and "region group" functions in ArcGIS Spatial Analyst were then used to clean ragged edges of the potential inundation objects and assign a unique number to each object. It should be noted that water and live trees might both appear as dark features in the LiDAR intensity imagery and have similar intensity values, although trees are not particularly common in this region. As a result, some trees were misclassified as inundation objects. To correct the misclassifications and obtain reliable inundation objects, we further refined the potential inundation objects using additional criteria with the aid of the LiDAR DEM. First of all, we assumed that each inundation object must occur within a topographic depression in order to retain water. In other words, all inundation objects must intersect with depression objects derived using the "sink" function in ArcGIS Spatial Analyst. Secondly, given the relatively flat and level surface of inundated regions, the standard deviation of pixel elevations within the same inundation object should be very small. By examining the standard deviation of pixel elevations of some typical inundation objects and tree objects, we chose a threshold of 0.25 m, which is slightly larger than the vertical accuracy of the LiDAR data (0.15 m). This step can be achieved using the "zonal statistics as table" in ArcGIS Spatial Analyst. Thirdly, we only focused on wetlands greater than 500 m^2. Therefore, inundation objects with areas smaller than 500 m^2 were eliminated from further analysis.~~

Using the above procedures, we identified 15,784 inundation objects (i.e., depressions ≥ 500 m^2 with water as determined through LiDAR-based analyses), which were then compared against the NWI wetland polygons in our study area. We have made the inundation map publicly available at https://GISTools.github.io/ (accessed December 30, 2016). The identified inundation objects encompassed an area of approximately 278.5 km^2, accounting for 10.1 % of the Pipestem subbasin. Using the empirical area-to-volume equation developed for this region of the PPR (see Gleason et al., 2007; Wu and Lane, 2016), we estimated that the 15,784 inundated depressions stored approximately 448.5 million m^3 of water. The histogram of inundation polygons is shown in Fig. 5(a). The median size of the inundation polygons identified using the LiDAR intensity data was ~~1828~~ 1.8×10^3 m^2, which was slightly larger than the reported median size of NWI polygons (Table 2). ~~Surprisingly~~Contrary to expectations, 18,957 out of 32,016 NWI wetland polygons did not intersect with the inundation objects. In other words, 59.2% of the NWI wetland polygons mapped in the 1980s ~~were found to be partly or completely dried out or destroyed~~did not contain visible waterbodies during the LiDAR collection period. The total area of these 'dried' NWI wetlands were 43.6 km^2, accounting for 15.6% of the original NWI wetland areas (279.5 km^2). The histogram of the 'dried' NWI wetlands is shown in Fig. 5(b). It is worth noting that most of these 'dried' NWI wetlands were relatively small with a median size of ~~1212~~ 1.2×10^3 m^2 (Table 2). The LiDAR intensity data were acquired in late October 2011, an extremely wet month according to the Palmer Hydrological Drought Index (Fig. 6). During this wet season, most wetlands would be expected to have abundant standing water. If no standing water could be detected in a wetland patch during this extremely wet period, it is possible that some of these small wetlands might have ~~we can safely conclude that the~~

~~wetland patch had probably~~ dried out during the past ~~decades~~weeks to months~~, although we could not infer the exact time when it occurred~~. It is possible that land use change surrounding the 'dried' wetlands (e.g., row-cropping replacing pasture lands) may have affected their hydrology (Wright and Wimberly, 2013); water diversion via drainage or ditches could also be responsible for the lack of inundation, though we did not explore either of these potential drivers of change in this study. However, it is also likely that some of the 'dried' wetland might become wet again in the spring following snowmelt. The 'dried' NWI wetlands could also be attributed to the source of error in the original NWI data, which has a minimum mapping unit (i.e., the minimum sized wetland that can be consistently mapped) of 0.1 ha for the PPR (Tiner, 1997). Figure 5(b) shows that 37% of the 'dried' NWI polygons are smaller than the minimum mapping unit (1000 m^2). This implies that these small 'dried' NWI polygons could be due to the NWI mapping error. Figure 7 illustrates the difference in shape and extent between the LiDAR-derived wetland inundation maps and the NWI wetland polygons. The areas of disagreement (discrepancy) can be partly explained by the different image acquisition dates. As mentioned earlier, the NWI maps for Pipestem subbasin of the PPR were created in the early 1980s while the LiDAR data were acquired in 2011. Clearly, most small NWI wetlands (see ~~blue~~yellow-outline polygons in Fig. 7) appeared to not have visible standing water. Conversely, large NWI wetlands exhibited expansion and coalesced to form even large wetland complexes (see ~~yellow~~blue-outline polygons in Fig. 7).

4.2 Nested wetland depressions and catchments

We applied the localized contour method on the LiDAR-derived DEM and identified 33,241 wetland depressions. It should be noted that the 'wetland depression' refers to the maximum potential ponding extent of the depression. The inundated wetland depressions identified in the prior section can be seen as a subset of these depressions with water in them. The total area of the identified wetland depressions was approximately ~~554.5~~ 0.55×10^9 ~~k~~m^2 (Table 3), accounting for 20% of the entire study area. This histogram of the wetland depressions is shown in Fig. 8(a). The median size of wetland depressions was ~~2592~~ 2.6×10^3 m^2, which is larger than that of the NWI wetland polygons as well as the inundation polygons (see Table 2). Using Eq. (1), we estimated that the potential water storage capacity of the Pipestem subbasin resulting from these wetland depressions is 782.8 million m^3, which is 1.75 times as large as the estimated existing water storage (448.5 million m^3) for the 15,784 inundated wetlands mentioned above. As noted by Hayashi et al. (2016), wetlands and catchments are highly correlated and should be considered as integrated hydrological units. The water input of each wetland largely depends on runoff from the upland areas within the catchment. Using the method described in Section 3.3, we delineated the associated wetland catchments for each of the 33,241 wetland depressions. The histogram of the delineated wetland catchments is shown in Fig. 8(b). The median size of wetland catchments was ~~25,780~~ 26×10^3 m^2, which is approximately ten times larger than that of the wetland depressions (Table 3).

Using Eq. (3), we calculated the proportion of depression area to catchment area (A_w / A_c) for each wetland depression. It was found that the proportion ranged from 0.04% to 83.72%, with a median of 14.31% (Table 3). Our findings are in general agreement with previous studies (Hayashi et al., 2016). For instance, Hayashi et al. (1998)

reported an average proportion (A_w / A_c) of 9% for 12 prairie wetlands in the Canadian portion of the PPR. Similarly, Watmough and Schmoll (2007) analyzed 13 wetlands in the Cottonwood Lake Area during the high-stage period and reported an average proportion (A_w / A_c) of 18%. It should be noted that the average proportion of wetland area to catchment area (A_w / A_c) reported in the above studies were calculated on the basis of a limited number of wetlands. On the contrary, our results were computed from more than 30,000 wetland depressions and catchments, which provides a statistically reliable result for the study area due to a much larger sample size.

4.3 Potential ~~F~~flow paths and connectivity lengths

Based on the LiDAR DEM and wetland depression polygon layer, we derived the ~~complete~~ potential flow path network for our study area using the least-cost path algorithm. We have made the interactive map of modeled hydrologic connectivity in the Pipestem subbasin publicly available at https://GISTools.github.io#wetland-connectivity ~~/~~ (accessed December 30, 2016). A number of data layers derived from our study are available on the map, such as the inundation polygons, wetland depressions, wetland catchments, and potential flow paths. NWI polygons, NHD flowlines, LiDAR intensity image, LiDAR shaded relief, and time-series aerial photographs are also available for results comparison and visualization. A small proportion of the map is shown in Fig. 9. Clearly, the derived potential flow paths not only captured the permanent surface water flow paths (see the thick blue NHD flowline in Fig. 9), but also the potential intermittent and infrequent flow paths that have not been mapped previously. By examining the potential flow paths overlaid on the color infrared aerial photograph (Fig. 9(b)), we can see that the majority of potential flow paths appeared to be collocated with vegetated areas. This indicates that flow paths are likely located in high soil moisture areas that are directly or indirectly related to surface water or groundwater connectivity. It should be ~~noted~~reiterated that the derived flow paths are only potential flow paths. Water may not have flowed along a fraction of them to date.

In total, there are 1840 NHD flowlines in the Pipestem subbasin. The mean and median length of NHD flowlines are 762 m and 316 m, respectively (Table 4). However, the potential flow lengths derived from our study, which connected not only stream segments but also wetlands to wetlands, revealed much shorter flow paths than the NHD flowlines. This finding is within our expectation. The histogram of the derived potential flow lengths is shown in Fig. 10. The median potential flow length is 83 m, which is approximately 1/4 of the median NHD flowlines. The median elevation difference between an upstream wetland and a downstream wetland connected through the potential flow path is 0.89 m.

5 Discussion

~~It should be noted that t~~The LiDAR data we used in this study were collected in ~~the~~ late October ~~of~~ 2011, which was an extremely wet period according to the Palmer Hydrological Drought Index (see Fig. 6). ~~During such a wet period, m~~Most wetlands exhibited high water levels and large water extents, which can be evidenced from the LiDAR intensity image in Fig. 7 and the aerial photograph in Fig. 9. It can be clearly seen that most wetlands, particularly those larger ones, appeared to have larger water extents compared to the NWI polygons. A substantial number of

inundated NWI wetlands were found ~~inundated~~ to coalesce with ~~adjacent~~ adjoining LiDAR-based wetland depressions~~s~~ and form larger wetland complexes. LiDAR data acquired during high water levels is desirable for studying maximum water extents of prairie wetlands. However, the use of wet-period LiDAR data alone is not ideal for studying the fill-and-spill hydrology of prairie wetlands. Since LiDAR sensors working in the near-infrared spectrum typically could not penetrate water, it is impractical to derive ~~bathymetric~~ bathymetry ~~information~~ of the wetland depressions. As a result, the delineation and characterization of individual wetland depressions nested within larger inundated wetland complexes were not possible. Bathymetric LiDAR systems with a green laser onboard offer a promising solution for acquiring wetland basin morphometry due to the higher penetration capability of the green laser (Wang and Philpot, 2007). In addition, the derivation of antecedent water depth and volume of wetland depressions is difficult, which can only be estimated using empirical equations based on the statistical relationship between depression area and depression volume (Hayashi and Van der Kamp, 2000; Gleason et al., 2007). As noted earlier, the volume of water in the 15,784 inundated wetlands was estimated to be 448.5 million m^3. Ideally, using multiple LiDAR datasets acquired in both dry and deluge conditions in conjunction with time-series aerial photographs would be essential for studying the fill-and-spill mechanism of prairie wetlands. In this case, we ~~can~~ could use the dry-period LiDAR data to delineate and characterize the morphology of individual wetland depressions before the fill-and-spill processes occur. Furthermore, we can derive the potential flow paths and project the coalescing of wetland depressions after the fill-and-spill processes initiate. The wet-period LiDAR data and time-series aerial photographs can serve as validation datasets to evaluate the fill-and-spill patterns.

It is also worth noting that the proposed methodology in this study was designed to reflect the topography and hydrologic connectivity between wetlands in the Prairie Pothole Region. We have made assumptions to simplify the complex prairie hydrology. Physically-based hydrological models (e.g., Brunner and Simmons, 2012; Ameli and Creed, 2017) have not yet been integrated into our framework. However, fill-and-spill is a complex and spatially distributed hydrological process highly affected by many factors, such as surface topography, surface roughness, soil infiltration, soil properties, depression storage, precipitation, evapotranspiration, snowmelt runoff, and groundwater exchange (Tromp-van Meerveld and McDonnell, 2006b, a; Evenson et al., 2015; Zhao and Wu, 2015; Evenson et al., 2016; Hayashi et al., 2016). Nevertheless, our study presents the first attempt to use LiDAR data for deriving nested wetland catchments and simulating flow paths in the broad-scale Pipestem subbasin in the PPR. Previous studies utilizing high-resolution digital elevation data (e.g., LiDAR, Interferometric Synthetic Aperture Radar [IfSAR]) for studying prairie wetlands were mostly confined in small-scale areas (e.g., plot scale, small watershed scale) with a limited number of wetlands, whereas broad-scale studies using physically-based hydrological models have rarely used LiDAR data to delineate and characterize individual wetland depressions or catchments. Coupled surface-subsurface flow models with hydrologic, biogeochemical, ecologic, and geographic perspectives have yet to be developed for broad-scale studies in the PPR (Golden et al., 2014; Amado et al., 2016). Further efforts are still needed to improve the understanding of the integrated surface-water and groundwater processes of prairie wetlands.

6 Conclusions

Accurate delineation and characterization of wetland depressions and catchments are essential to understand and correctly analyze the hydrology of many landscapes, including the Prairie Pothole Region. ~~for understanding the hydrology of prairie wetlands.~~ In this study, we ~~accurately~~ delineated the inundation areas while reducing the confounding factor of live trees by using the LiDAR-derived DEM in conjunction with the coincident LiDAR intensity imagery. In addition, we developed a semi-automated framework for identifying nested hierarchical wetland depressions and delineating their corresponding catchments using the localized contour tree method. Furthermore, we quantified the potential hydrologic connectivity between wetlands and streams based on the overland flow networks derived using the least-cost path algorithm on LiDAR data. Although the results presented in this study are specific to the Pipestem subbasin, the proposed framework can be easily adopted and adapted to other ~~PPR regions, as well as other~~ wetland regions where ~~fine resolution~~ LiDAR data are available. The new tools that we developed and have made freely available to the scientific community for identifying potential hydrologic connectivity between wetlands and stream networks can better inform ~~wetland regulation debates~~ regulatory decisions and enhance the ability to better manage wetlands under various planning scenarios. The resulting flow network delineated ~~putative temporary or seasonal~~potential flow paths connecting wetland depressions to each other or to the river network at scales finer than available through the National Hydrography Dataset. The results demonstrated that our proposed framework is promising for improving overland flow modeling and hydrologic connectivity analysis (Golden et al., 2016).

Broad-scale prairie wetland hydrology has been difficult to study with traditional remote sensing methods using multi-spectral satellite data due to the limited spatial resolution and the interference of tree canopy (Klemas, 2011; Gallant, 2015). LiDAR-derived DEMs can be used to map potential hydrologic flow pathways, which regulate the ability of wetlands to provide ecosystem services (Lang and McCarty, 2009). This study is an initial step towards the development of a spatially distributed hydrologic model to fully describe the hydrologic processes in broad-scale prairie wetlands. Additional field work and the integration of physically-based models of surface and subsurface processes would benefit the study. Importantly, the results capture temporary and ephemeral hydrologic connections and provide essential information for wetland scientists and decision-makers to more effectively plan for current and future management of prairie wetlands.

Data and code availability

The data and ArcGIS toolbox developed for this paper are available for download at https://GISTools.github.io/.

Competing interests

The authors declare that they have no conflict of interest.

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680 **Table 1.** Summary statistics of the National Wetlands Inventory (NWI) for the Pipestem subbasin, North Dakota.

~~Wetland type~~	~~Count~~	~~Min (m^2)~~	~~Max (m^2)~~	~~Median (m^2)~~	~~Sum (m^2)~~	~~Percentage~~
~~Freshwater Emergent Wetland~~	~~31,046~~	~~500~~	~~3,105,826~~	~~1,770~~	~~241,733,542~~	~~86.5%~~
~~Freshwater Forested/ Shrub Wetland~~	~~108~~	~~548~~	~~343,950~~	~~2,572~~	~~1,175,739~~	~~0.4%~~
~~Freshwater Pond~~	~~760~~	~~533~~	~~719,339~~	~~1,772~~	~~14,719,510~~	~~5.3%~~
~~Lake~~	~~50~~	~~3,746~~	~~9,410,427~~	~~188,600~~	~~21,055,438~~	~~7.5%~~
~~Riverine~~	~~52~~	~~634~~	~~429,838~~	~~4,021~~	~~811,488~~	~~0.3%~~
~~Total (all polygons)~~	~~32,016~~	~~500~~	~~9,410,427~~	~~1,778~~	~~279,495,717~~	~~100.0%~~

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Wetland type	Count	Min (10^3 m^2)	Max (10^6 m^2)	Median (10^3 m^2)	Sum (10^6 m^2)	Percentage (%)
Freshwater Emergent Wetland	31,046	0.50	3.1	1.8	241.7	86.5
Freshwater Forested/ Shrub Wetland	108	0.55	0.34	2.6	1.18	0.4
Freshwater Pond	760	0.53	0.72	1.8	14.7	5.3
Lake	50	3.7	9.4	188.6	21.1	7.5
Riverine	52	0.63	0.43	4.0	0.81	0.3
Total (all polygons)	32,016	0.50	9.4	1.8	279.5	100.0

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Table 2. Summary statistics of NWI wetland polygons and inundation polygons derived from LiDAR intensity data.

~~Type~~	~~Count~~	~~Min (m^2)~~	~~Max (m^2)~~	~~Mean (m^2)~~	~~Median (m^2)~~	~~Sum (m^2)~~
~~NWI polygons~~	~~32,016~~	~~500~~	~~9,410,427~~	~~8,728~~	~~1,778~~	~~279,495,717~~
~~Inundation polygons~~	~~15,784~~	~~500~~	~~7,348,000~~	~~17,650~~	~~1,825~~	~~278,523,863~~
~~Dried NWI polygons~~	~~18,957~~	~~500~~	~~112,100~~	~~2,299~~	~~1,212~~	~~43,574,627~~

Type	Count	Min (10^3 m^2)	Max (10^6 m^2)	Mean (10^3 m^2)	Median (10^3 m^2)	Sum (10^6 m^2)
NWI polygons	32,016	0.50	9.4	8.7	1.8	279.5
Inundation polygons	15,784	0.50	7.3	17.7	1.8	278.5
Dried NWI polygons	18,957	0.50	0.11	2.3	1.2	43.6

Table 3. Summary statistics of 33,241 wetland depressions and catchments derived from LiDAR DEM.

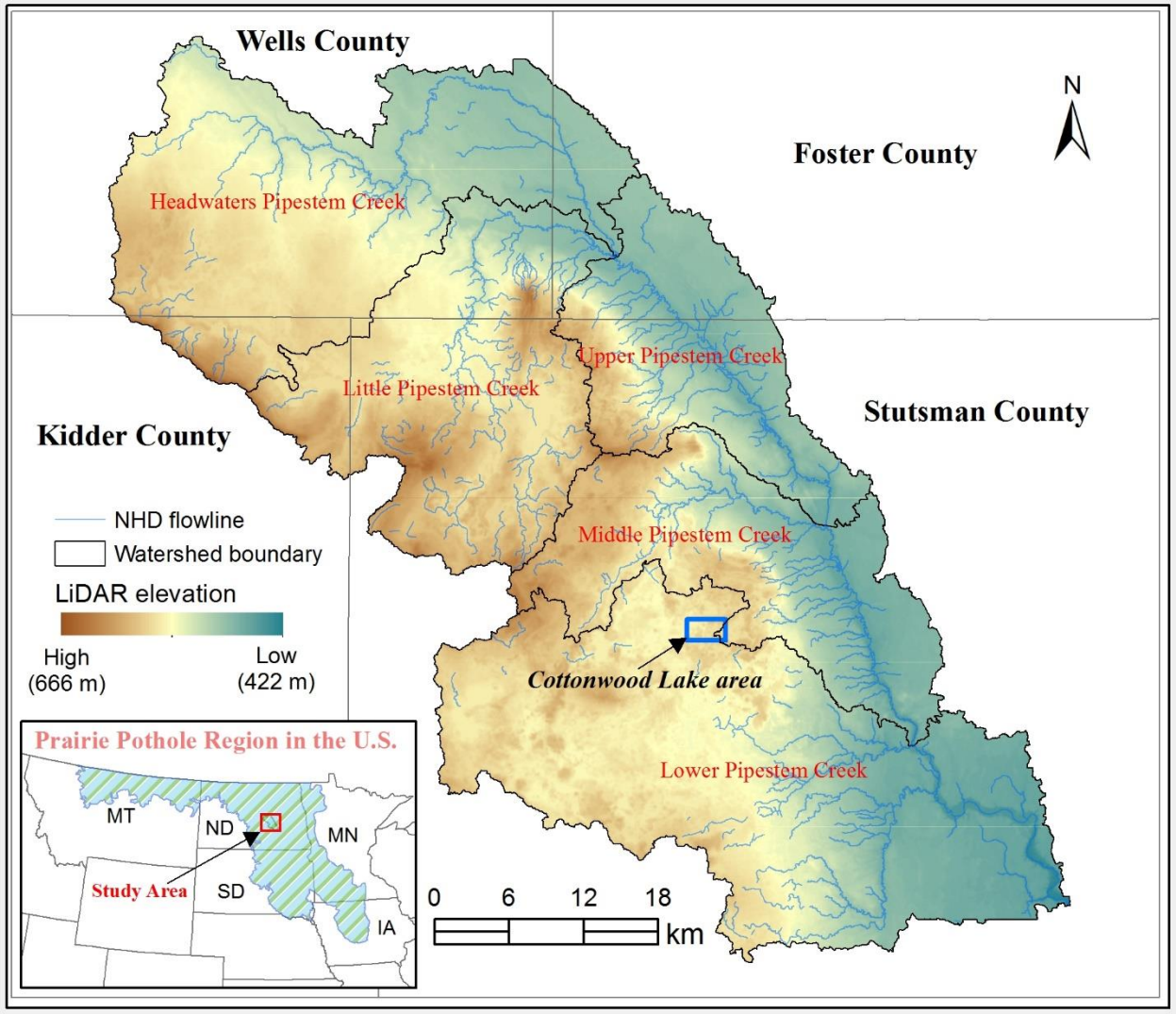
~~Type~~	~~Min~~	~~Max~~	~~Mean~~	~~Median~~	~~Sum~~
~~Depression area (m^2)~~	~~1008~~	~~20,030,000~~	~~16,590~~	~~2592~~	~~554,506,299~~
~~Catchment area (m^2)~~	~~1818~~	~~57,900,000~~	~~82,710~~	~~25,780~~	~~2,770,116,549~~
~~Depression volume (m^3)~~	~~1~~	~~153,000,000~~	~~23,420~~	~~420~~	~~782,886,383~~
~~Proportion of depression area to catchment area (%)~~	~~0.04~~	~~83.72~~	~~16.59~~	~~14.31~~	~~20.06~~

Type	Min	Max	Mean	Median	Sum
Depression area (m^2)	1.0×10^3	20.0×10^6	16.6×10^3	2.6×10^3	0.55×10^9
Catchment area (m^2)	1.8×10^3	57.9×10^6	82.7×10^3	26×10^3	2.77×10^9
Depression volume (m^3)	1	153×10^6	23.4×10^3	0.42×10^3	0.78×10^9
Proportion of depression area to catchment area (%)	0.04	83.72	16.59	14.31	20.06

Table 4. Summary statistics of wetland depression ponding depth, NHD flowlines, ~~connectivity~~ flow path length, and elevation difference.

~~Type~~	~~Count~~	~~Min (m)~~	~~Max (m)~~	~~Mean (m)~~	~~Median (m)~~	~~Sum (m)~~
~~Ponding depth~~	~~33,241~~	~~0.01~~	~~7.64~~	~~0.23~~	~~0.16~~	~~NA~~
~~NHD flowlines~~	~~1840~~	~~3.89~~	~~15,530~~	~~762~~	~~317~~	~~1,402,226~~
~~Connectivity length~~	~~41,449~~	~~1.5~~	~~4,658~~	~~138~~	~~83~~	~~5,014,495~~
~~Elevation difference~~	~~41,449~~	~~0.01~~	~~70.89~~	~~2.14~~	~~0.89~~	~~NA~~

Type	Count	Min (m)	Max (m)	Mean (m)	Median (m)	Sum (m)
Ponding depth	33,241	0.01	7.6	0.23	0.16	NA
NHD flowlines	1840	3.9	15.5×10^3	762	317	1.4×10^6
Flow path length	41,449	1.5	4.7×10^3	138	83	5.0×10^6
Elevation difference	41,449	0.01	70.9	2.1	0.89	NA



694

695 **Figure 1.** Location of the Pipestem subbasin within the Prairie Pothole Region of North Dakota.

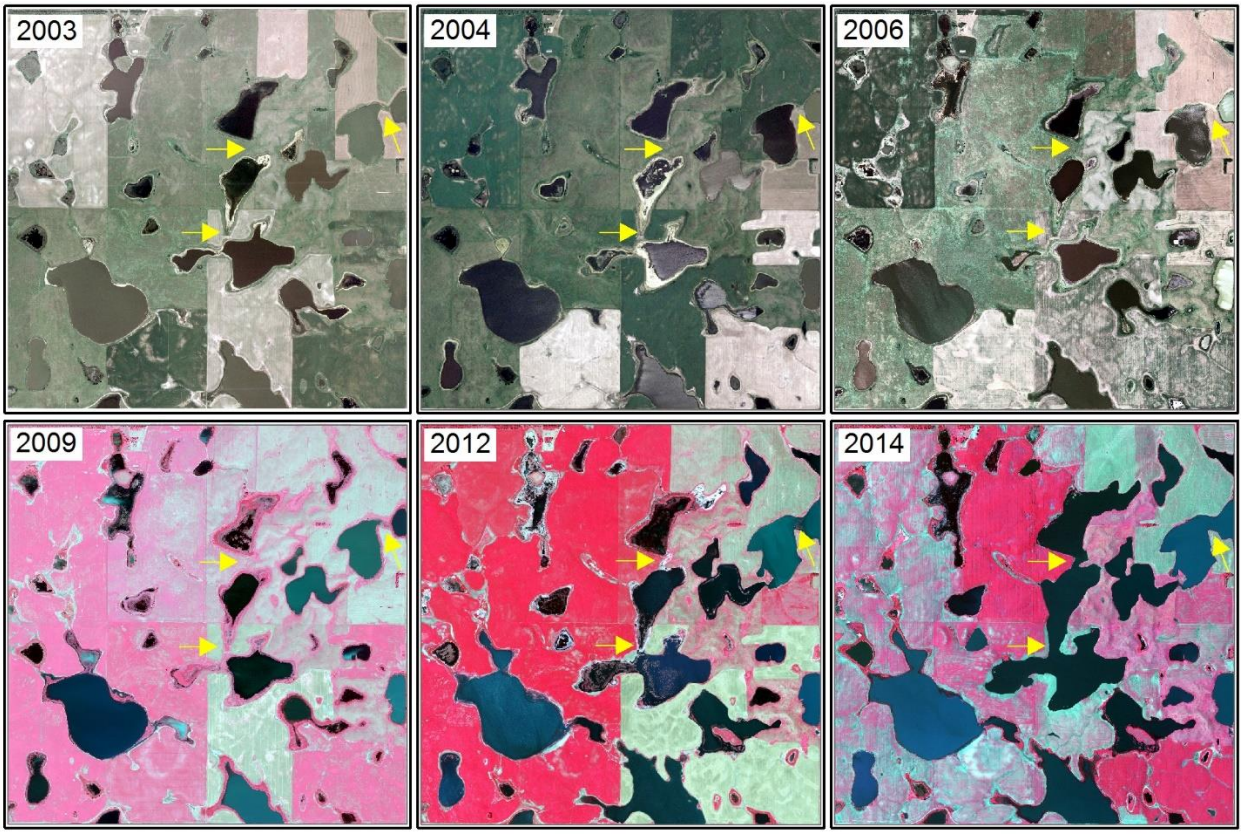


Figure 2. Examples of the National Agriculture Imagery Program (NAIP) aerial imagery in the Prairie Pothole Region of North Dakota illustrate the dynamic nature of prairie pothole wetlands under various dry and wet conditions. The yellow arrows highlight locations where filling-spilling-merging dynamics occurred (imagery location: 99°8'34.454" W, 47°1'23.519" N).

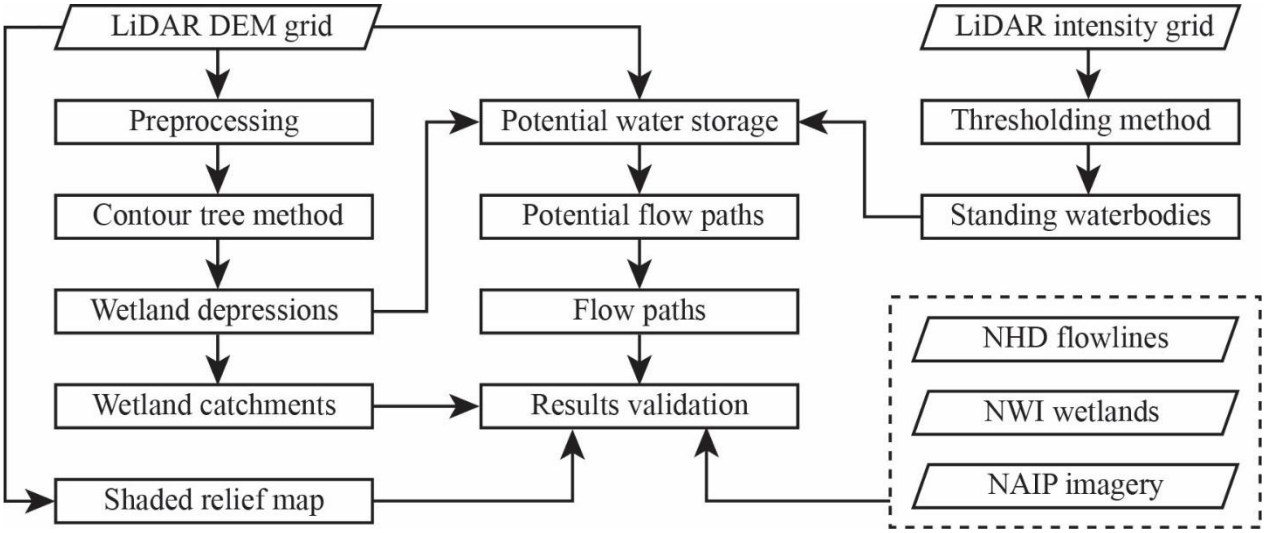
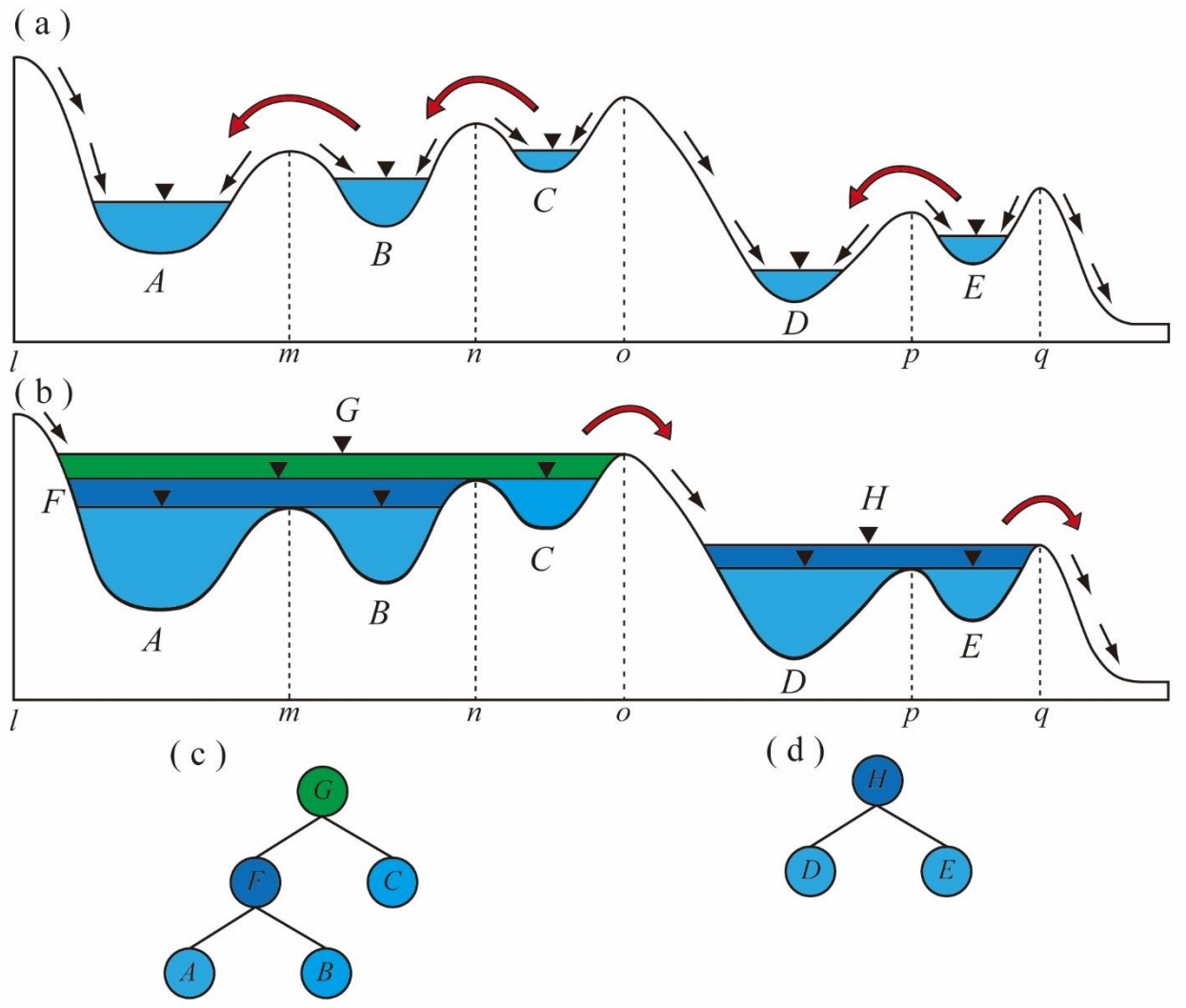


Figure 3. Flowchart of the methodology for delineating wetland catchments and flow paths.



703

704 **Figure 4.** Illustration of the filling-merging-spilling dynamics of wetland depressions: (a) first-level depressions; (b)
705 nested hierarchical structure of depressions under fully-filled condition; (c) corresponding contour tree
706 representation of the composite wetland depression (left) in (a); and (d) corresponding contour tree representation of
707 the composite wetland depression (right) in (a). Different color of nodes in the tree represents different portions of
708 the composite depression in (a): light blue (first-level), dark blue (second-level), and green (third-level).

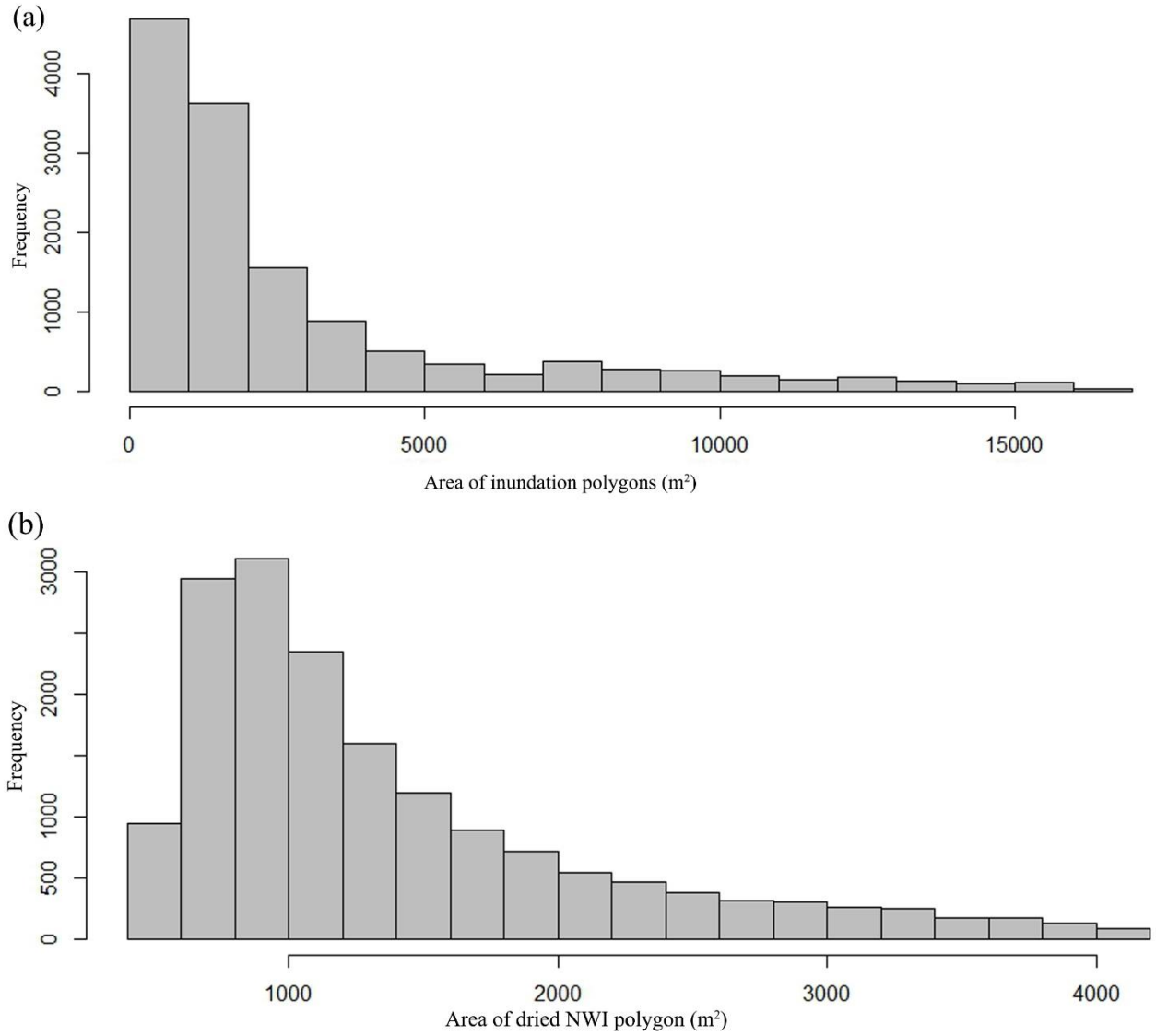


Figure 5. Histograms of inundation and NWI wetland polygons. (a) Inundation objects derived from LiDAR intensity data; (b) dried NWI wetland polygons not intersecting inundation objects.

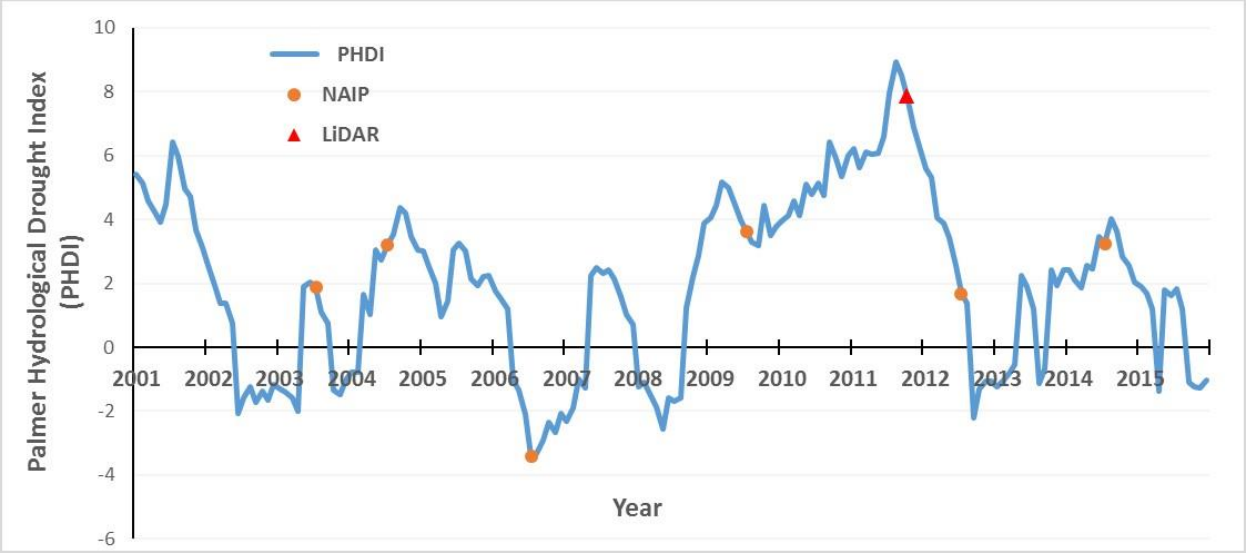


Figure 6. Palmer Hydrological Drought Index (PHDI) of the Pipestem subbasin (2001-2015).

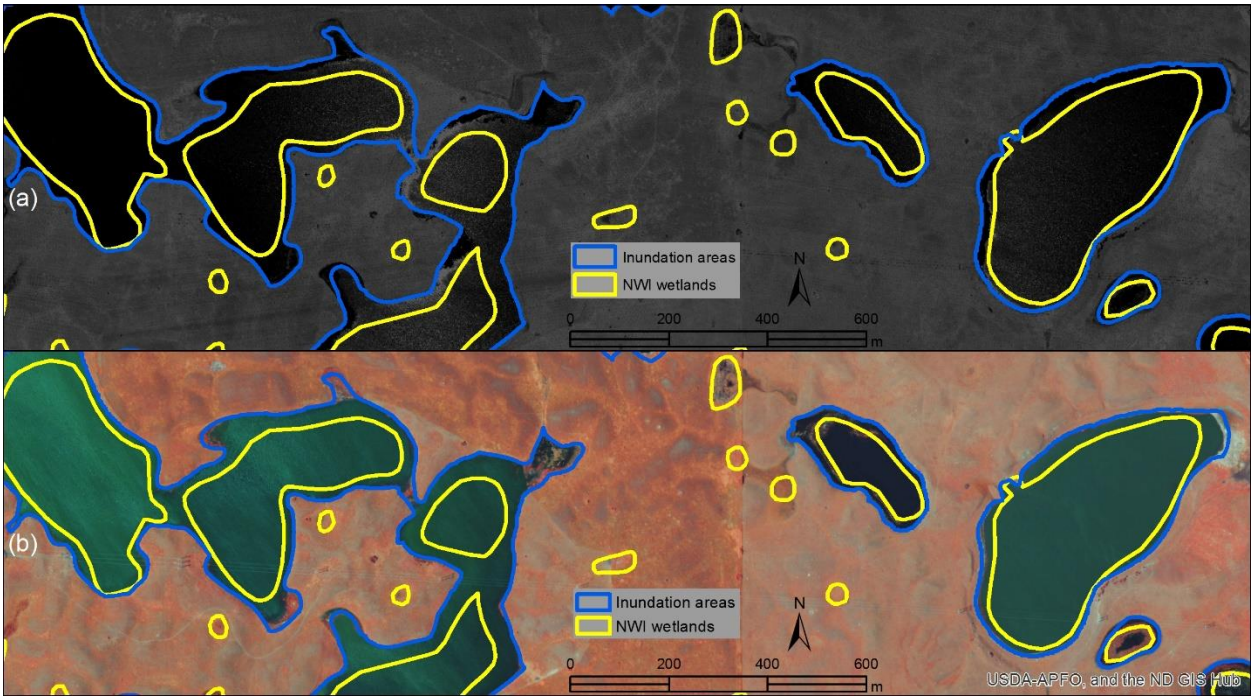
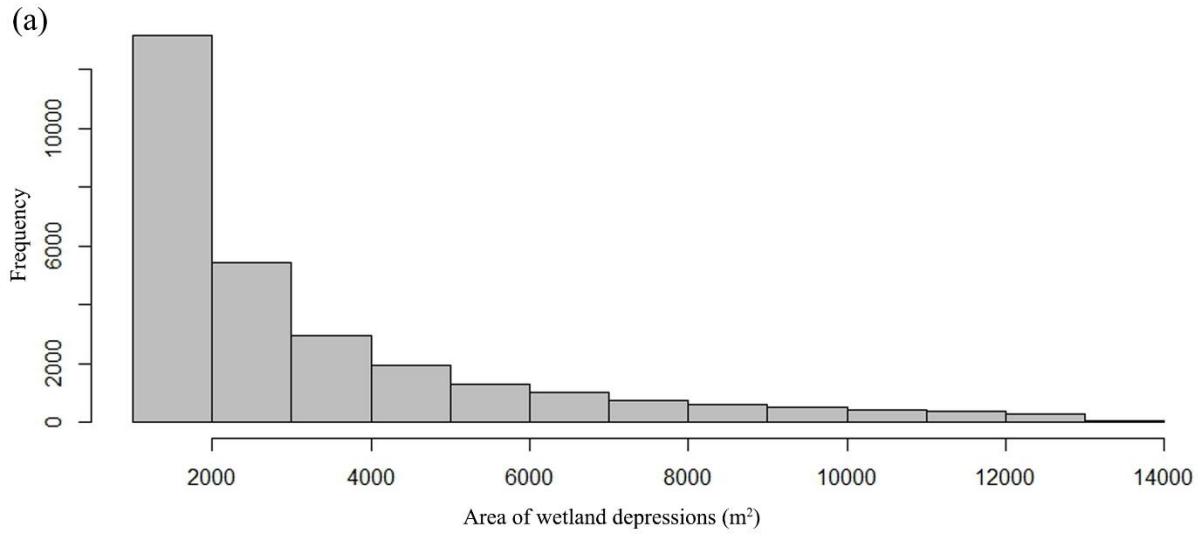
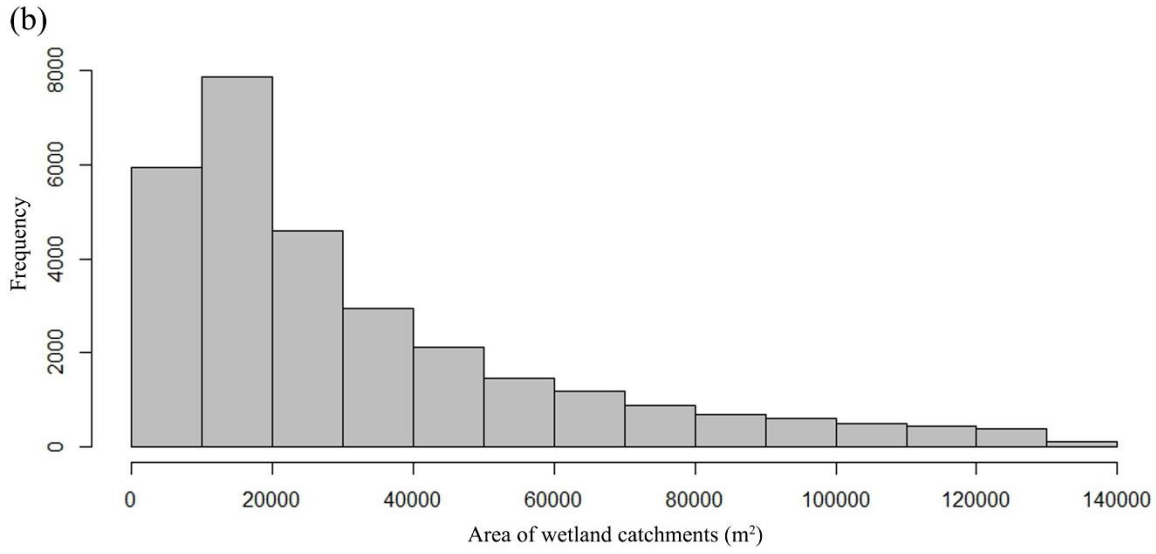


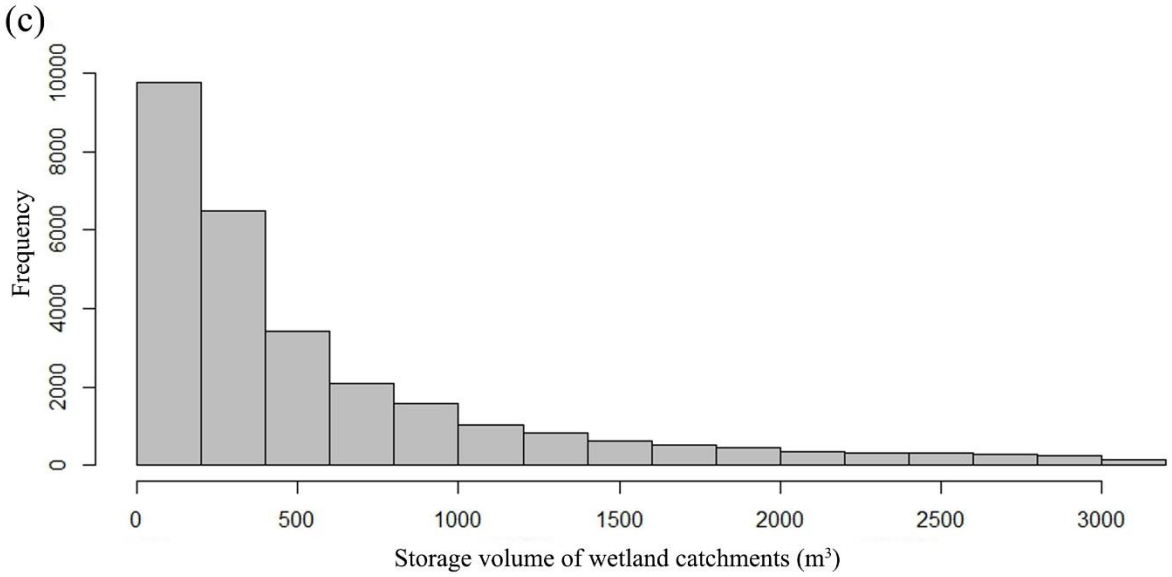
Figure 7. Comparison between inundation areas (derived from LiDAR intensity data) and NWI wetland polygons (image location: 99°9'53.9" W, 47°3'34.474" N). (a) Inundation areas and NWI wetlands overlaid on LiDAR intensity image; and (b) inundation areas and NWI wetlands overlaid on color infrared aerial photograph (2009).


(a)
Frequency
0
2000
6000
10000
2000
4000
6000
8000
10000
12000
14000
Area of wetland depressions (m²)

720


(b)
Frequency
0
2000
4000
6000
8000
0
20000
40000
60000
80000
100000
120000
140000
Area of wetland catchments (m²)

721


(c)
Frequency
0
2000
4000
6000
8000
10000
0
500
1000
1500
2000
2500
3000
Storage volume of wetland catchments (m³)

722

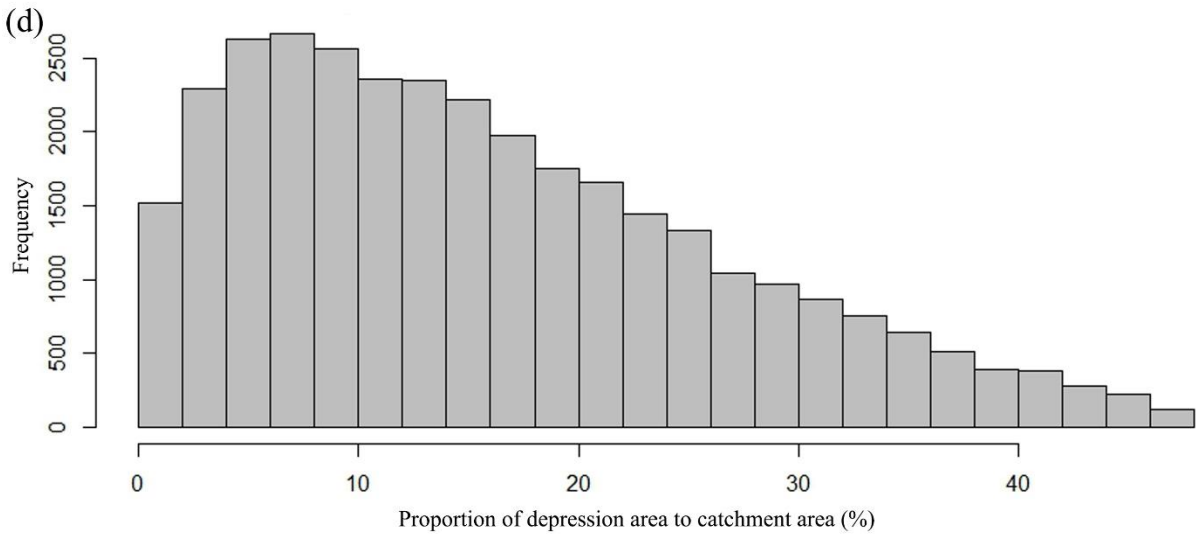


Figure 8. Histogram of wetland depressions and catchments. (a) Wetland depressions; (b) wetland catchments; (c) potential storage capacity; and (d) proportion of depression area to catchment area.

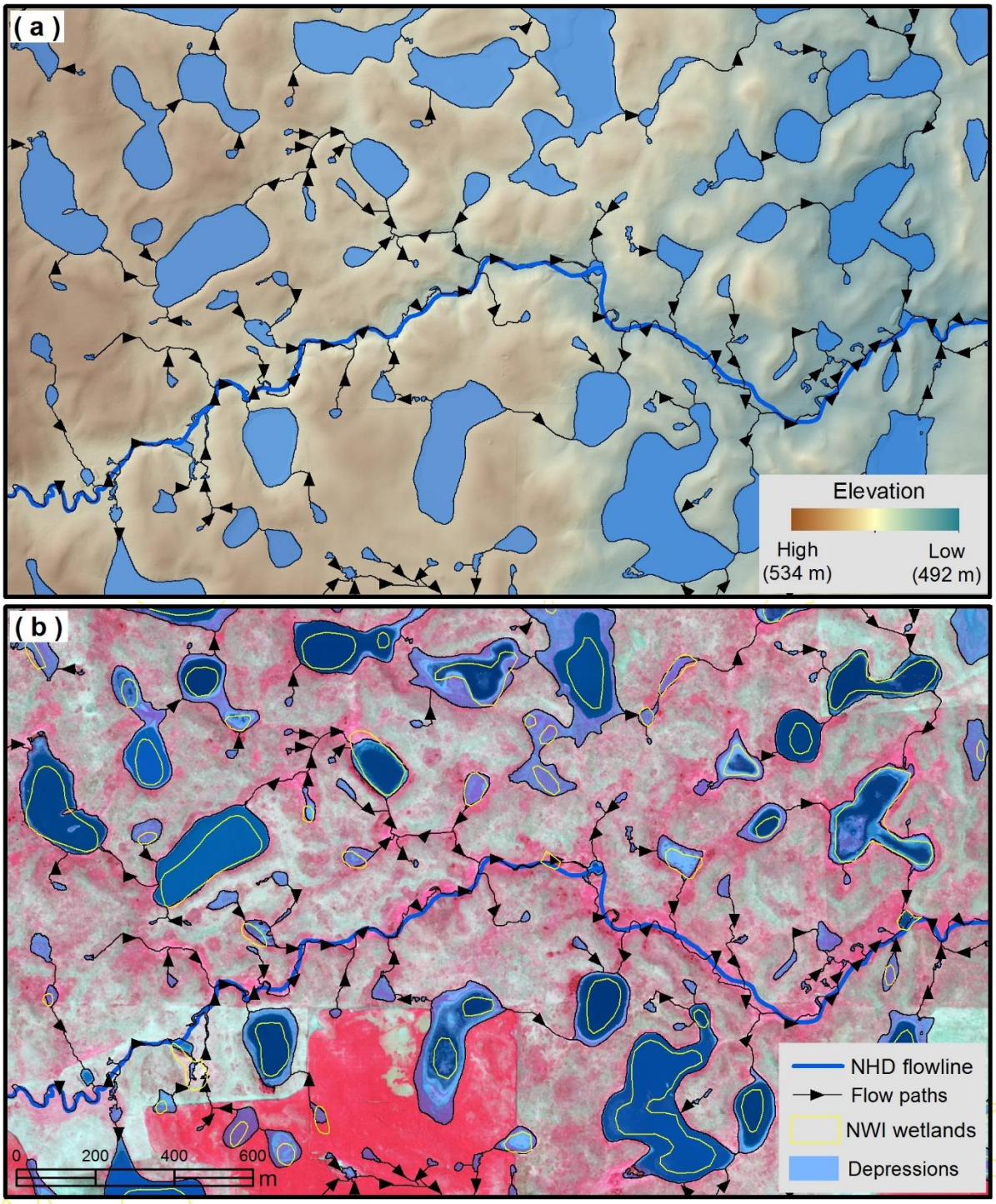


Figure 9. Examples of LiDAR-derived wetland depressions and flow paths in the Pipestem subbasin (image location: 98°59'48.82" W, 47°1'32.679" N). (a) Wetland depressions and flow paths overlaid on LiDAR shaded relief map; and (b) NWI polygons, wetland depressions and flow paths overlaid on color infrared aerial photograph (2012).

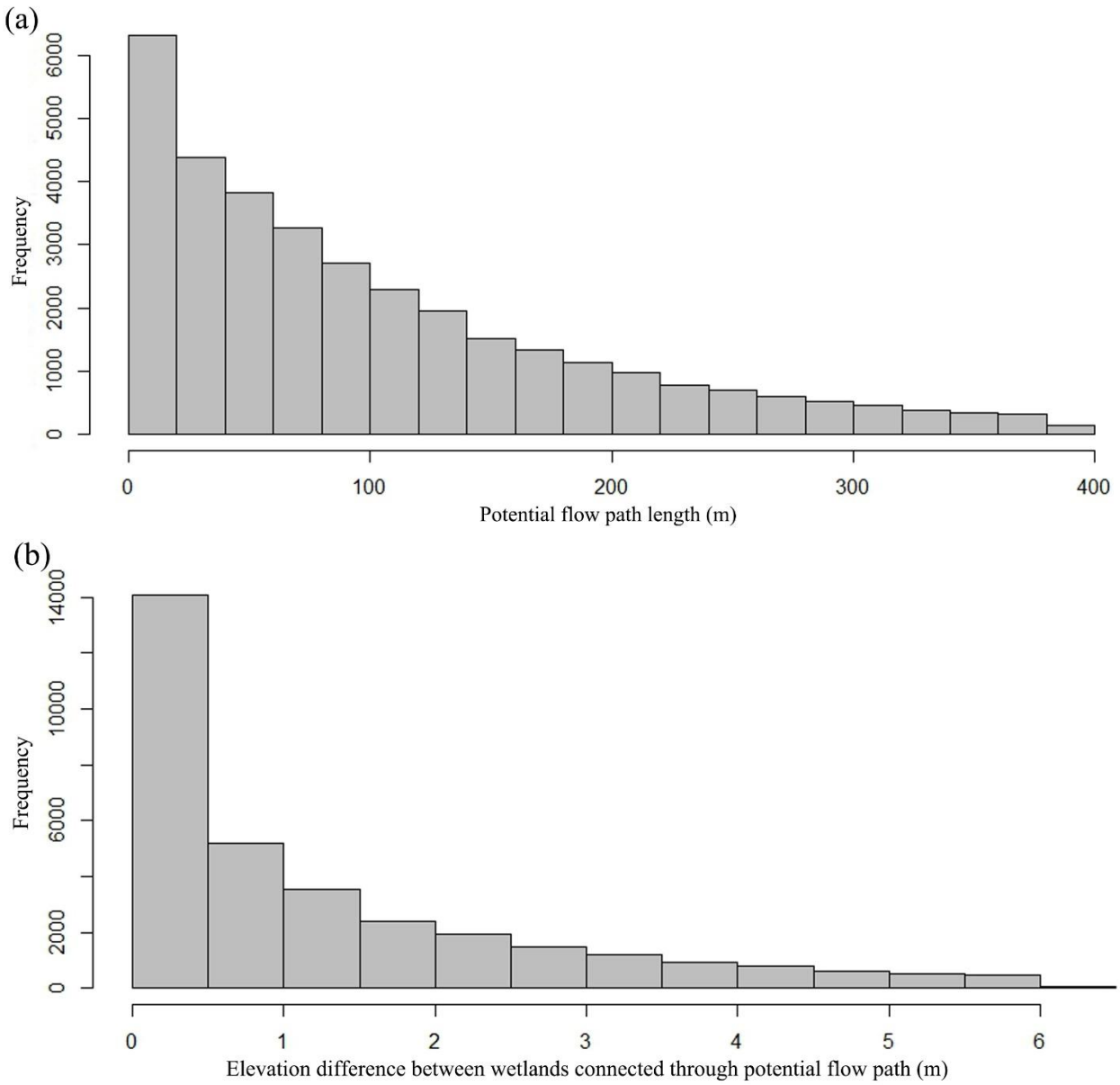


Figure 10. Histogram of potential wetland connectivity. (a) Potential ~~Connectivity~~ flow path lengths; and (b) elevation differences between ~~connected~~ wetlands connected through potential flow paths.