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# Effects of land management on inundation of prairie pothole wetlands in the Des Moines Lobe using AnnAGNPS

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## Abstract

The Prairie Pothole Region (PPR) of North America contains millions of shallow wetlands, called potholes, in a landscape that was originally midgrass and tallgrass prairie. Since the 1900s, the prairie pothole landscape has been altered through the installation of subsurface drainage to make the land suitable for agricultural production. Currently, many of these potholes are farmed but they are often areas of poor crop yields because of early growing season flooding. The objective of this study was to investigate the influence of different land use practices on depth, duration, and aerial extent of ponding in two potholes (termed Walnut and Bunny) in central Iowa. Three management scenarios were simulated and inundation levels were compared using the Annualized Agriculture Non-Point Source model (AnnAGNPS) — current: conventionally tilled farmed conditions in corn/soybean rotation with surface inlets in the potholes connecting to a subsurface drainage system; retired: pothole is converted to a mixture of grass, weeds, and low-growing brush, with surface inlets removed and the drainage system underneath the potholes disconnected; and conserved: conservation tillage throughout the field with surface inlets and drainage maintained in potholes. The average annual water depth for the conserved and retired scenarios was 7–8% lower than the average annual water depth for the current scenario. However, for the retired scenario, an increase in inundation was observed in Bunny because disconnecting the surface inlets reduced infiltration in the model. The potholes tend to flood more frequently in the early stages of plant development, which can lead to delayed management operations and potentially reduced yields. Over the 17 year simulation period, Bunny pothole exceeded its maximum volume storage capacity and overflowed five times. This information is important to prioritize areas for and to understand the hydrologic impacts of pothole restoration efforts in intensive agricultural landscapes.



## Keywords

AnnAGNPS, Farmed wetlands, Hydrology, Inundation, Land management, pothole/Prairie pothole region


## Disciplines

Agriculture | Bioresource and Agricultural Engineering

## Comments


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***Abstract***

*The Prairie Pothole Region (PPR) of North America contains millions of shallow wetlands, called potholes, in a landscape that was originally midgrass and tallgrass prairie. Since the 1900s, the prairie pothole landscape has been altered through the installation of subsurface drainage to make the land suitable for agricultural production. Currently many of these potholes are farmed but they are often areas of poor crop yields because of early growing season flooding. The objective of this study was to investigate the influence of different land use practices on depth, duration, and aerial extent of ponding in two potholes (termed Walnut and Bunny) in central Iowa. Three management scenarios were simulated and inundation levels were compared using the Annualized Agriculture Non-Point Source model (AnnAGNPS) — current: conventionally tilled farmed conditions in corn/soybean rotation with surface inlets in the potholes connecting to a subsurface drainage system; retired: pothole is converted to a mixture of grass, weeds, and low-growing brush, with surface inlets removed and the drainage system underneath the potholes disconnected; and conserved: conservation tillage throughout the field with surface inlets and drainage maintained in potholes. The average annual water depth for the conserved and retired scenarios was 7-8% lower than the average annual water depth for the current scenario. However, for the retired scenario, an increase in inundation was observed in Bunny because disconnecting the surface inlets reduced infiltration in the model. The potholes tend to flood more frequently in early stages of plant development, which can lead to delayed management operations and potentially reduced yields. Over the 17 year simulation period, Bunny pothole exceeded its maximum volume storage capacity and overflowed five times. This information is important to prioritize areas for and to understand the hydrologic impacts of pothole restoration efforts in intensive agricultural landscapes.*

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## 1 Introduction

The Prairie Pothole Region (PPR) of North America extends through three Canadian provinces (Saskatchewan, Manitoba, and Alberta) and five U.S. states (Minnesota, Iowa, North and South Dakota, and Montana). The portion of the PPR that extends into Iowa is referred to as the Des Moines Lobe. Agriculture and urban development have led to the drainage of nearly 90% of the four million acres of wetlands and prairie potholes which existed prior to the 1900s in the PPR of Iowa (Hewes and Frandson, 1952). Potholes are seasonal wetlands that typically flood during the early growing season, and thus are drained to support agricultural production, and the vast majority of the potholes in this area are now under agricultural land use (Gleason et al., 2008; Miller et al., 2009, 2012; Roth and Capel, 2012). Prairie potholes also provide a range of ecosystems services such as sediment entrapment, water quality improvement, flood control, and groundwater recharge (Gleason et al., 2008; Werner et al., 2013). Despite the benefits that wetlands provide, they have historically been seen as a nuisance and a hindrance to agricultural production (Van der Valk, 1989). This has led to many PPR wetlands being filled, drained, or otherwise manipulated to facilitate crop production (Renton et al., 2015). Farmed potholes are often areas of low productivity compared to the high yielding uplands across the PPR due to conditions such as poor soil quality, erosion, and water logging (Muth and Bryden, 2012).

This work was initially motivated by farmer concerns because of the difficulties in managing these in-field depressions, but was then bolstered by the need to understand pothole hydrological patterns and downstream nexus. The impacts of farmed potholes on downstream waters is largely undocumented; however, in 2015 the U.S. Environmental Protection Agency (EPA) Waters of the United States rule expanded the protection of all waters in the country, which would potentially categorize farmed potholes the same as intact longer-duration wetlands, for purposes of the Clean Water Act (CWA). Recently, the US EPA conducted a comprehensive review of over 1350 peer-reviewed papers with the aim of synthesizing existing scientific understanding of how wetlands and streams affect the physical, chemical, and biological integrity of downstream waters (US EPA, 2015). The report concluded that additional research focused on the frequency, magnitude, timing, duration, and rate of fluxes from geographically isolated wetlands (potholes) to downstream waters is needed to better identify wetlands with hydrological connections or functions that substantially affect other waters and maintain the long-term sustainability and resiliency of valued water resources (Wu and Lane, 2017).

The understanding of the hydrology of prairie potholes can be achieved by monitoring some features, and with the use of watershed models, such as the Soil and Water Assessment Tool (SWAT) or Annualized Agriculture Non Point Source Model (AnnAGNPS). Watershed models consist of tools that can be used to simulate a diverse number of features and flow patterns within a given basin of study, contributing to the decision-making process (Momm et al., 2011; P. Nejadhashemi et al., 2011; Tsai et al., 2017; Wu et al., 2015; Zema et al., 2010). The limitation of models, however, is that they usually require large amounts of input data, as well as extensive user technical knowledge (Tsai et al., 2017). Regarding prairie potholes, model application is limited by the small size of the features, and the fact that they have been functioning for a long time differently than their natural condition (Upadhyay et al., 2018). In an attempt to simulate prairie pothole hydrology, Amado et. al. (2016) developed HydroGeoSphere to simulate the hydrological connectivity of the densely farmed and drained landscape in the Prairie Pothole region, and concluded that although intermittent ponding was frequent during the simulated six years, hydrologic connectivity was infrequent. Despite the fact that information on pothole hydrology is important for current and future management decisions regarding the region, there is little information available regarding the potential impacts of changing the agricultural management of these farmed features. Because of the management challenges and potential new legislation regarding wetlands, there is increased interest in conservation management or removing potholes from agricultural production; however, these changes will impact pothole hydrology and potentially downstream hydrology.

Installing conservation practices help improve the resource management and cropping system. Prairie strips are a farmland conservation practice and research shows that by converting 10% of a crop-field to diverse, native perennial vegetation, farmers and landowners can reduce total water runoff from catchments by 37%, resulting in retention of 20 times more soil and 4.3 times more phosphorus (Schulte et al., 2017). It is possible that applying similar conservation strategies to potholes could also provide disproportionate environmental benefits as these restored potholes have high conservation value (Gleason et al., 2008). However, few studies have been conducted to date on the impacts of pothole conservation on water quantity or water quality benefits, especially in farmed systems. Three decades ago, the U.S. adopted a federal policy of ‘‘no net loss’’ for wetlands, following George H.W. Bush’s presidential campaign pledge (1988). Under this policy, wetland losses that cannot be avoided must be mitigated through restoration or creation (Aronson and Galatowitsch, 2008). Changing management of low productivity farmed potholes may be an opportunity to restore some ecosystem services at a lower cost than removing high productivity upland areas from production. Evidence suggests that perennial crops perform better in potholes compared to corn (Zea mays L.) and soybean (Glycine max) crops (Bailey-Serres et al., 2012; Edmonds, 2017; Mann et al., 2013). Incorporating alternative management practices, such as conservation restoration programs or planting perennial grasses, may help to minimize or eliminate crop yield losses in flood-prone pothole areas (Edmonds, 2017).

There is limited knowledge of how different pothole management options impact pothole inundation patterns. Further, there are very few studies which have monitored water depth fluctuations in farmed potholes. For water management planning and decision-making, it is a common practice to use computer simulation models. In the absence of empirical studies on the effect of land management on pothole water dynamics, we chose the Annualized Agriculture Non-Point Source model (AnnAGNPS), a watershed scale, continuous simulation, daily time step approach. Our previous work (Upadhyay et al., 2018) demonstrates that this model is capable of replicating observed patterns of inundation in these features; this provides us the opportunity to use this modeling approach to explore the potential impacts of alternative management strategies. Therefore, the goal of this paper is to investigate the influences of agricultural practices (current) and altered land use practices (retired and conserved) on depth, and duration, and aerial extent of ponding using AnnAGNPS. This information is also important to understand and predict the impact of management operations on pothole inundation and resulting crop yield loss.

## 2 Methodology

### 2.1 Study area

This study focuses on two potholes located in a single conventional farm field straddling adjacent Hydrologic Unit Code (HUC-12) watersheds in the Des Moines lobe region near Ames, IA. These potholes are the same as those presented in Logsdon (2015) and Upadhyay et al. (2018). The potholes are managed in a corn-soybean rotation with conventional tillage and their positions in relation to the Walnut Creek and Worrell Creek HUC-12 watersheds are shown in Figure 1. According to the USDA NRCS Soil Survey, the field is 10% Okoboji silt clay loam, 25% Nicollet loam, 7% Harps loam, 3% Webster clay loam, 9% Clarion loam, 25% Canisteo clay loam, and 21% Clarion loam (USDA-NRCS, 2014). Except for the Clarion and Nicollet series, the soils are classified as hydric; formed in saturated conditions and could support wetland vegetation species when not drained.

The potholes have different drainage areas, and thus the potential to store different volumes of water. The pothole in the Worrell Creek watershed is referred to as “Bunny” and is classified as a “second-level puddle”. It is composed of two depressions with a common outlet (Chu, 2015), which are distinct but merge with sufficient inundation. Bunny has two surface inlets to the drainage system in the western portion of the pothole; the eastern depression in the pothole does not have a surface inlet. The size of Bunny Pothole is about 5 ha and its catchment area is about 40 ha. The pothole located in the Walnut Creek watershed is referred to as "Walnut" and it has one surface inlet. The size of Walnut Pothole is about 3 ha and its catchment area is about 9.5 ha. The locations of the subsurface drainage lines in the field are largely unknown, except where they connect to the surface inlets.

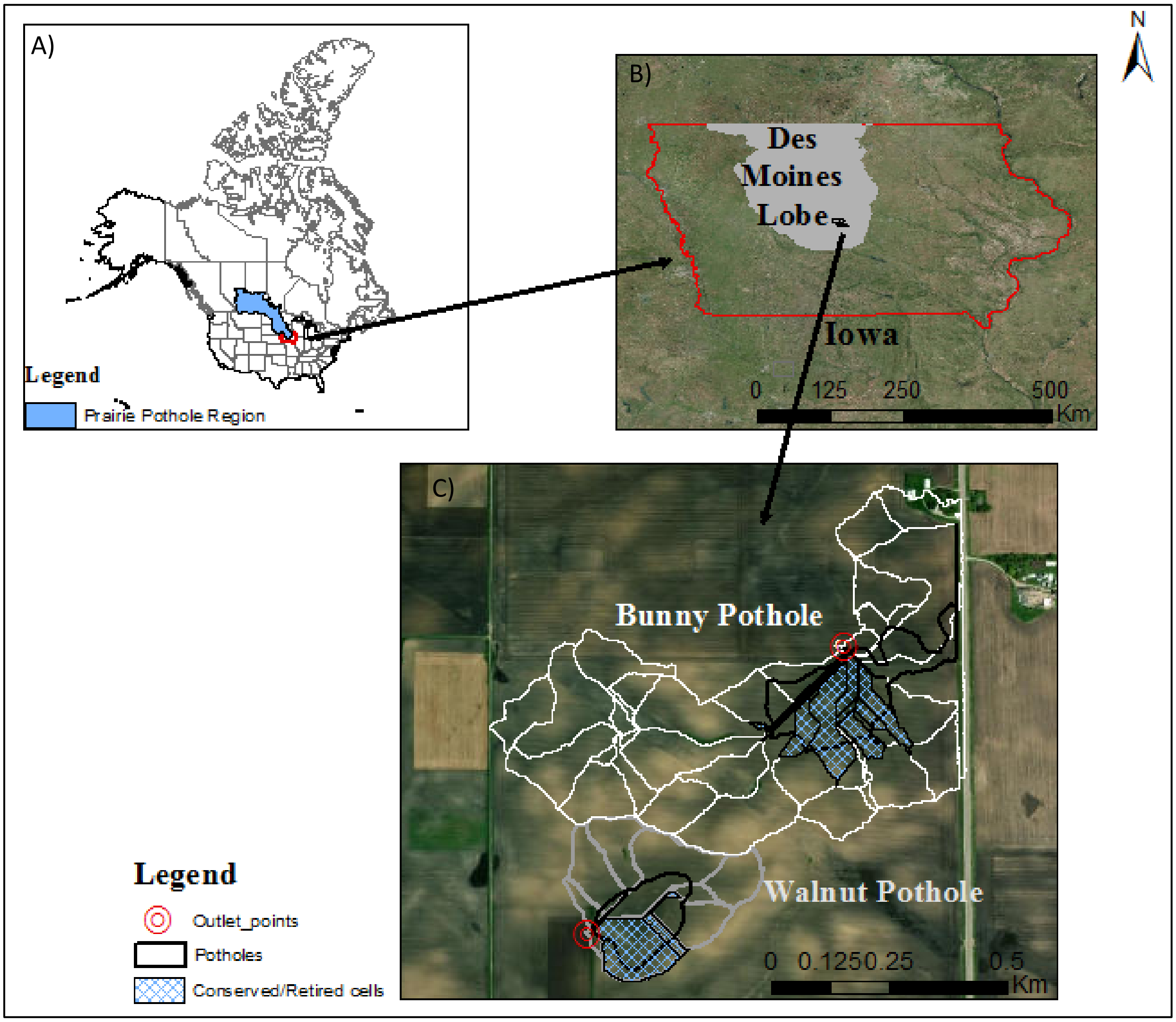



**Figure 1. Location of study area in (A) Prairie Pothole Region (PPR) of North America (B) Des Moines Lobe region with the Hydrologic Unit Code (HUC-12) watersheds in Iowa, (C) Walnut and Bunny potholes with their outlets (Red circles) and their sub-watersheds (microwatersheds) divided into cells (In grey and white, respectively).**

## 2.2 Current, retired and conserved management scenarios

Three management scenarios were compared, the current scenario corresponded to conventionally farmed conditions with corn/soybean rotation, poor hydrologic condition (<50% ground cover or heavily grazed with no mulch) and with surface inlets in the potholes connecting to a subsurface drainage system. In the retired scenario the pothole is converted to a mixture of grass, weeds, and low-growing brush, with surface inlets removed and the drainage system underneath the potholes disconnected. For the retired scenario, retired areas are located toward the outlet of the microwatersheds; these areas are saturated more frequently than upland areas, and more suitable for conversion to alternative vegetation (Fig. 1). The cells with a centroid located inside the pothole boundary were 21.17% and 9.13% area of the Walnut and Worrell microwatersheds, respectively, and were considered retired while the remainder of the microwatershed remained in row crop production. Lastly, a conserved scenario considered row crop under conservation tillage practices, good hydrologic condition (>75% ground cover and light or only occasionally grazed), and with surface inlets maintained in the potholes. The representation of each scenario in the model parameters is presented in Figure 1 (C).

### 2.3 Watershed model

Annualized Agricultural Non-Point Source model (AnnAGNPS) is a watershed evaluation tool developed jointly by the USDA Agriculture Research Service (ARS), and the USDA Natural Resources Conservation Services (NRCS) (Yuan et al., 2003). AnnAGNPS is a watershed scale, continuous simulation, daily time step model. The GIS based wetland component of AnnAGNPS known as AgWET can be used for identifying and characterizing topographic depressions (puddles/potholes) during DEM preprocessing, which makes this model appropriate for investigation of the effect of different land management on pothole inundation (Momm et al., 2016). AnnAGNPS is well-suited to small scale watersheds, and is able to produce satisfactory hydrologic outputs for the Midwest United States (Richardson et al., 2008; Upadhyay et al., 2018; Yuan et al., 2011; Yuan et al., 2003). For example, the drainage areas computed by AnnAGNPS for Walnut and Bunny potholes are approximately 24 and 100 acres, respectively, and pothole water depth variations was successfully modeled at this scale (Upadhyay et al., 2018). The areas of Walnut and Worrell Creek HUC-12 watersheds, by comparison are approximately 23.2 and 12.5 thousand acres. Thus, because of their very small size, we refer to the drainage areas of potholes as microwatersheds.

First, watershed topography was assessed to generate hydrological units, the cells. To capture the detail of these microwatersheds, the maximum AnnAGNPS cell area that was treated as a homogeneous unit in the model was set to 1 ha and maximum reach length for uniform surface flow was set to 10 meters. These are denoted as “Critical Source Area” (CSA) and “Minimum Source Channel Length” (MSCL). The division of the cells by the model is based on hydrology patterns suggested by the topography.

The MSCL generates the reaches in the watershed. In larger watersheds, the reaches will correspond to rivers. However, at the microwatershed scale, the reaches indicate the preferential flow path of surface water. Based on the DEM and the user-identified outlet location, the model divides the watershed into cells. The objective of the division of the drainage area is to represent the spatial variability. For each cell, parameter values describing soil, land cover and climate are attributed. Daily load generated by the cells is transported through the reaches to the outlet.

AnnAGNPS includes a hydrology component; surface and near-surface runoff is simulated based on the SCS Curve Number (CN) method for runoff depth, and the extended TR-55 procedure for peak flow rate (Bosch et al., 1998). To calibrate the model, we first regulated the water load generated by the microwatersheds, and therefore the rising water depth in the potholes, by testing a range of curve number (CN) values to achieve the best fit. After the water depth rise was consistent with the observed data, the infiltration rate was calibrated to estimate the rate at which water was leaving the system; tile flow was incorporated through calibration of infiltration rates. Actual evapotranspiration is a function of potential evapotranspiration calculated using the Penman equation (Penman, 1948) and soil moisture content. When there is standing water in the wetland ET is calculated using the potential ET, and when there is no water in the wetland, then ET is calculated as the amount coming from the soil of the cell. Model calibration and efficiency were discussed in detail in Upadhyay et al. (2018). Here, the model is used to estimate the depth, duration, and aerial extent of ponding of the features in the current, retired and conserved scenarios.

For the current scenario, the runoff potential of the microwatersheds is expressed by the curve number while the infiltration rate was adjusted to represent infiltration and drainage. Both values were selected for optimal calibration of water depth. In case of Bunny, since two different calibrated values were obtained for the two calibrated years (2010 and 2011) we took the average of those two for this analysis (Upadhyay et al., 2018). Similar CN values were able to capture the water load in both potholes, as both the fields were under the same crop rotation and have very similar soil types. Alternatively, because of the two surface inlets, the values for infiltration rate were higher for the Bunny pothole. The CN and infiltration rate values for Walnut and Bunny potholes for all three analyzed scenarios are provided in Table 1.

**Table 1: Curve number and infiltration values for the three scenarios.**

| **Scenario** | Current (Calibrated) | | Retired | | Conserved | |
|---|---|---|---|---|---|---|
| **Wetland ID** | Walnut | Bunny | Walnut | Bunny | Walnut | Bunny |
| **Daily infiltration (mm/day)** | 33 | 77 | 26 | 26 | 33 | 77 |

| **Curve Number Classification** | Row Crop – Poor Condition | Row Crop – Poor Condition | Row Crop –Poor Condition | Mixture of grass, weeds, and low-growing brush | Row Crop –Poor Condition | Mixture of grass, weeds, and low-growing brush | Row Crop – Good Condition | Row Crop – Good Condition |
|---|---|---|---|---|---|---|---|---|
| **CN Hydr. Soil Group B** | 81 | 81.5 | 81 | 61 | 81.5 | 61 | 75 | 75 |
| **CN Hydr. Soil Group C** | 88 | 88 | 88 | 74 | 88 | 74 | 82 | 82 |

For the retired scenario, the curve number was selected based on land-cover type and hydrologic condition descriptions given in the National Engineering Handbook, Chapter 9 (USDA-NRCS 2004). Also, in the retired scenario, pothole infiltration was decreased to 26 mm/day for both features, to simulate the effect of removing surface inlets and disconnecting the subsurface drainage. This value was obtained by calibrating a monitored pothole in similar field conditions and which had been converted back to its natural state of vegetation, and retired from cultivation; using the procedure outlined in Upadhyay et.al. (2018). In the conserved scenario, we simulate conservation tillage throughout the microwatersheds, including the potholes, by selecting a curve number that represents straight row crop in good hydrologic condition with significant residue cover. We assume drainage is maintained in the potholes, so we did not adjust the infiltration rate of the pothole compared to the current scenario, although in practice, the use of conservation tillage would likely improve infiltration rate over time. Figure 2 illustrates the management of the cells in the current, conserved and retired scenarios.

## 2.4 Weather data and model initiation period

The precipitation data were downloaded from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) datasets, at the field site. The other weather parameters (maximum temperature, minimum temperature, dew-point temperature, wind velocity, wind direction and solar radiation) data were obtained from the 'Sustaining the Earth's Watersheds, Agricultural Research Data System' (STEWARDS) project which provides access to soil, water, climate, land-management, and socio-economic data from fourteen watersheds. It is developed by Conservation Effects Assessment Project (CEAP) - Watershed Assessment Studies (WAS) and is supported by the United States Department of Agriculture (USDA). The STEWARDS weather station used in this assessment was located approximately 5 km from the field site. Since the potholes are located very close to each other, same weather parameters are used for both the potholes.

Twenty five years of daily rainfall, temperature, wind velocity, wind direction and solar irradiance data (1992 – 2016) were obtained from PRISM system and the STEWARDS weather station, and the summary statistics of weather parameters are presented in Table xx. The initial 8 years were used as the initialization years in the AnnAGNPS model. The initialization period is the time that the simulation will run before starting to collect results and is needed to initialize variables prior to start of the simulation (Browning, 2014). Daily water depths in the potholes were simulated from 2000 to 2016.

**Table 2. Summary statistics of weather parameters (1992 – 2016)**

| | Rainfall (mm) | Tmax ($^0$C) | Tmin ($^0$C) | DewP ($^0$C) | WindV (m/s) @ 2m | SolarRad (J/sec/m$^2$) |
|---|---|---|---|---|---|---|
| Min. | 0.00 | -25.30 | -75.00 | -75.00 | 0.00 | 0.00 |
| Max. | 124.29 | 37.00 | 25.80 | 25.90 | 12.60 | 383.94 |
| Mean [st. dev.] | 2.47 [7.30] | 14.55 [12.50] | 3.34 [11.50] | 3.6 [13.77] | 3.24 [1.60] | 158.22 [92.35] |

## 2.5 Pothole inundation analysis

We summarized the pothole inundation model output in four ways. First, we assessed the maximum water depth for each month and average water depth for each year in both potholes over the entire simulation period. The average water depth was calculated by averaging the total water depth simulated over the entire simulation period by the number of days on which water depth was observed. This illustrates the water dynamics of the potholes in the current, retired and conserved scenarios, particularly under extreme events where the potholes are most likely to impact watershed-level storage. Using the maximum depth, an overflow assessment was performed. Overflow occurs when water exceeds the maximum depth of the pothole, this information is important to determine the influence of upstream potholes to downstream potholes and provide insight into surface pothole connectivity in relation to the rest of the watershed.

Second, we counted the total number of days in each simulated year in which there was water in the potholes, as these days of inundation have direct implications for crop production. An analysis of average number of inundation days in the potholes on a monthly basis was also performed, this analysis provides us the information on the months in which inundation was more frequent, and estimations of its impact on management operations and crop yields.

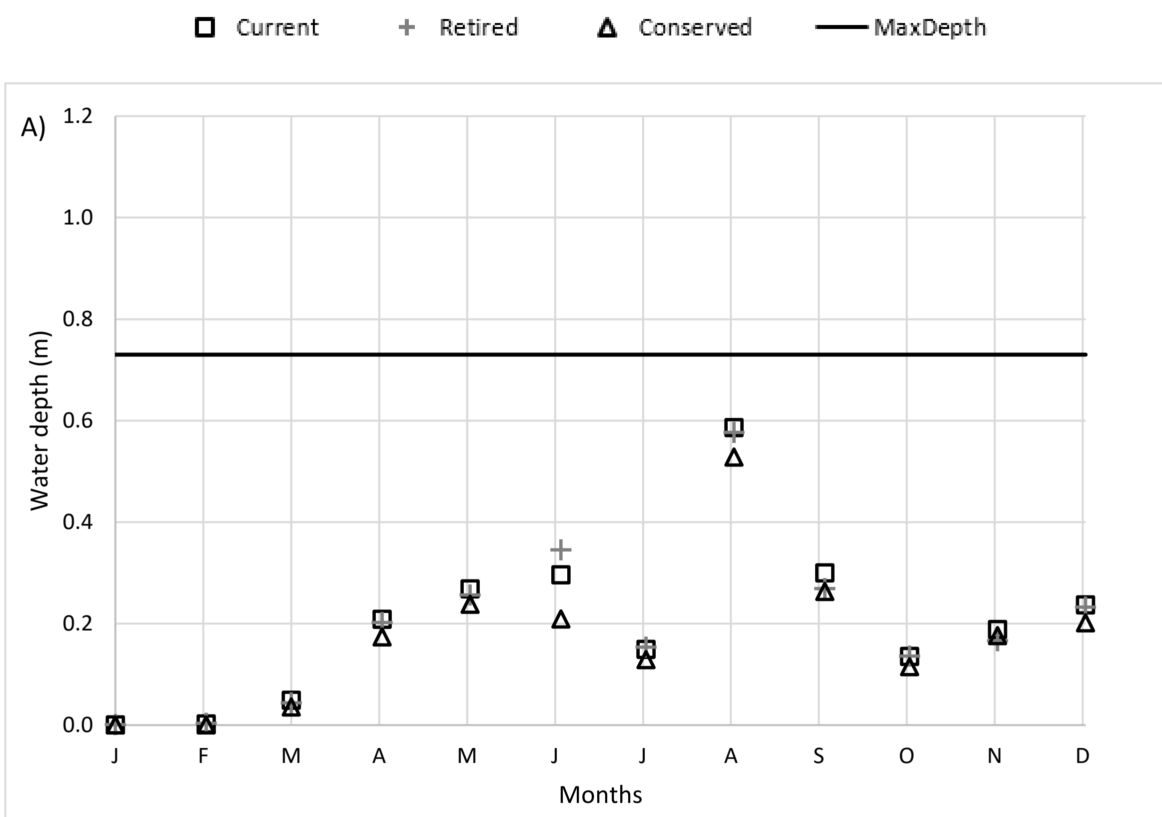
Third, we enumerated the occurrences of consecutive days of inundation. Days of consecutive inundation were considered because this information is important to determine how long water stays in the pothole before it leaves the system. In this analysis, every time inundation is observed in the feature, a count will start. In the next day, if there is still water, one will be summed with the previous value, and this process will continue while water is observed in the pothole. If the water depth is zero, the count ends and will start again with the following inundation event.

Finally, maximum area of inundation was evaluated. First, we calculated the maximum water depth in the potholes in a particular year, then the area corresponding to that maximum depth was obtained using topography data in ArcGIS. That area was compared with the areas for all other simulated years to find the number of years having inundation more than this particular year. This assessment provided the information on the ponded area, for any given number of years.

## 3 Results and discussion

### 3.1 Maximum and average water depth in the potholes

Figure 2 illustrates the maximum water depth in each month over the entire simulation period for the current, retired and conserved scenarios for both the Walnut and Bunny potholes. This assessment provides a means for understanding how the management scenarios impact the maximum inundation and the risk of spillover outside the pothole.



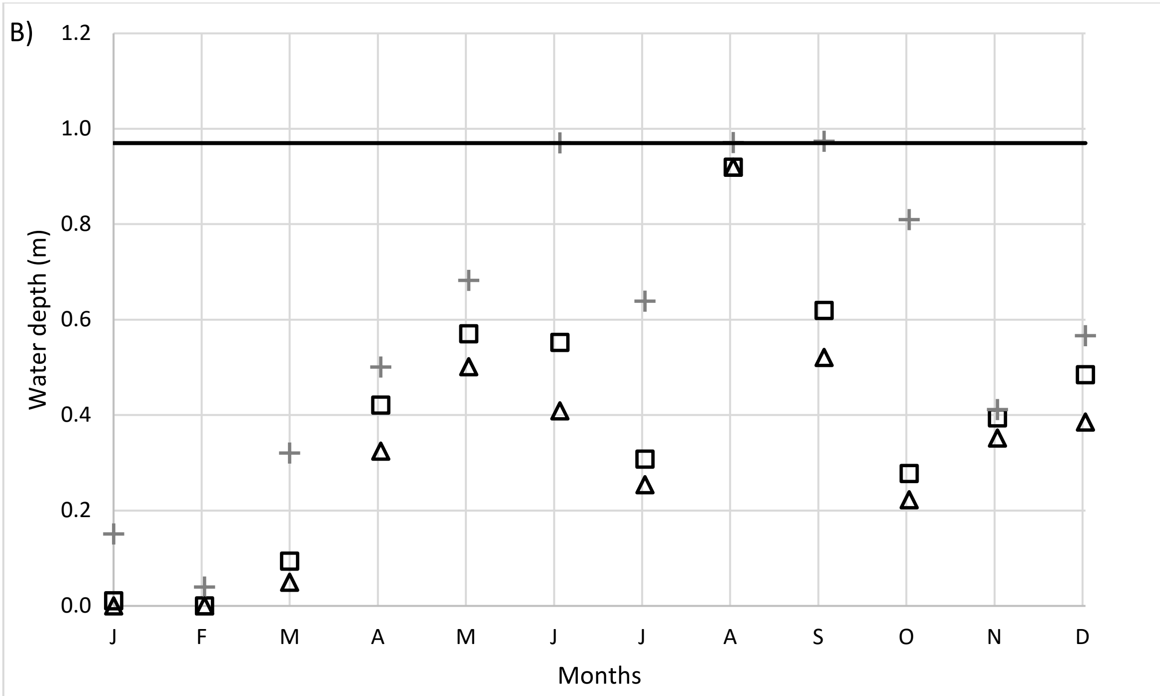



**Figure 2. Monthly maximum water depth over the entire simulation period in A) Walnut and B) Bunny potholes in the current, retired and conserved management scenarios.**

From figure 2, we can see that in the Walnut pothole, the monthly maximum water depths are greatest for the current scenario and are lowest for the conserved scenario. The monthly maximum water depth over the entire simulation period are presented in the Table 3. From the maximum water depth data we can also consider how often the potholes will overflow, to understand their potential nexus downstream (Leibowitz and Vining, 2003; Singh, 2015). Overflow occurs when water exceeds maximum depth of the potholes, which corresponds to 0.73 and 0.97 m for Walnut and Bunny potholes, respectively, after considering evapotranspiration (ET).Daily some amount of water will be lost due to ET. Thus, in case of overflow, the model output appears to be a little lower than the maximum depth (Fig. 2) because once the wetland reaches the maximum water depth, some water will be lost to ET. The potholes did not exceed their maximum volume storage capacity under the current and conserved scenarios. However, in the retired scenario, the potholes stored more water through the year, and overflowed during wet conditions. This is likely due to the absence (removal) of the surface inlets to the drainage system in the retired scenario. In the retired scenario, during the simulation period from 2000 to 2016, Walnut never exceeded its maximum volume storage capacity, but Bunny exceeded its maximum volume storage capacity 5 times. Bunny's current scenario as simulated reflect two surface inlets, whereas Walnut's current scenario has only one inlet. Thus the impact of removing the inlets at Bunny in the retired scenario was more pronounced.

**Table 3: Monthly maximum water depth over the entire simulation period.**

| Months | Water Depths (m) | | | | | |
|---|---|---|---|---|---|---|
| | Walnut Pothole | | | Bunny Pothole | | |
| | Current | Retired | Conserved | Current | Retired | Conserved |
| Jan. | 0.000 | 0.001 | 0.000 | 0.010 | 0.151 | 0.000 |
| Feb. | 0.002 | 0.003 | 0.000 | 0.000 | 0.040 | 0.000 |
| Mar. | 0.049 | 0.043 | 0.036 | 0.094 | 0.320 | 0.050 |
| Apr. | 0.208 | 0.202 | 0.174 | 0.421 | 0.501 | 0.325 |
| May | 0.268 | 0.256 | 0.238 | 0.571 | 0.682 | 0.501 |
| Jun. | 0.296 | 0.345 | 0.209 | 0.552 | 0.971 | 0.409 |
| Jul. | 0.149 | 0.153 | 0.129 | 0.308 | 0.639 | 0.254 |
| Aug. | 0.586 | 0.577 | 0.528 | 0.919 | 0.971 | 0.919 |
| Sept. | 0.299 | 0.269 | 0.263 | 0.619 | 0.974 | 0.521 |
| Oct. | 0.135 | 0.136 | 0.115 | 0.277 | 0.809 | 0.222 |
| Nov. | 0.188 | 0.166 | 0.176 | 0.394 | 0.412 | 0.352 |
| Dec. | 0.236 | 0.232 | 0.201 | 0.485 | 0.567 | 0.385 |

For the Walnut pothole, the average annual water depth for the current scenario is approximately 8% higher than the average annual water depth for the retired and conserved scenarios. This is likely because compared to the current scenario, the retired scenario included a portion of the watershed (inside the pothole boundaries) converted to a mixture of grass, weeds, and low-growing brush, which reduced runoff in the model, while the conserved scenario's conservation tillage also resulted in a decrease in runoff to the pothole.

Behavior of the Bunny pothole, however, was different; in this pothole the retired scenario had the greatest water depths (both maximum and average). We attribute this to the disconnection of the surface inlets and drainage system. Because the Bunny pothole had two surface inlets and an initially high infiltration rate as a result of the drainage in the current scenario (Table 1), this change had a more significant impact in this pothole. Additionally, the Bunny pothole has a larger microwatershed area in relation to Walnut, which was probably the reason for the installation of the two inlets. In this case, the effect of the reduced infiltration was high and average annual water depths in the pothole increased when compared to the current condition by 27%. However, the average annual water depth for the conserved scenario was 7% lower than the current scenario for this pothole, again illustrating the effect of reducing runoff through changes in tillage practices.

These findings suggest that in the conversion of potholes with surface inlets and larger microwatersheds, additional conservation practices may be needed to offset the runoff and decreased outflow through surface intakes that occurs.

### 3.2 Pothole days of inundation

Figure 3 shows the total number of inundated days for each simulated year, from 2000 to 2016 for current, retired and conserved scenarios, for both potholes, including all days in which there was any simulated water depth in the potholes respectively.

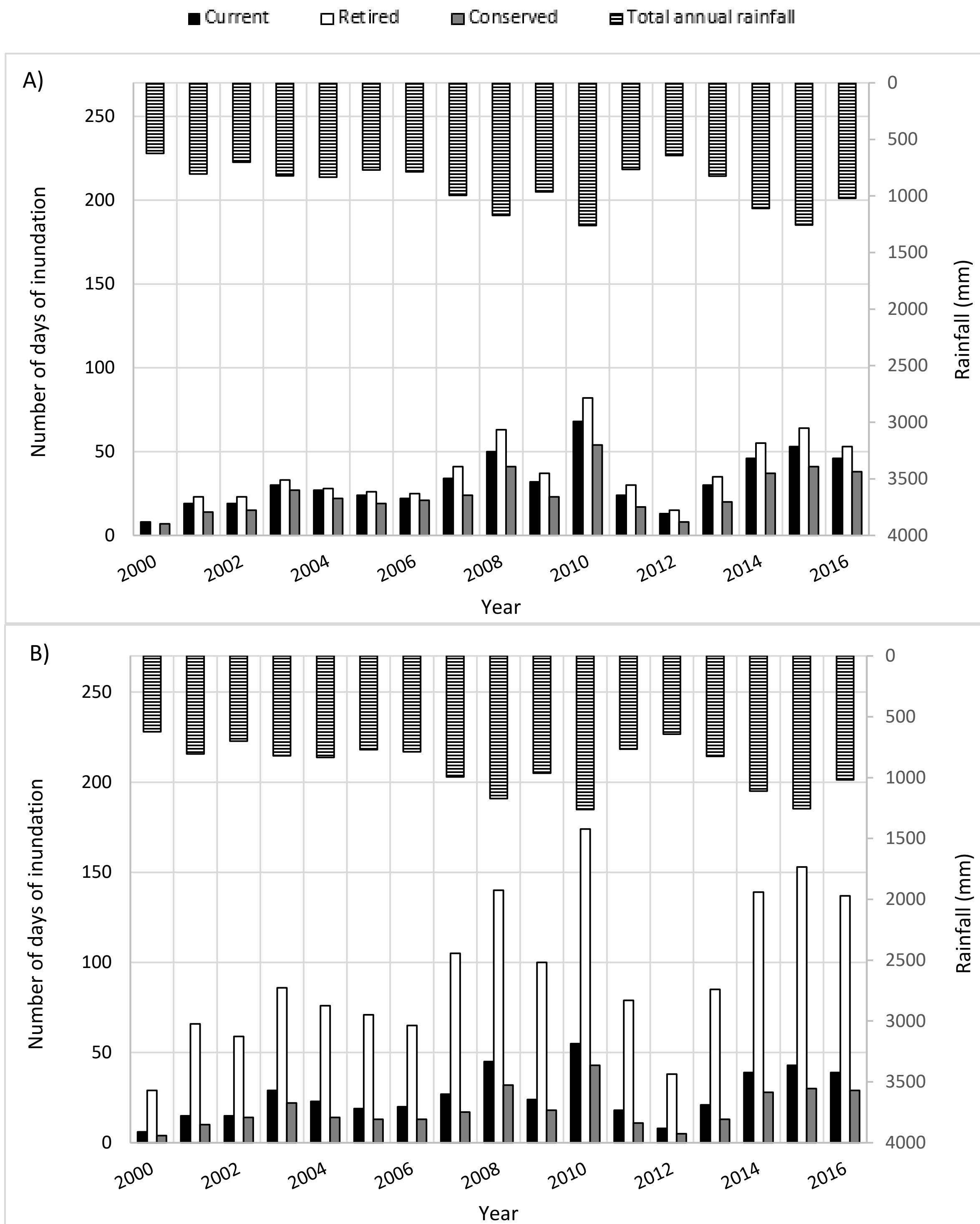



**Figure 3: Comparison between the number of days of inundation between current, retired and conserved conditions for A) Walnut and B) Bunny potholes.**

In the current condition, Walnut and Bunny potholes had similar patterns through the years, which is expected, due to their proximity and similar management. Based on these simulations, the water regime of the potholes can be classified as semipermanent, since these tend to flood every year (Galatowitsch and Valk, 1996). The years of 2008, 2010 and 2015 had the most inundations, whereas 2000 and 2012 had the fewest. In the current scenario, the average number of inundations per year was 32 and 26 for Walnut and Bunny, respectively. For all simulations, the difference between current and retired scenario was higher in Bunny, likely for the reasons discussed above, which suggests that the conservation of this pothole would have a higher impact on downstream hydrology.

The average number of inundations per month under the current and conserved scenario for both potholes are shown in Table 2 along with the corresponding estimated plant growth stage for corn and soybeans. The retired option is not presented because it assumes crops will not be present in the potholes and thus the occurrence of inundation with respect to the corn/soybean growing season is not relevant. The plant growth stages are: Initial, Development, Maturation, and Senescence, and correspond approximately to 15, 25, 40 and 20% of the growing season, respectively according to the FAO (Doorenbos and Pruitt, 1975).

**Table 4: Average number of inundation days in the potholes during the growing season.**

| | | Current* | | Conserved+ | |
|---|---|---|---|---|---|
| **Growth Stage** | **Months** | Walnut | Bunny | Walnut | Bunny |
| Initial/Development | May | 5 | 4 | 4 | 3 |
| Development | June | 5 | 4 | 4 | 3 |
| | July | 4 | 4 | 3 | 2 |
| Development / Maturation | Aug | 6 | 5 | 5 | 4 |
| Maturation | Sep | 4 | 3 | 3 | 3 |
| Senescence | Oct | 2 | 1 | 1 | 1 |
| **Total days** | | 26 | 21 | 20 | 16 |

* Row crop with corn and soybean rotation with poor hydrological conditions and surface inlets.
+ Row crop with corn and soybean rotation with good hydrological conditions and surface inlets.

As shown in Table 4, the potholes tend to flood more frequently in early stages of plant development. In the current scenario, Walnut pothole is inundated for an average of 5 days in May and 5 days in June and in conserved scenario, Walnut pothole is inundated for 4 days in May and 4 days in June, across all the years of simulation. Though the differences between current and conserved scenarios might look small, these differences can be crucial for plant survival as just one additional day can have a significant impact on plant survival. Depending on the growth stage of the plant it can survive 2 to 4 days of inundation, but one more day of inundation might result in crop loss. Considering that these are the months when seeding occurs, it is likely that these conditions could cause delay in field operations, which can result in reduced yields in the areas where the potholes are located.

### 3.3 Consecutive days of inundation

The number of consecutive days of flooding in the pothole has several impacts. For one, crop development in the pothole is affected as soil oxygen is depleted within 48 hours of soil saturation. Without oxygen, the plants cannot perform critical life sustaining functions; e.g. nutrient and water uptake is impaired and root growth is inhibited (Wiebold, 2013). Conversely, when these features are managed as wetlands rather than cropland, prolonged inundation affects the efficiency of the wetland in the improvement of water quality, since, the longer water is stored in potholes, the higher opportunity for nutrient sorption and sediment settling (Johnson et al., 2008; Woltemade, 2000).

Growth stage is a critical factor in survivability due to flooding. Technically, the larger a plant, the more oxygen it requires to stay alive. However, smaller plants are more likely to become submerged and to remain submerged for longer periods. As a rule, smaller crops in the earliest growth stages are more at risk and usually receive greater damage due to flooding, ponding and saturated soils (Butzen, 2017). The major crops grown in the Midwest, corn and soybeans, often survive for two to four days under flooded conditions without requiring replant. Soybeans are thought to be more tolerant to temporary flooding than corn and many other crops. When the growing point of corn is just at or below the soil surface, corn can only survive two to four days of totally saturated soil conditions (Butzen, 2017), while soybeans easily survive 48 hours underwater, and have even been known to survive submersion for a week under ideal conditions during and after flooding. Four days or more of flooding stresses the crop, delays plant growth, and causes the plants to be shorter with fewer nodes. Flooding for six days may depress yields significantly, and longer periods under water may destroy the entire stand. Any ponding lasting more than two days will have negative impacts on plant growth and yield (Nielsen, 2011).

From 2000 to 2016, at least 47% of the events of inundation lasted more than two days during the current scenario, potentially killing vegetation in the field. Figure 5 illustrates the consecutive days of inundation in a histogram format, for the assessment of consecutive inundations in the current, retired and conserved scenarios.

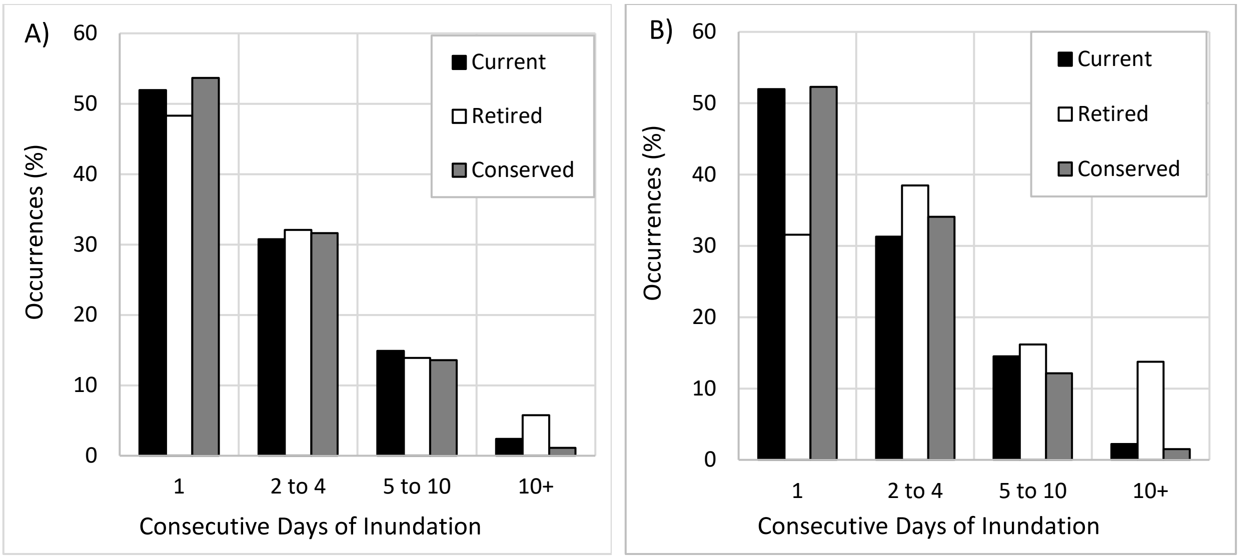



**Figure 4: Consecutive days of inundations in the potholes over the entire simulation period A) Walnut and B) Bunny in the current, retired and conserved scenario.**

For most of the inundation events, the relative number of inundation days (occurrences) was similar for the current and conserved scenarios, which is expected because both scenarios have similar drainage. However, for the retired scenario when we removed the drainage, low occurrences were observed for a lower number of consecutive days of inundation and relatively high occurrences was observed for higher number of consecutive days of inundation (Fig. 4). For example, in Bunny the retired scenario had 20% less simulated occurrences with only 1 consecutive day of inundation and 12% more 10+ consecutive days of inundation, when compared to the current and conserved scenarios.

### 3.4 Maximum area of inundation

The preceding discussion focuses on days of any inundation. However, for agricultural production another metric is aerial extent of flooding and thus the area subjected to yield-limiting excess-water stress. The maximum area of inundation provides insight into the area of the pothole that is not suitable for agricultural crops in the field due to the water depth in the potholes. Figure 5 illustrates the maximum area of the potholes inundated in each year, corresponding to simulated years in percentage, for a better understanding of the area of the inundation.

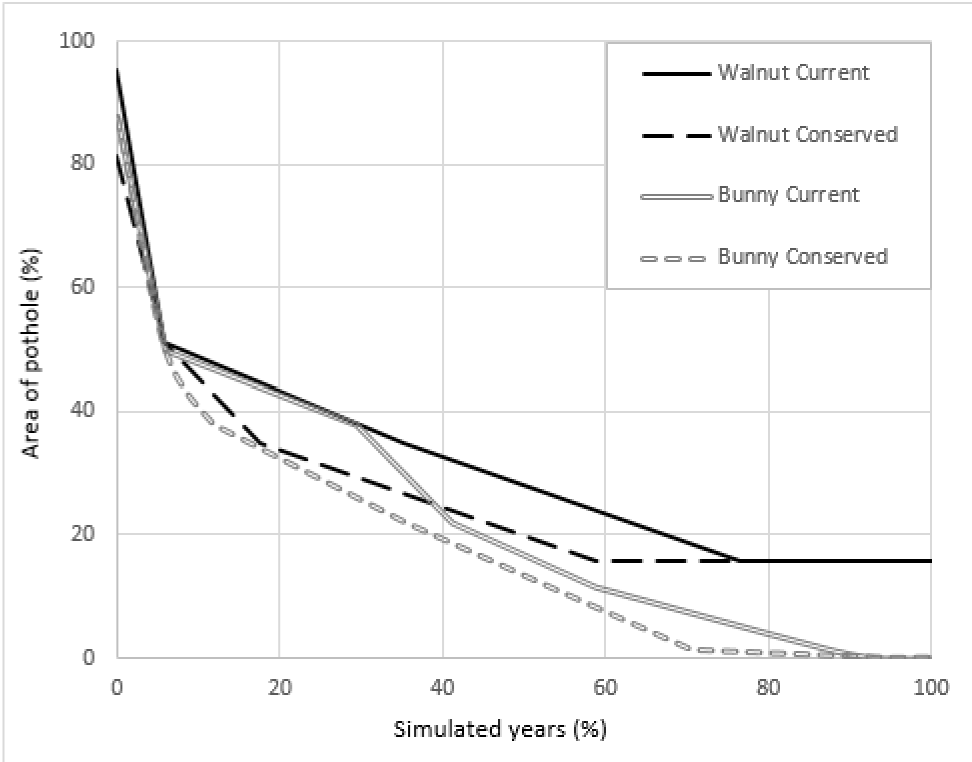



**Figure 5: Area inundated corresponding to maximum depth in each year for all simulation years in the current and conserved scenarios.**

For approximately 6% of the simulated years, the inundation was more than 50% of the total area in all scenarios (Fig. 5). In current scenario, for 50% of the simulated years which is approximately 8 years, 28% and 18% of the total area of the potholes was inundated in Walnut and Bunny potholes, respectively. In the conserved scenario, 20% and 12% area of the Walnut and Bunny potholes was inundated corresponding to 50% of the simulated years, which shows that there was a reduction of approximately 8% and 6% inundated areas in Walnut and Bunny potholes, respectively, when the land management was shifted from current to conserved conditions. Additionally there are also potential logistical benefits to reducing the flooded area, as drown-out represents an adverse condition to the farmer in other respects, like areas that cannot be effectively accessed with machinery and weed development in the areas with no active crop growth.

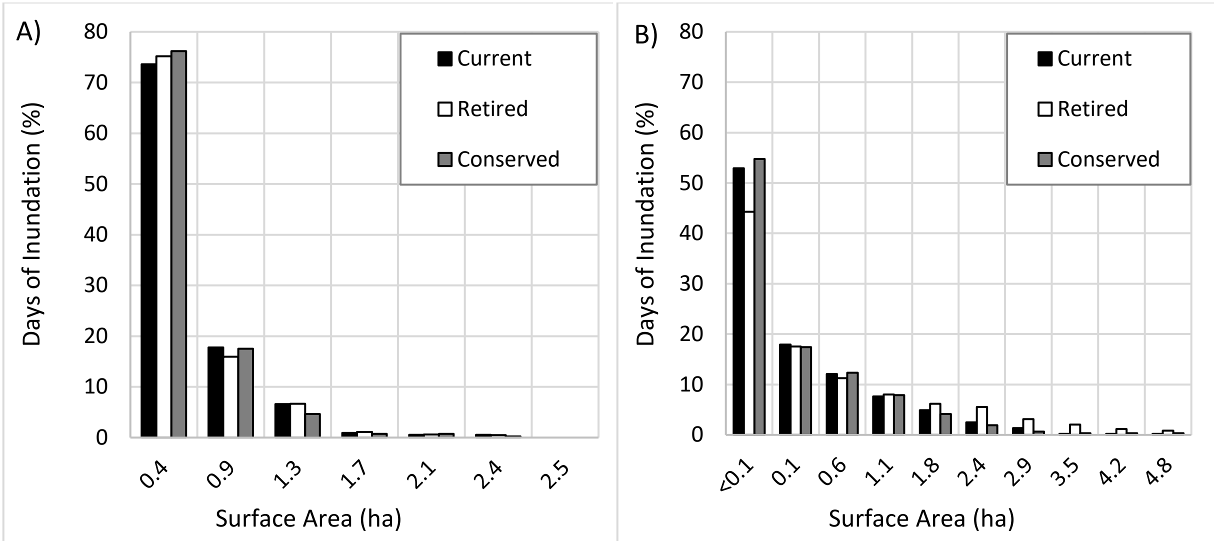



**Figure 6: Intensity of inundation in the potholes A) Walnut and B) Bunny in the current, retired and conserved scenarios**

Figure 6 illustrates the intensity histogram of both potholes for the three scenarios. With this assessment, we observed that Walnut and Bunny potholes have similar hydrological patterns, and both of them will accumulate shallow depths of water, from 0 to 0.1m depth of surface water for approximately 75% and 50% of the inundations in the current scenario for Walnut and Bunny potholes, respectively. The area compromised for agricultural purposes varies in Walnut compared to Bunny, since the later pothole is larger. In addition to the size of the pothole, the number of potholes in a field also affect the area suitable for agricultural production. The higher the number of potholes in a field, the higher the percentage of area unsuitable for crop production.

As predicted, the conversion to retired scenario had a higher impact on water depths in Bunny when compared to Walnut, because of the larger drainage area, and higher reduction in infiltration rate due to disconnection from the drainage system. In the retired scenario, in the occurrence of inundation, the water depth in Walnut was usually between 0 and 0.2 m, and the frequency of inundation decreased as the water depth in the potholes increased, similar to the current scenario. On the other hand, although the pattern of higher occurrence of inundation was similar in both the potholes, water depth varies more in the Bunny pothole with relatively more days of inundation at higher depths.

## 4 Conclusions

Land management scenarios were analyzed to prioritize areas for restoration in a highly modified agricultural landscape. Two pothole features were assessed with the AnnAGNPS model to estimate their hydrological patterns in different management scenarios. Three different management scenarios were developed and simulated by AnnAGNPS including a baseline scenario based on the current management conditions and two alternatives with modified land management. The three scenarios were current (row crop, poor hydrologic condition with surface inlets), retired (row crop, poor hydrologic condition and mixture of grass, weeds, and low-growing brush with no surface inlets) and conserved (row crop, good hydrologic condition with surface inlets).

Simulations indicate that potholes frequently flood during the growing season, which is at odds with their current use, lands designated to agricultural production. Results also show that these features have potential to complicate crop production for farmers early in the season, by interfering in the dates of field operations, and could impact crop yields. Under the current scenario, potholes rarely overflowed, which implies that the features did not directly connect with downstream potholes. When drained, potholes tend to flood less often, however, drained water merges with other sources of flow in the drainage tiles, which suggests an indirect influence and nexus downstream. In the retired scenario, these features were more likely to overflow directly causing effects downstream, although the combined number of overflow events over the entire simulation period was only 5. When tiles in the potholes are disconnected, it is important to consider the use of conservation practices such as conservation tillage, cover cropping, mulching and extended crop rotations to reduce runoff production in the microwatershed. Furthermore, the role of input data quality – including model parameterization as well as driving weather data – on model performance and output uncertainty is another area for further study (Upadhyay et al., 2018).

There are very few studies which have monitored water depth in potholes. We often need long period of observations for making a meaningful conclusion out of the observed data. For potholes, the field data collection is also very difficult and time consuming. In the absence of widespread observational data, a modeling study is a good alternate. This is the first study of its kind, this paper represents a first attempt at a topic that needs further study. The identification and prioritization of these land management scenarios can be used as a policy support tool in discussions of alternative management and investment decisions such as applying conservation reserve program (CRP) and wetlands reserve program (WRP) funding to these features. This approach can also be used to estimate the contributing area and the importance of pothole wetlands to perennial streamflow in watersheds, which is needed to support policy and decision making regarding wetland services.

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