Characterization of prairie pothole inundation using AnnAGNPS under varying management and drainage scenarios

Nahkala, Brady A.[a], Kaleita, Amy L.[b†], and Soupir, Michelle L.[c]

[a]Graduate Student. 3332 Elings, 605 Bissell Rd. Ames, IA 50011-1098. Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA. email: bnahkala@iastate.edu

[b]Professor. 3352 Elings, 605 Bissell Rd. Ames, IA 50011-1098. Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA. email: kaleita@iastate.edu

[c]Professor. 3358 Elings, 605 Bissell Rd. Ames, IA 50011-1098. Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA, USA. email: msoupir@iastat.edu

†Corresponding author.

ABSTRACT

Farmed prairie potholes are small, isolated depressions frequently classified as semi-permanent wetlands that make up a significant portion of land area in the Des Moines Lobe (DML) of the larger Prairie Pothole Region (PPR). Historically, these depressions have been subjected to significant drainage to improve their agricultural capacity. However, many assessments of the economic return of continuing to farm these depressions suggest that continued attempts to produce conventional row crops is not profitable and has other ecological consequences beyond crop drownout. This study expands the existing discussion of land use and drainage alternatives in a watershed modeling context. This study utilized the Annualized Agricultural Non-Point Source (AnnAGNPS) model to individually simulate the long-term hydrology of 6 prairie potholes using a matrix of land use and drainage modifications. Results suggest the presence of artificial drainage is the dominant factor in prairie pothole hydrology, while retirement and no-till practices can provide moderate reductions in flood inundation. Conservation tillage induces minimal change on flood metrics. Results show that average annual maximum inundated surface area is reduced by at most 50% across all simulations and the median annual days flooded could be reduced by 25 days, though this is less consistent when isolating high-precipitation years. Regardless of drainage status, in all scenarios there are, on average, more than two inundations events per year lasting 2-4 days. Longer events occur approximately once per year on average. Area inundation frequency curves suggest up to a 20% reduction in maximum pothole area inundated annually can be achieved at the 2-year return frequency. The availability of this data helps characterize the hydrology of farmed potholes more generally over a wide range of conditions, providing a reference for the prioritization of potholes for conservation or alternative management.

Keywords: Prairie Potholes, AnnAGNPS, precision agriculture, targeted conservation, farmed wetlands

1 INTRODUCTION

Prairie potholes are surface depressions left behind after deglaciation in regions of the Midwest, Montana and three Canadian provinces, known as the Prairie Pothole Region (PPR). These hydrologically isolated depressions are small, shallow, semi-permanent waterbodies fed mostly by surface runoff. The Des Moines Lobe (DML) of the PPR extends from central Iowa through state's north-central region and into southern Minnesota. This region is of interest due to its intensive agriculture and significant historic modifications made to pothole hydrology. It has been estimated that surface and subsurface drainage activities have directly affected over 95% of potholes (Green et al., 2019). Despite these changes, frequent flood events continue to have an impact on crop survival (Upadhyay et al., 2018; Rhine et al., 2010; Zaidi et al., 2004). Furthermore, they are a nuisance for farmers, delaying fieldwork due to their wetness or necessitating driving around them to avoid getting stuck, and often cause economic losses because of this crop failure (Fey et al., 2016).

Management practices within potholes generally mirror those of the field, but programs and practices exist that improve either the environmental or economic outcomes of potholes and have gained some traction. The Conservation Reserve Program (CRP) is a US federal government program that provides economic incentive for agricultural landowners to remove marginal or sensitive land from production in long-term contracts (Gleason et al., 2011). More recently, the NRCS released the Prairie Pothole Water Quality and Wildlife program, which makes prairie potholes located in the DML up to 2 acres (0.80 ha) in size eligible for payments through the Environmental Quality Incentives Program (EQIP) if they are retired from production (USDA, 2020). Other practices to keep these areas in production include investing in more drainage or modifying tillage practices to improve soil quality and infiltration capacity in the field, thereby reducing direct runoff to potholes. Landowners frequently need to evaluate drainage upgrades or alternative management because the extensive drainage network is aging and potentially undersized or increasingly overwhelmed due to higher precipitation as a result of climate change (Castellano et al., 2019).

Pothole inundation causes significant agricultural management problems. Impacts include agricultural economics, water quality management, and natural resource conservation, to name a few. Investing in seed, fertilizer, or drainage infrastructure in potholes reduces profitability despite frequent yield reductions or total crop loss in that area (Fey et al., 2016). Pothole drainage results in high nitrate and potentially high phosphorus export from the field (Martin et al., 2019b, King et al., 2015). These wetlands, once drained, are removed from the historic wetland network that was once pervasive across north-central Iowa. This wetland network can provide high quality nesting sites and energy sources for migratory birds or other species if restored and maintained (Janke et al., 2019). These issues highlight the importance of monitoring and modeling pothole hydrology, water quality and crop failure. Comprehensive monitoring leads to robust model calibration, which can be used to create decision-making frameworks for farmers, public entities, and policymakers. Classification of the issues presented as “wicked problems” (Churchman, 1967) is becoming more widely recognized, for example the extreme hypoxia experienced in the Gulf of Mexico due to high nitrate loading from the Mississippi watershed (Patterson et al., 2013). Local-scale support is undoubtedly required to empower change through modeling and decision support tools.

Modeling prairie potholes has been of interest in recent years due to their ambiguous definition under the Clean Water Act 'Waters of the US' (Cohen et al., 2016; Golden et al., 2014). This includes understanding their surface water connectivity, or spill-and-fill dynamics that have been modeled in a modified Soil and Water Assessment Tool (SWAT) model (Evenson et al., 2016), and using a new and highly specific U.S. Geological Survey model, The Pothole Hydrology-Linked Systems Simulator (PHyLiSS) (McKenna et al., 2018). These studies attempt to show the connectivity of geographically isolated wetlands, such as potholes, and assess their impact on downstream waters.

Understanding individual pothole dynamics is as important as understanding watershed-scale dynanmics for enabling local decision making. Understanding hydrologic fluxes in prairie potholes at the field scale allows for specific and targeted input into how they are managed, something difficult to do when assessing watershed hydrology at scale. Individual potholes have been modeled using the USDA Annualized Agricultural Non-Point Source Pollution Model (AnnAGNPS) by modifying the cell and reach resolution and wetland parameters (Upadhyay et al., 2018). AnnAGNPS is well suited to very small watersheds such as those that drain to prairie potholes. Calibration of these models found moderate success in simulating flood depth, but updates to the source code provided stronger calibration to standing water volume in the pothole at a daily time step (Nahkala, 2020). Furthermore, Upadhyay et al. (2019) included an exploratory study of how simple changes in the AnnAGNPS model might affect flooding in farmed prairie pothole systems. This limited exploration included modeling two individual prairie potholes using three different land management scenarios, and did not consider different drainage strategies. Thus a more extensive study, including a larger number of potholes, and deeper exploration of land use and drainage intensities is needed.

The current study is adds to our understanding of pothole flood dynamics by: 1) introducing four more potholes to the assessment completed by Upadhyay et al. (2019), and by 2) modeling a range of natural to intensive drainage conditions, perennial and row crop land uses, and conventional and conservation-oriented tillage strategies that can be used in prairie pothole systems. This watershed modeling in AnnAGNPS includes all combinations of drainage, tillage, and land use variables described later that reflect real management alternatives for landowners. The goal of this study is thus to more broadly describe the influence of a multitude of land management practices on prairie pothole flooding via watershed modeling, by quantifying impacts of model inputs on the temporal and spatial extent of flooding.

2 METHODS

2.1 STUDY AREA

The prairie pothole study area sits on the border of two adjacent HUC-12 watersheds near Ames, IA, within the DML of the PPR. Five potholes reside in two adjacent fields, managed by Iowa State University (ISU) that straddle the Walnut Creek and Worrell Creek watersheds on the border of Story and Boone County (Figure 1). A sixth pothole resides approximately 6 km northwest on an ISU research farm. These potholes named Bunny, Walnut, Lettuce, Cardinal, Hen and Mouth have been previously modeled on an individual basis (Upadhyay et al., 2018; Upadhyay et al., 2019, Nahkala, 2020) and are the only potholes described in this study.

With the exception of Mouth, all modeled potholes were conventionally farmed during the 2016-2018 model calibration period, which included a corn and soybean rotation, conventional tillage, no irrigation, and standard fertilizer and pesticide application. The western portion of Mouth is registered in the Conservation Reserve Program while the eastern portion is also conventionally farmed.

The potholes have varying surface and subsurface drainage, which has been extensively described in previous studies at this location (Martin et al., 2019a). Bunny is the most intensely drained, with multiple surface inlets, while Hen and Mouth are assumed to have no surface or subsurface drainage. Lettuce has subsurface drainage, while Walnut and Cardinal have a surface inlet connected to subsurface drainage. Hourly water levels were recorded during the growing seasons of 2016-2018 using pressure transducers installed at the bottom of each pothole, and the methods are fully described by (Martin et al., 2019a).

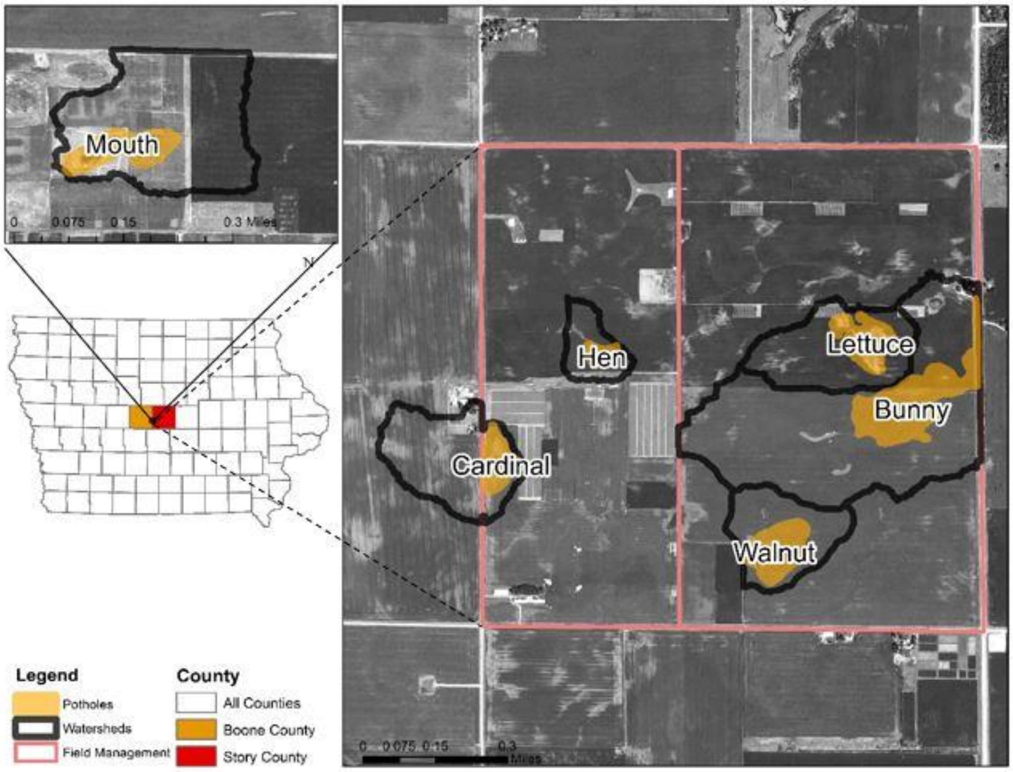

Figure 1. Study site for the 6 monitored and modeled prairie potholes in this study.

2.2 SCENARIOS

Individual models of the six potholes shown in Figure 1 were built using the AnnAGNPS model and were calibrated to daily water level and volume data (Nahkala, 2020). Then, we identified alternative management scenarios that might affect prairie pothole inundation: changes to the drainage intensity, switching to tillage practices that improve infiltration, modifying the planting schedule, and retiring the pothole or its entire microwatershed. These scenarios are realistic alternatives for common practices within the Des Moines Lobe, and did not consider emerging agricultural markets and pothole agricultural uses such as biofuel production in marginal areas (Feng et al., 2017). Model scenarios are listed in

Table 1, which lists modifications to runoff curve number (CN) for the hydrologic soil groups at these sites and to the modeled infiltration of the pothole. Other data files for field management and schedule were modified to call the correct management inputs within the model, but only management schedule directly references hydrologic parameters that differ between the scenarios we investigated.

Changes to the baseline calibrated models included: 1) modifying artificial drainage by changing infiltration to represent additional or removed infrastructure, 2) changing tillage practices by changing CN in the pothole or field to conservation- or no-till, 3) retiring the pothole to perennial vegetation or, in one scenario, retiring the whole watershed by replacing the cropping system with pasture, which includes modifying CN and management schedule, including crop seeding, within the model, and 4) modifying the planting schedule across all years simulated.

Table 1 displays a matrix of the most significant changes of interest (drainage, tillage, and land retirement) are presented in to represent all scenarios modeled for each pothole. The simulation identifiers for this study are listed in this table, which includes drainage status codes, field land use codes, and tillage practice codes. The planting schedule changes (four additional scenarios) are not included in this table but are discussed separately later. For those scenarios, planting schedule was modified while maintaining the existing conditions for each pothole. These scenarios adjusted all planting operations by 2-week increments representing a range of -2 weeks to +6 weeks from normal operation. Changes in planting schedule represent one component of uncertainty within the existing model, as planting date can change significantly year to year based on soil temperature and wetness (Zipper, 2016).

Table 1. Descriptions of drainage, land use, and tillage parameters and simulation ID codes modeled in AnnAGNPS. A scenario coded D1-CS-NT, for example, would therefore be corn/soybean rotation in no-till, where the pothole as subsurface drainage but no surface inlets.

Scenario Code – Drainage	**Condition**
D0-XX-XX	Natural drainage – no subsurface drainage added
D1-XX-XX	Low drainage – subsurface drainage at typical intensity
D2-XX-XX	Medium drainage – D1 subsurface drainage plus a surface inlet
D3-XX-XX	High drainage – D1 subsurface drainage plus multiple surface inlets
Scenario Code – Pothole Land Use	**Condition**
XX-**CS**-XX	Corn/soybean rotation
XX-**R**-XX	Retired – perennial grasses
Scenario Code – Watershed Land Use and TIllage	**Condition**
XX-XX-**CV**	Corn/soybean rotation, conventional tillage
XX-XX-**CT**	Corn/soybean rotation, conservation tillage
XX-XX-**NT**	Corn/soybean rotation, no-till
XX-R-**R**	Entire watershed retired to perennial grasses; no tillage (this only pairs with retired pothole land use, for XX-R-R; no scenarios where the pothole was in crop rotation while the rest of the watershed was retired were evaluated)

2.3 DATA AND MODEL CONSTRUCTION

AnnAGNPS utilizes topographic, climatic, soil, and land use data for watershed simulations and calculates outputs at a daily time step. Topographic data includes a DEM that is converted to spatially aggregated cells, or subwatersheds. Dominant soil class is assigned to each cell, which influences infiltration rates. Land use data includes land cover or cropping information, included management schedules, vegetative cover, curve number, and other land use parameters. A wetland data section includes data on where wetlands are placed on the reach network within a watershed. This data includes surface area, infiltration, and overflow parameters, to calculate a water balance within the wetland.

2.3.1 Model Setup and Calibration

A 1-meter DEM was used for the delineation of subwatershed cell and reach networks, the basic units used by AnnAGNPS to determine runoff and routing. The data, parameters, and process used for physical model setup is previously described in Upadhyay et al. (2019) and Nahkala (2020). Briefly, the modeled pothole wetlands were placed at the end of the cell and reach network for the respective microwatershed.

Pressure transducers installed at the lowest elevation of each pothole measured hourly water level during the growing season (approx. May – September) in 2016, 2017 and 2018. These data were aggregated to a daily time step to match the AnnAGNPS model time step, and the model was driven using the weather data described below. An iterative method using Python was performed to calibrate agricultural curve numbers and infiltration within the pothole, matching the simulated daily ponded water volume to the observed values using multiple statistical metrics. Details for this method can be found in Nahkala (2020). These values were then used as the baseline model, and changes to model inputs described below allowed for the simulation of additional

2.3.2 Land Use Data and Representation

These calibrated values of SCS CN and wetland (pothole) infiltration were then the baseline for modifications to simulate scenarios beyond the actual field conditions. From monitoring the water balance of these potholes, approximately 33% and 50% of infiltrated outflow was accounted for by surface inlets in Bunny and Walnut respectively (Martin et al., 2019a), which were used to inflate the infiltration rate in the pothole for medium (D2) and high (D3) drainage. A value of 10% was chosen where only low drainage (D1) was present. Where no drainage was present, the maximum drainage from D soils (24 mm d^{-1}) was used from Huffman et al., (2013). Where this value was higher than the calibrated value of infiltration for current conditions, the appropriate drainage outflow contribution ratio (10%, 33%, or 50%) was used to estimate a natural drainage condition. This was necessary for the Walnut model, where values of 14, 16, and 22 mm d^{-1} where used to represent D0, D1, and D2. These values are within the natural infiltration range for monitored potholes in Iowa (Schilling et al., 2019; Roth and Capel, 2012).

Table 2 shows the typical values for each CN parameter and any modifications made during calibration. Calibrated models used modified curve numbers for conventional tillage, where CN was adjusted upwards compared to NRCS standard published values for Bunny, Walnut, Lettuce and Cardinal. CN was calibrated downwards from standard values for Hen and Mouth. Conservation tillage was represented by row crop – straight row (RC-SR), in good conditions and no modifications were made to the standard values. Additionally, the RC-SR no till value was used without modifications (NRCS, 2008). These CN values are closely correlated with surface residue irrespective of specific tillage practice, but are not specific *in situ* measurements within these poorly drained areas (Elhakeem and Papanicolaou, 2009). Retirement to perennial plantings was represented by pasture in good conditions with no modifications to the standard values.

Table 2. Modifications to SCS CN based on changes in tillage and land use in prairie pothole hydrologic simulations. CN-B and CN-C represent calibrated curve number for HSG B and HSG C soils, respectively. B, W, L, C, H, and M refer to the potholes Bunny, Walnut, Lettuce, Cardinal, Hen, and Mouth, respectively.

	Code	**CN Description**	**CN-B**	**CN-C**	**Modifications**
Tillage					
Conventional	CS-CV	Row Crop, SR, Poor Condition	81	88	+2 (B, W, L, C), -2 (H, M)
Conservation	CS-CT	Row Crop, SR, Good Condition	75	82	NA
No-Till	CS-NT	Row Crop, SR, No Till	69	75	NA
Land Use					
Retired	R	Pasture, Good Condition	58	71	NA

2.3.3 Climate

The Parameter-Elevation Regressions on Independent Slopes Model (PRISM) and the Sustaining the Earth’s Watersheds, Agricultural Research Data System (STEWARDS) were combined to create a climate dataset for this study. Daily precipitation was sourced from PRISM, which include statistically generated precipitation depths with high spatial resolution, based on local weather stations. Other climate parameters, including wind velocity, wind direction, maximum and minimum temperature, dew-point temperature, and solar radiation, were sourced from STEWARDS from a weather station within 6 km from the managed field plots. The years 1992-2018 were used, with the first two years accounting for a model warmup period. The long-term simulation is necessary to generate appropriate confidence in the range of annual and seasonal precipitation expected when assessing flood events in the potholes.

2.4 ASSESSMENT METHODS

We treated the modifications to planting date as a simple way to measure sensitivity of the curve number to planting date. These were analyzed separately from the main output evaluation but were used for context when considering the uncertainty of the model. The rest of the following analyses were conducted considering the drainage, tillage, and land use matrix described in Table 1.

We assessed the maximum surface area flooded during each month in the simulation, and calculated as an average of all years in the simulation. The volumetric time series output from the model was converted to surface area via two regressions. Prior studies had determined depth-volume-area relationships using a quadratic relationship between depth and volume and depth and area (Martin et al., 2019a). For depths less than 0.1 meter, a linear model was used. These models were fit resulting in an R^2 of greater than 0.99 for all potholes. For the analysis in this study, a conditional solving algorithm was used to solve the quadratic for water depth. The depth time series was then converted to area using the second quadratic relationship. We then calculated the maximum inundation area in each month of the simulation and averaged these values by month for all years in the simulation.

We assessed the number of flood days in the growing season. AnnAGNPS is a daily time-step model and thus this was denoted by the presence or absence of water at the end of a simulated day. This assessment was summarized on a monthly basis to understand how flood dynamics of consequences in the agricultural operational system.

We counted the number of consecutive days of inundation. Each series of consecutive days was considered a flood event. The length of flood events is directly related to the biophysical risk a crop experiences during the growing season. Scenarios were compared based on the frequency and total number of events that lasted long enough to threaten crops. General risk began at events longer than 2 days, especially during the first half of the growing season, while extreme risk was considered to be events of 4 days or longer at any point during the growing season (DeBoer and Ritter, 1970; Mukhtar et al., 1990; Rhine et al., 2010).

Analogous to flow-duration curves for streams, area-inundation frequency curves were generated for each scenario and pothole. These graphs could be replicated for pothole depths or volume, however, key operational parameters in flood risk assessments and risk management for farmers are typically communcated on an aerial basis, as seen through 100-year floodplain mapping through FEMA programs or the acre-by-acre yield and soil mapping utilized in precision agriculture. A frequency curve was created describing the frequency (percent of simulated years) with which incremental extents of the pothole surface area were flooded, as a percentage of total pothole surface area. The percent of years that a pothole flooded to incremental pothole extents as a percentage of the maximum area was calculated at increments of 10% of the total surface area. Individual scenarios were compared, while further comparison was done between constant drainage or land use characteristics. The loess smoothing method was used to aggregate the curves based on drainage and land use conditions for a general comparison.

3 RESULTS

The results of changes in planting date reflect a general sensitivity of the model to land management activities. These dates can be highly variable year to year, as most keenly observed during wet years such as 2018 and 2019, when many farmers were prevented from planting millions of acres for extended periods of time due to wet conditions.

These simulations span an 8-week planting window from mid-April until mid-June, suggesting that in the early stages of crop growth, ponding will go largely unaffected simply based on planting schedule. Median differences in ponding when ponding was present (volume not equal to zero) were 12, -28, -47 and -84 cubic meters across all potholes for 2 weeks early, 2 weeks late, 4 weeks late, and 6 weeks late respectively. Daily median pothole volumes changed by less than 3% across all potholes due to planting date modifications. This shows that the explicit change in hydrology due to management activities with implications for parameters such as SCS CN are minimally affected by realistic temporal changes in scheduling.

3.1 MAXIMUM SURFACE AREA

The flood extents on an aerial basis are of interest when assessing potential damage to row crops, the typical land cover in prairie potholes. Assessing potential maximum land extents where yield is reduced or eliminated helps understand the economic return based on agronomic inputs and outputs. The averages of monthly maximum inundated areas are reported by pothole and simulation scenario in Figure 2, shown as a fraction of each pothole's maximum surface area. Each bar represents the 25-year average of the maximum monthly surface area flooded.

These data are reported for each scenario and pothole combination, representing the full spectrum of drainage, tillage, and land use characteristics. Data are grouped by drainage in each subpanel (A-D). The greatest reductions in inundated area, whether in scenarios with changed drainage, tillage or retirement, occurred outside of the growing season. This is possibly observed because improved infiltration from better management or drainage installation has a potential to handle the more frequent, smaller storms that occur outside of the April-June time period, a period of more intense rainfall.

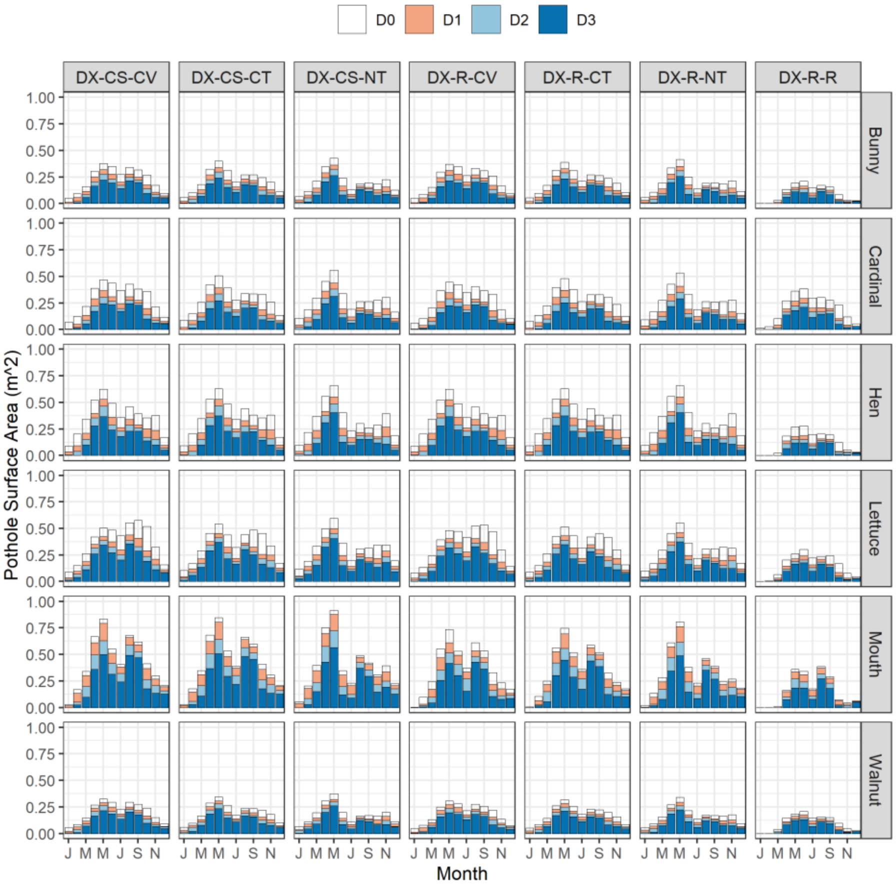

Figure 2. Simulation averages of monthly maximum surface area inundation, split by individual potholes, reported as a fraction of each pothole's maximum surface area before spill. D stands for drainage, and DX represents variable drainage status, which is constant by color in each graph. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets. CS is corn-soybean, while R is perennial grass (retired). CV is conventional tillage, CT is conservation tillage, and NT is no-till.

3.1.1 Effects of Drainage

An assessment of the maximum area inundated based on drainage condition is presented in Table 3. This table does not include DX-R-R scenarios in the averages. If D0 is considered the baseline, the presence of subsurface drainage (D1) produces an average monthly decrease in maximum surface area by 35%. For drainage statuses D2 and D3, this value is 49% and 61% respectively, representing incremental percent differences of 40% and 24% between each drainage level. This data suggests installing more drainage via surface inlets has diminishing returns, despite significant increases in the volumetric drainage capacity provided by those inlets (infiltration values were inflated by 10%, 33% and 50% for D1, D2, and D3). Growing season (April – September) reductions were smaller than off-season reductions. Average reductions from the 27 to 54% surface area flooded (Table 3) for the growing season only were 25%, 36%, and 48% for D1, D2 and D3. Within the growing season, drainage helped reduce the monthly maximum most in June and July. Ranges of reduction within the growing season from the baseline for D1, D2 and D3 levels by pothole varied from 15-32%, 30 – 42% and 40 – 53% respectively.

Table 3. Average fraction of maximum pothole surface area flooded by month and drainage status. Growing season months (April – September) are shaded as the key time period of interest. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets.

	Average Fraction of the Maximum Pothole Area Flooded			
Month	**D0**	**D2**	**D2**	**D3**
1	0.07	0.02	0.01	<0.01
2	0.14	0.08	0.04	0.02
3	0.25	0.16	0.11	0.08
4	0.44	0.33	0.28	0.22
5	0.54	0.42	0.37	0.30
6	0.38	0.28	0.23	0.18
7	0.27	0.19	0.16	0.12

8	0.37	0.29	0.26	0.23
9	0.35	0.26	0.23	0.20
10	0.31	0.18	0.14	0.10
11	0.27	0.16	0.12	0.08
12	0.15	0.10	0.08	0.07

3.1.2 Effects of Management Activities

The effects of conservation tillage were minimal during the growing season. The average monthly reduction in maximum inundated area during the growing season was 4% and 17% for conservation tillage and no till, respectively, from an average of 27% of the maximum pothole area. Tillage practices had a bigger impact later in the growing season; greater than 10% reduction in maximum surface area was observed for the months of July through December, from a baseline 20% of the maximum area. Retirement of the entire watershed from conventional operations produces a 56% reduction (all months, baseline 30% of maximum area) in maximum monthly surface area when there is no additional drainage present. However, when drainage remains in place and the watershed is retired from conventional management, retirement only provides an average 10% reduction in maximum surface area (baseline equals 20% of maximum area). This is also consistent with growing season reductions of 10% when retiring just the pothole, considering changes from all drainage and tillage levels. The presence of perennials in retirement had a larger effect in the early and late growing season, with maximum flood extents reduced by 10-27%. This was not the case during June and July. This may stem from similar water use requirements between cropped and retired systems during the maturation stage of crop growth. The presence of perennials earlier and later in the season have a more pronounced difference, both in terms of surface roughness and water use, compared to bare soil.

3.2 FLOOD DAYS

The number of days a pothole is flooded is of interest when considering their impact on management, scheduling, and crop survival. Flooding impacts when managers can till, spray, plant or harvest, and extended periods of flooding kills crops. Additionally, understanding the permanence of standing water in a pothole helps provide their legal classification for farmability and conservation. The range of total annual days of inundation are displayed as boxplots in Figure 3, representing the range of values across variable annual precipitation and individual pothole differences. Each boxplot in the top panel represents 6 samples (potholes) with 25 years of simulation. Boxplots are grouped by increasing drainage from left to right (D0 through D3).

More informative is the distribution of annual days flooded in relation to total annual precipitation. Panel B of Figure 3 splits the data from panel A based on ranked total annual precipitation, representing 9, 8, and 8 years of data respectively. The highest precipitation years include 1998, 2007, 2008, 2009, 2010, 2014, 2015, 2016, and 2018. This shows that 6 of the last 10 years in the simulation had abnormally high annual precipitation, in agreement with observed and expected climate trends for the region. Splitting the data as such, high precipitation years induce a significant change in the median number of days per year of inundation. The medians are averaged by drainage status within each simulation in

Table 4. For increasing drainage, the median increases from 24.7 to 67.9 days, 10.2 to 33.1 days, 6.3 to 22.7 days, and 3.7 to 15 days per year when comparing between medium and high precipitation years. In years where rainfall is high, 15 days of inundation could be expected based on the median, even with subsurface drainage and inlets installed (D3). These are the conditions to be expected within the Des Moines Lobe, with much of the rainfall occurring during early growing season months.

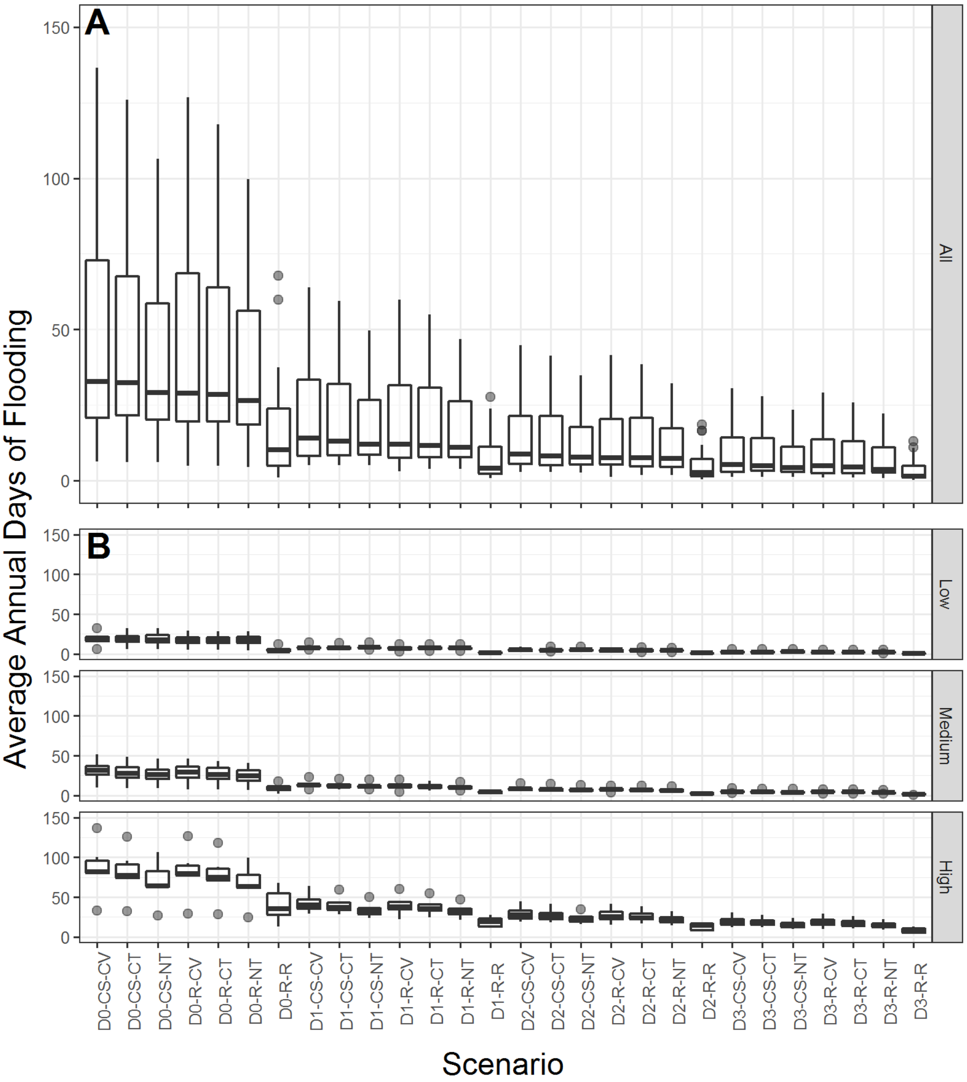

Figure 3. Distribution of annual days flooded across 25 years of simulation for 6 modeled potholes. Panel A shows data aggregated by simulation for all potholes and years, while Panel B splits the data in thirds by ranked annual precipitation. D stands for drainage, and DX represents variable drainage status, which is constant by color in each graph. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage

with multiple inlets. CS is corn-soybean, while R is perennial grass (retired). CV is conventional tillage, CT is conservation tillage, and NT is no-till.

Table 4. Median annual days of inundation per simulation averaged by drainage condition and precipitation rank. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets.

Drainage	Low Precipitation	Medium Precipitation	High Precipitation
D0	15.7	24.7	67.9
D1	6.7	10.2	33.1
D2	4.2	6.3	22.7
D3	2.1	3.7	15.0
ALL	**7.2**	**11.2**	**34.7**

The number of days that potholes are inundated has implications for both crop survival and farming operations. Based on simulations, the most effective practice while maintaining cropping system is to install drainage, but connecting multiple surface inlets to drain tile may not provide significant benefit over a single inlet. The benefits of additional drainage can potentially be limited by downstream capacity despite the increased drainage potential from surface inlets, as many systems are undersized (Castellano et al., 2019). However, increasing drainage leads to increased nutrient export and increased streamflow, among other effects (Schottler et al., 2014; Amado et al., 2017).

3.2.1 Effects of Drainage

The largest differences occur based on the presence or absence of any artificial drainage, which is enumerated in Table 5. These data represent summaries of the annual averages per simulation, not the raw data, which includes every year individually. Both the medians and ranges of the data are large when no drainage is present, expressing both a wide variability of natural drainage, and highlighting the impact of extreme weather on unaltered systems, discussed in more detail previously. The average maximum and minimum annual days of flooding across all potholes and undrained scenarios (D0), without including the D0-R-R scenario, ranges from

5.4 to 118.9 days with an IQR of 20.0 – 64.4 days. Retirement of the entire watershed reduces the range and IQR to 1 to 37.4 days and 4.8 – 23.7 days, respectively (D0-R-R). With any drainage, the minimum number of days is not significantly reduced, while the average of maximum values is reduced from 118.9 to 55.7, 38.8 and 26.5 average annual days for low, medium and high drainage conditions respectively.

Table 5. Five-number summaries for annual days of inundation in all potholes, aggregated from Figure 3. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets.

	D0		D1		D2		D3	
	Not All Retired	All Retired	Not All Retired	All Retired	Not All Retired	All Retired	Not All Retired	All Retired
Minimum	5.4	1.0	4.3	0.8	2.2	0.4	1.0	0.3
Q1	20.0	4.8	7.9	2.2	5.0	1.3	2.6	0.9
Median	29.6	10.1	12.2	4.1	7.8	2.5	4.5	1.4
Q3	64.6	23.7	30.0	11.2	19.7	7.2	12.8	4.9
Maximum	118.9	37.4	55.7	23.8	38.8	11.8	26.5	10.7

* Values were averaged from individual scenarios based on drainage status. The “All Retired” scenarios represent the DX-R-R scenarios while all other scenarios are averaged.

3.2.2 Effects of Management Activities

The influence of tillage is less pronounced, shown in Table 6. Conservation and no-till management do not significantly affect the lower range of flood days, but slightly increased the averages in the simulations. However, tillage helped reduce the upper 50% of the data. The median days flooded decreased from 14.2 days under conventional management to 13.8 and 12.6 days under conservation and no-till respectively. Similarly, maximum values decreased from 66.6 days to 61.4 and 51.9 days for conservation and no-till management. Full retirement was shown to significantly reduce flooding.

The effect of retiring only the pothole is minimal when considering the annual days flooded, shown in Table 6. The median annual flood days were reduced by 0.4 days and 1.6 days for conservation and no-till respectively, while full watershed retirement induced the largest change, decreasing the median from 14.2 to 4.5 days. Retiring only the pothole (B, column 2) from conventional management reduced the median from 14.3 to 12.8 days.

Considering these changes in the context of biophysical risk to crops, it is unlikely that a reduction of less than 2 days annually would significantly increase the chance of crop survival throughout the growing season. We see that full watershed retirement has a significant reduction;this result is less concerning for farmers but may help conservationists with restoration monitoring and management.

Table 6. Five-number summaries for average annual days of inundation in all potholes, aggregated from Figure 3. Values were averaged from individual scenarios based on tillage status and pothole land use. CV is conventional tillage, CT is conservation tillage, and NT is no-till. CS is corn-soybeans, while R is retired to perennial grass.

	Tillage				Pothole Land Use	
Statistic	CV	CT	NT	R	CS	R
Minimum	3.2	3.3	3.2	0.6	3.8	2.7
Q1	8.9	9.0	8.7	2.3	9.3	8.5
Median	14.2	13.8	12.6	4.5	14.3	12.8
Q3	34.4	32.9	28.0	11.7	32.5	31.0
Maximum	66.6	61.4	51.9	20.9	62.0	57.9

3.3 FLOOD EVENTS

The frequency of long flood events is of interest due to the direct impact on crop survival. Average total number of inundation events for each simulation (average of 6 pothole simulations for each scenario) was 238 events, 185 events, 146 events, and 107 events for simulations with the D0, D1, D2, and D3 levels respectively, excluding the DX-R-R (whole watershed retired) scenario. Figure 4 reports these values by scenario and bins the length of events into 1-day events, 2- to 4- day events, 5- to 9-day events, and events greater than 10 days in length. For scenarios with the whole watershed retired, the number of events in the simulation are 119, 83, 64, and 47 events for the D0, D1, D2, and D3 levels.

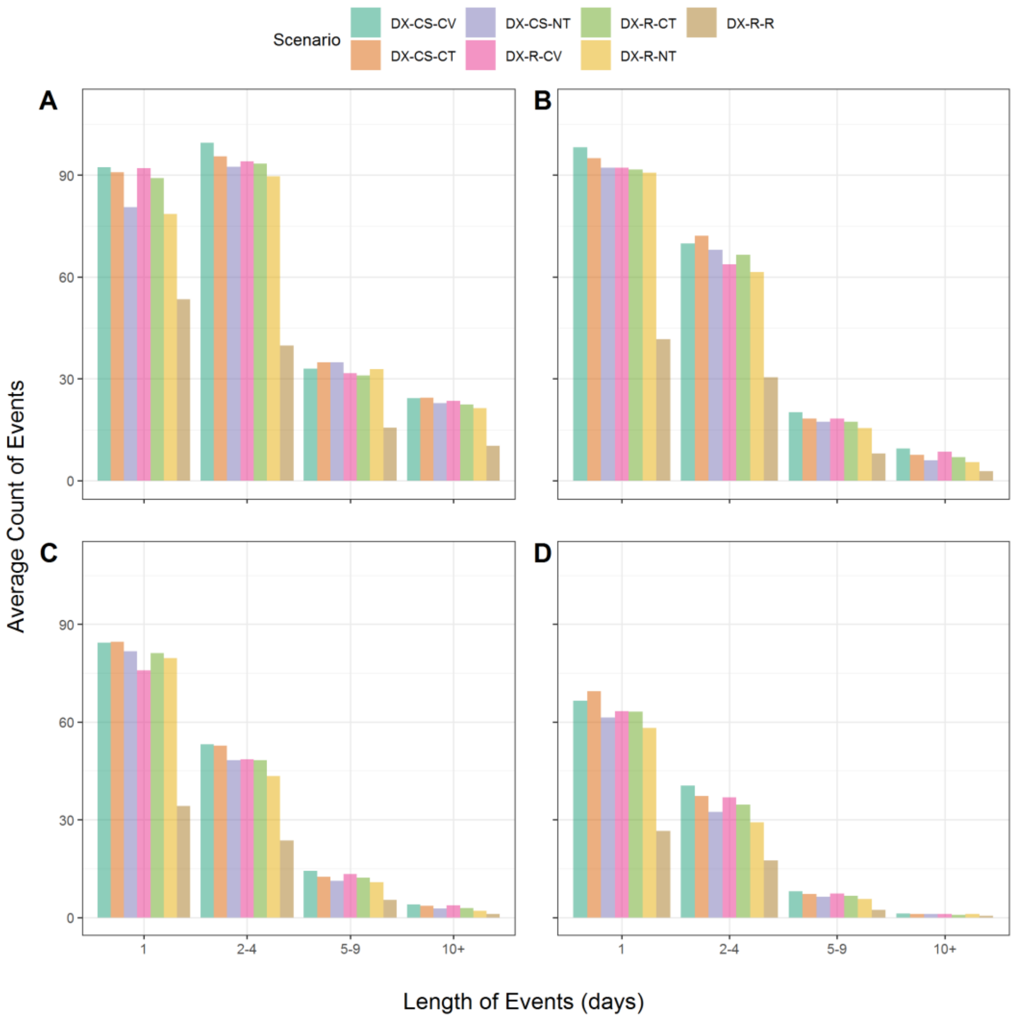

Figure 4. Average count of event lengths for all 25 years of simulation (averaged across 6 potholes). Counts are divided into 1-day events, 2- to 4-day events, 5- to 9-day events and 10+ day events. In the legend, DX represents variable drainage status, where drainage conditions is held constant for each graph panel. Panels are A) no drainage (D0), B) subsurface drainage (D1), C) subsurface drainage plus a surface inlet (D2), and D) subsurface drainage with multiple inlets (D3). CS is corn-soybean, while R is perennial grass (retired). CV is conventional tillage, CT is conservation tillage, and NT is no-till.

In general, the addition of drainage decreases the number of flood events for all bins within Figure 4. However, in panel B, the number of 1-day events increased from panel A for 6 of the scenarios. This is likely due to the shortening of flood events due to increased drainage, though the increased drainage does not eliminate the inundation events.

3.3.1 Effects of Drainage

The effects of drainage are presented on an annual basis in Table 7. The presence of subsurface drainage (as represented in the model) increases the average number of 1-day events compared to no drainage but decreases all other average event lengths. The presence of an inlet reduces the average number of events for all durations.

Regardless of drainage condition, simulations had an average of 3 1-day events, 2.26 2- to 4-day events, 0.65 5- to 9-day events, and 0.32 10+ day events per year. Installation of subsurface drainage would be expected to halve the number of 5- to 9-day events and reduce the number of long (10+ day) events by over 67%.

Table 7. Average number of events per year aggregated by drainage level, with total number of events listed in the bottom row and the average number of events per event-length bin reported. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets.

	D0	D1	D2	D3	Average
1	3.30	3.44	2.98	2.33	3.01
2-4	3.45	2.47	1.82	1.30	2.26
5-9	1.22	0.66	0.46	0.25	0.65
10+	0.85	0.27	0.11	0.04	0.32
Total	8.82	6.83	5.36	3.92	

3.3.2 Effects of Management Activities

The effects of tillage and pothole retirement are presented on an annual basis in

Table 8. Conservation tillage on average has no measurable effect on the annual count of events other than for events of 10+ days. However, no till on average can produce some measurable reduction in the number of flood events, which was similarly shown in section 4.2.2 by the incremental reduction in median annual days flooded (Table 5). Retirement of the watershed and pothole returns pronounced effect on the number of events in each bin with a greater than 50% reduction. Retirement of the pothole only results in minimal reduction of the mean number of flood events, with changes noticeable only on the 2- to 10-year time horizons.

Table 8. Average number of events per year aggregated by tillage status and pothole land use. CV is conventional tillage, CT is conservation tillage, and NT is no-till. CS is corn-soybeans, while R is retired to perennial grass.

	Tillage				Pothole Land Use	
Days	CV	CT	NT	R	CS	R
1	3.3	3.3	3.1	1.6	3.3	2.8
2-4	2.5	2.5	2.3	1.1	2.5	2.1
5-9	0.7	0.7	0.7	0.3	0.7	0.6
10+	0.4	0.3	0.3	0.1	0.4	0.3

3.4 AREA-INUNDATION FREQUENCY CURVES

How frequently a pothole fills or significantly floods enables landowners to assess the viability of farming a pothole using a long-term outlook. This most clearly depicts the extents of risk to crop that a landowner might face annually, allowing them to weigh options in an informed manner. Figure 5 depicts the fraction of the years in the 25-year simulation where the aerial flood extent reaches at least a certain fraction of the maximum pothole area, where the maximum pothole area occurs at its overflow elevation. The bottom right corner of each graph represents that no flooding occurs at least 100% of the years, while the top left corner represents that 100% of the pothole floods only a fraction of the years, or in some scenarios, never.

From this data, we see that 100% of Bunny floods in 4-20% of years based on all alternative scenarios. For Walnut, Lettuce, Cardinal, Hen and Mouth, the percent of years where the pothole was 100% flooded are 4-8%, 16-40%, 4-24%, 8-36% and 44-84% of years respectively, depending on the scenario. While these values represent a range of real and simulated conditions, they show the respective character of each pothole, and have implications for efficient management. For example, Mouth floods completely a high percentage of the years, reflecting that it may be a good target for conservation. The fact that Mouth is the only pothole studies to exist in a retired state supports that argument.

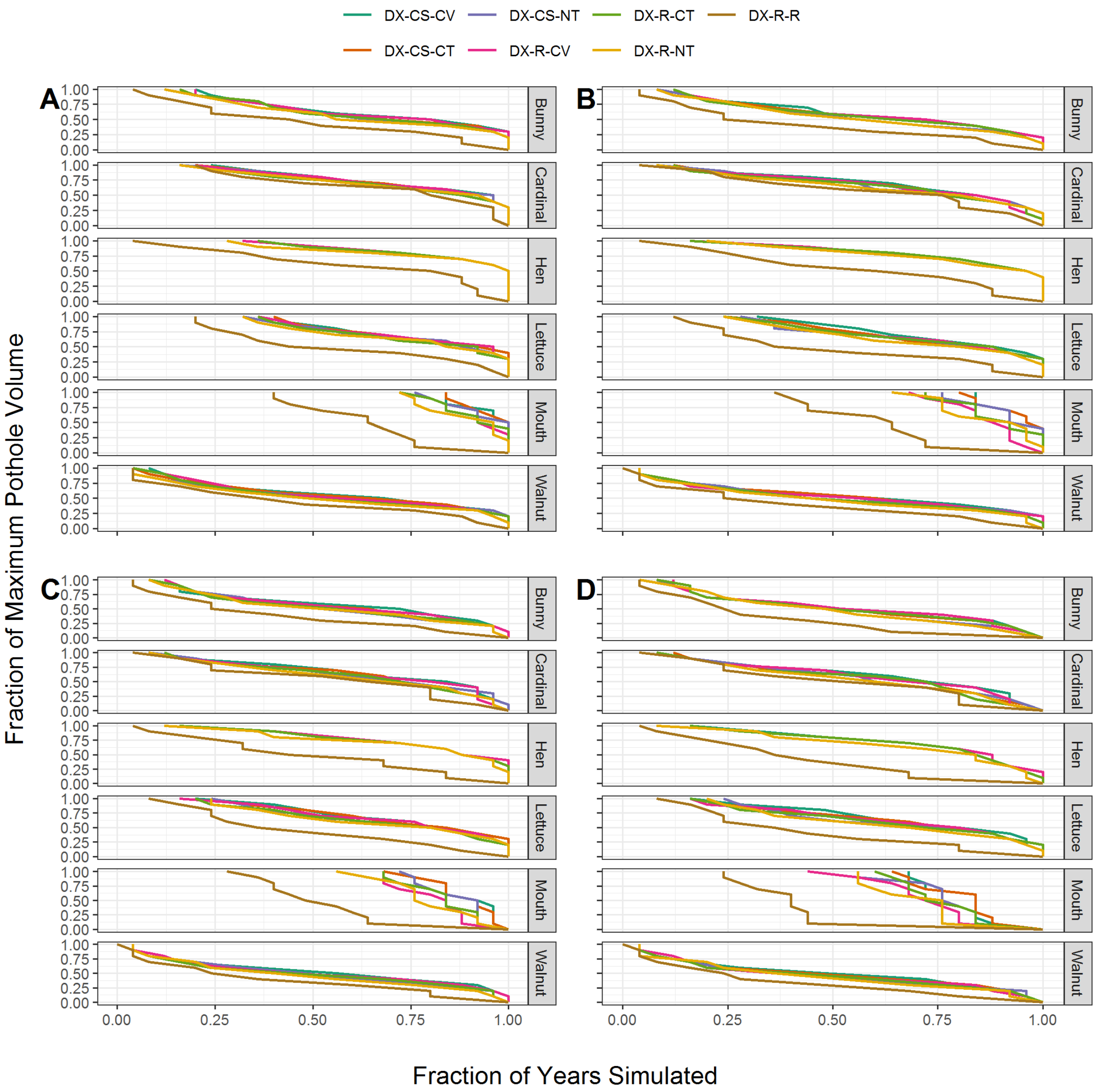

Figure 5. Area inundation frequency curves for simulated scenarios. In the legend, DX represents variable drainage status, where drainage condition is held constant for each graph panel. Panels are, A) no drainage (D0), B) subsurface drainage (D1), C) subsurface drainage plus a surface inlet (D2), and D) subsurface drainage with multiple inlets (D3). CV is conventional tillage, CT is conservation tillage, and NT is no-till. CS is corn-soybeans, while R is retired to perennial grass.

Similar trends are observable at smaller pothole extents. We see that 50% of the pothole area is inundated at least once 48-80%, 36-68%, 68-96%, 60-96%, 84-100%, and 72-100% of years for Bunny, Walnut, Lettuce, Cardinal, Hen and Mouth respectively. The low end of this data reflects the number of years in which it is nearly guaranteed to experience crop loss due to drowning in 50% of the crop area. Thus potholes with smaller flood extents that occur infrequently, such as Bunny and Walnut, may be good targets for drainage, as crops could be viable in at least 50% of the pothole greater than 50% of the time. Conversely, other potholes that experience 50% aerial inundation a minimum of 1 in 3 or every other year (33-50%) may be more suited for retirement or alternative management when considering profitability.

3.4.1 Effects of Drainage

Figure 6A shows the smoothing of all scenarios based on drainage condition, excluding instances where the whole watershed was retired and excluded Mouth simulations. Smoothing was completed using defaults of the ‘loess’ method within the ‘*geom_smooth*’ function in the ‘ggplot2’ package in R. The frequency of flooding for Mouth behaves significantly different compared to most other watersheds. Mouth floods to a greater spatial extent in a high percentage of the simulated years compared to other modeled potholes. This may be due to its low overflow depth, which correlates to its small storage volume, coupled with the largest watershed area to pothole area ratio observed in the dataset. This might suggest that separate curves are necessary for smaller potholes in watersheds with a larger yield.

The effects of drainage on the frequency and extent of inundation are less pronounced for extreme events, at the top left of the Figure 6A and 6B. While the smoothing and confidence bands do not represent the full range of inundation observed for the modeled potholes, we can observe that drainage does not significantly alter the frequency of events which inundate the pothole to 90% of its area. At the other extreme, additional drainage may help reduce the certainty of ~20% of the pothole flooding annually to approximately 8% (for the D3 condition). Additionally, we find that drainage can reduce the 2-year return period surface area by up to 20% based on the smoothed data.

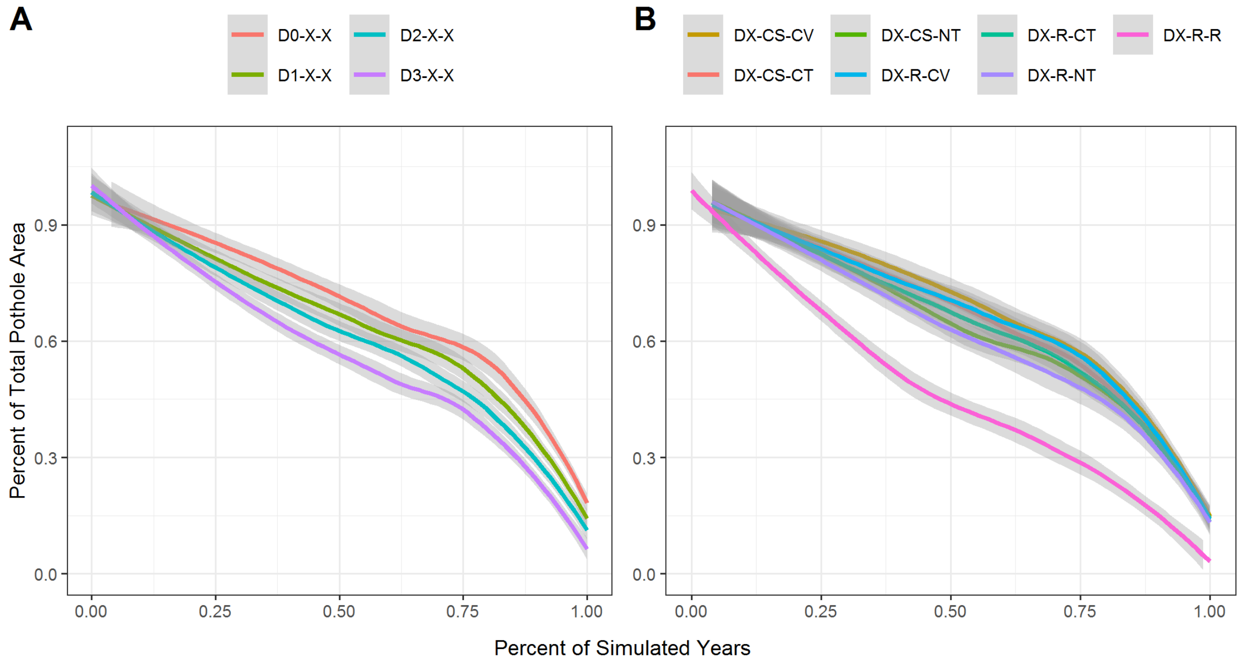

Figure 6. A) Loess smoothing of inundation frequency curves for all potholes and scenarios, excluding DX-R-R scenarios and Mouth Pothole. B) Loess smoothing of inundation frequency curves for all potholes and scenarios, excluding Mouth Pothole. The X in simulation code represents all potential levels of that factor. Natural drainage (D0) represents a situation with no subsurface drainage added; low drainage (D1) includes subsurface drainage; Medium drainage (D2) represents subsurface drainage plus a surface inlet, and high drainage (D3) represents subsurface drainage with multiple inlets. CV is conventional tillage, CT is conservation tillage, and NT is no-till. CS is corn-soybeans, while R is retired to perennial grass.

3.4.2 Effects of Management Activities

Figure 6B shows the smoothing of all scenarios based on drainage condition, excluding simulations where the whole watershed was retired and excluded all Mouth simulations due to its irregularity. With confidence bands, we see that there is minimal effect of tillage and retirement on the extreme ends of the data. Inundation with a probability <0.25 remains consistent across all scenarios except the retired watershed, while the high probability events (>0.9) are also consistent when smoothed. However, there is some observable effect of tillage and retirement practices, where no-till practices help reduce the area which floods in 50% of years by approximately 10% of the maximum area. Full watershed retired produces a significant decrease at all levels but is a less likely scenario to be adopted by landowners. However, a retired pothole watershed would help reduce extreme inundation percentages by 15% and 30% at the 4-year and 2-year return intervals. This has implications for major wetland restoration activities and should be considered when addressing restoration activities which reintroduce wildlife components that are highly sensitive to wetland hydroperiod.

4 DISCUSSION

Drainage has the single largest effect on all inundation metrics assessed, but despite many substantial and realistic improvements in drainage capacity, the expected reduction in crop loss within farmed prairie potholes may not tip the scales of profitability. The representation of subsurface drainage and surface inlets in AnnAGNPS models consistently reduced the number of days that a pothole flooded, which generally increased the percentage of inundation events that were short (1-3 days long). While this helps farmers in a practical sense, being able to navigate equipment through potholes during more days throughout the growing season, a high proportion of the inundation events across all potholes would still be harmful to corn and soybean plants. While the intensity of flooding that individual crops experience (measured by the length of inundation) may be reduced, the total area of crops exposed to stress remains largely unchanged, as shown that the addition of drainage may only save 20% of the typical maximum flood extents experienced biannually (Figure 6). This implies that similar pothole extents will remain a concern year after year despite continued monetary investment.

Retiring potholes from production can marginally reduce the spatial extent and duration of flooding within a pothole. Retiring the entire pothole watershed (in effect, the entire field) from production significantly reduces the pothole flooding. This would be an expected result based on changes to infiltration and evapotranspiration rates and soil health. Additionally, retiring only the pothole area tends to reduce the amount of ponded water, while maintaining field management practices. This can be beneficial when considering how much land needs to be retired; the risk of inundating the surrounding field edges would not increase based on pothole retirement. When potholes are retired and drainage is removed however, care needs to be taken regarding how much land is retired. The balance of conserved area has implications for restoration activities that incorporate plants or attempt to attract wildlife that are sensitive to variations in hydroperiod, or can affect adjacent planted areas via weed pressure. For example, the lesser scaup has been seen to prefer larger open water densities and high amphipod density. Full watershed retirement could significantly reduce the extents of flooding but would provide more consistent natural habitat overall. This could have other consequences regarding monitoring and success, as the restored wetland delineation may be smaller than farmed conditions. This could have further implications for subsidy programs that credit wetland conservation on an aerial basis as well.

Conservation tillage (including no till) practices moderately affected the flooding. Conservation tillage provides minimal reduction in flooding while no till had a more pronounced effect on flood reduction. However, field studies show that these practices can significantly improve infiltration via preferential flow through macropores over time, which may not be fully captured in the long-term simulation with the model through changes to the baseline CN based on land management. Conversely, field studies reporting a consensus on the effects of tillage practices on curve number, which is more dependent on residue cover, are limited. Regardless, there may be a more significant interaction between potholes and shallow subsurface flow when infiltration in the field is increased. Unless water is being routed significantly far from the pothole, the surface and shallow subsurface flow may be largely interchangeable. More study on the effects of tillage in poorly drained areas would help improve model validation by developing a more quantitatively robust understanding of the effect on infiltration and runoff generation.

Modeling a variety of potholes across the PPR would significantly improve the characterization of their flooding under different climatic and field conditions. Further work in the precision farming realm should incorporate assessments of individual potholes and relate their flood dynamics to consistent morphologic or field parameters.

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