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Evaluation of AnnAGNPS for simulating the inundation of drained and farmed potholes in the Prairie Pothole Region of Iowa

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Abstract

Closed surface depressions, also known as "potholes" play an important role in the hydrologic cycle and provide multiple environmental services including flood mitigation, water quality improvements and wildlife habitat. In the Prairie Pothole Region, which covers approximately 715,000 km2, including parts of three Canadian provinces (Saskatchewan, Manitoba, and Alberta) and five states in the U.S. (Minnesota, Iowa, North and South Dakota, and Montana), these potholes are typically farmed and are a dominant feature in the landscape. In this study, we evaluate the Annualized Agriculture Non-Point Source (AnnAGNPS) model for simulating the inundation behavior of two farmed potholes, termed Bunny and Walnut, in Prairie Pothole Region (PPR) of Iowa. Performance analysis considered the entire growing season (GS), corresponding to the span in which there was observed data, and only days in which water storage (WS) was observed. Results show that AnnAGNPS predicted pothole water depth acceptably but not pothole water volume because of the model's inability to accurately represent the depth-volume relationship of a pothole. When calibrated to depth, Nash-Sutcliffe efficiency (NSE) values were 0.77 and 0.24 in the Walnut pothole and 0.56 and 0.30 in the Bunny pothole, for the GS calibration and validation periods, respectively. Our results demonstrate that the AnnAGNPS model can be used to predict the inundation depth of drained and farmed potholes, which is useful for assessing landscape impacts of these features. Appropriate applications of this model could include impact of inundation on crop yield or simulations of alternative farm management strategies to compare water delivery to the potholes.

Keywords

AnnAGNPS, Closed depressions, Hydrology, Potholes, Prairie pothole region, Drained wetlands

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ABSTRACT

Closed surface depressions, also known as “potholes” play an important role in the hydrologic cycle and provide multiple environmental services including flood mitigation, water quality improvements and wildlife habitat. In the Prairie Pothole Region, which covers approximately 715,000 km^2, including parts of three Canadian provinces (Saskatchewan, Manitoba, and Alberta) and five states in the U.S. (Minnesota, Iowa, North and South Dakota, and Montana), these potholes are typically farmed and are a dominant feature in the landscape. In this study, we evaluate the Annualized Agriculture Non-Point Source (AnnAGNPS) model for simulating the inundation behavior of two farmed potholes, termed Bunny and Walnut, in Prairie Pothole Region (PPR) of Iowa. Performance analysis considered the entire growing season (GS), corresponding to the span in which there was observed data, and only days in which water storage (WS) was observed. Results show that AnnAGNPS predicted pothole water depth acceptably but not pothole water volume because of the model’s inability to accurately represent the depth-volume relationship of a pothole. When calibrated to depth, Nash-Sutcliffe efficiency (NSE) values were 0.77 and 0.24 in the Walnut pothole and 0.56 and 0.30 in the Bunny pothole, for the GS calibration and validation periods, respectively. Our results demonstrate that the AnnAGNPS model can be used to predict the inundation depth of drained and farmed potholes, which is useful for assessing landscape impacts of these features. Appropriate applications of this model could include impact of inundation on crop yield or simulations of alternative farm management strategies to compare water delivery to the potholes.

1. Introduction

Closed surface depressions, often called “potholes”, are a dominant landscape feature in areas where they occur, with unique hydrologic signatures. Potholes are hydrologically closed topographic depressions formed in recently glaciated landscapes, extending from Canada to the United States (Miller et al., 2012), a region known as the Prairie Pothole Region (PPR). These can vary in size from fraction of a hectare to several hectares, and are mostly shallow in depth (0.3 m to 1.5m); these morphological characteristics made these features drainable and farmable (Sloan, 1972). In the highly agricultural regions in which they are found, most potholes are under agricultural management, even though they have been shown to accumulate and retain water during the growing season (Logsdon, 2015; Roth and Capel, 2012). These potholes are classified as palustrine wetlands or wetlands (with a small watershed-wetland area ratio). In Iowa, an estimated 94% of potholes have been significantly altered by the installation of drainage systems (Miller et al., 2012), a factor in Iowa’s significant contribution of high nitrogen contributions to the Gulf of Mexico (Singh et al., 2007). Despite the preponderance of these features in Iowa and other parts of the PPR, relatively little is known about the hydrologic function of these farmed potholes (Schilling and Dinsmore, 2018).

The ecosystem services provided by potholes have been investigated by numerous researchers (De Leon and Smith, 1999; Euliss and Mushet, 1999). However, the literature mostly explores the behavior of potholes in their natural state as seasonal wetlands. As noted above, most of the potholes in agriculturally intense regions have been significantly altered by decades of cultivation and in many cases, by the addition of subsurface drainage. However, it has been observed that, even with artificial drainage, potholes flood periodically, leading them to be classified as ephemeral wetlands (Serrano, 2015). Futhermore, there is evidence showing that these features do play a role in local ecosystems. Murphy and Dinsmore (2015) investigated the diversity and abundance of waterbirds in drained farmed wetlands during spring migration. During the 4-year study they sampled 1913 unique wetlands and tallied 14,968 individuals of 53 waterbird species. Euliss and Mushet (1999) evaluated the influence of intensive agriculture on invertebrate communities of temporary wetlands and found that prairie pothole

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wetlands have been negatively impacted by human activities. Questions remain about the role that these features play in overall watershed and ecosystem function.

The shape of potholes – small and shallow with irregular geometry – combined with their lack of a readily-defined outlet makes their hydrology complex and challenging (Liu and Schwartz, 2011). In the absence of observed data on the hydrology of farmed potholes, watershed models are an alternative to study these features. This type of model is a useful tool in assessment of current conditions as well as in conservation planning of potholes (Rebelo et al., 2015). However, few watershed models have been evaluated for their ability to simulate the hydrologic behavior (hydroperiod and water level rise and fall) of pothole features, particularly those that are farmed and drained. Werner et al. (2016) studied the impact of tile drainage on a seasonal wetland basin in South Dakota using the WETLANDSCAPE model, simulations indicate that the placement of tile drains within the wetland watershed could significantly affect hydrologic function (hydroperiod, mean depth). However, no field data was available to evaluate these simulations. Evenson et al. (2016) used a modified SWAT model to represents the watershed-scale hydrologic effects of geographically isolated wetlands (GIWs) in North Dakota. These simulation results indicated that the modified model replicates streamflow with very good predictive power and an acceptable degree of uncertainty, but the scale of this model makes it not appropriate for in-field evaluation of potholes. Amado et al. (2016) developed a fully integrated, physically-based model (based on HydroGeoSphere) of a drained and farmed wetland complex in the Prairie Pothole Region of Iowa, to investigate their hydrologic connectivity. Tahmasebi Nasab et al. (2017) coupled SWAT with a Puddle Delineation (PD) algorithm to evaluate the impact of depressions on the hydrologic modeling of watersheds in North Dakota and found that at the HRU scale surface runoff initiation was significantly delayed due to the threshold control of depressions. Finally, Tangen and Finocchiaro (2017) recently used a catchment water-balance model to assess the potential effect of subsurface drainage on wetland hydrology and to assess the efficacy of drainage setbacks for mitigating these effects. Results suggest that overland precipitation runoff is an important component of the seasonal water balance of Prairie Pothole Region wetlands, accounting on average for 34% or 45% of the annual or seasonal input volumes, respectively. Most of these previous studies were conducted at the watershed scale rather than simulating the pothole wetland (the wetlands are merely included in the watershed area), partly due to inability of models to represent the potholes accurately and also due to lack of data on hydroperiods and water level rise and fall of individual potholes. The HydroGeoSphere study (Amado et al., 2016), in contrast, simulated pothole hydrology at a small scale, but the complexity of this model makes it less practical for widespread application than a simpler model.

Empirical approaches have also been used, but for identification of potholes in the landscape rather than assessing hydrology. Wu and Lane (2017) used high-resolution LiDAR data and aerial imagery to develop a semi-automated framework for identifying nested hierarchical wetland depressions and delineating their corresponding catchments for improving overland flow simulation and hydrologic connectivity analysis. Previous remote-sensing-based work on the hydrology of prairie wetlands mainly focused on mapping wetland inundation areas (Huang et al., 2014; Vanderhoof et al., 2017) or wetland depressions (McCauley and Anteau, 2014; Wu and Lane, 2016). Thus, there is still a lack of demonstrated simulation of pothole wetland inundation patterns.

Many existing watershed models are not suitable for pothole simulation, because in preparation of the topography data, they will "fill" the depressions to guarantee that runoff will flow from upper to lower areas in the watershed. Another challenge is that potholes are typically fairly small and shallow, and many hydrology models are lumped and not suited for the study of small size features such as these. Therefore, there is a call for treating prairie wetlands and catchments as highly integrated hydrological units because the existence of prairie wetlands depends on lateral inputs of runoff water from their catchments in addition to direct precipitation (Hayashi et al., 2016; Wu and Lane, 2017). One model that may be appropriate for this type of investigation is the Annualized Agriculture Non-Point Source (AnnAGNPS) model. It is a watershed scale, continuous simulation, daily time-step model. AnnAGNPS model has a GIS based wetland component known as AgWET, which can be used for identifying and characterizing topographic depressions (puddles/potholes) during DEM preprocessing, and potential wetland sites can be the first stage in generating watershed-wide management plans (Momm et al., 2016). AnnAGNPS is well-suited to small scale watersheds, and is able to produce satisfactory results for the Midwestern United States (Yuan et al., 2011), and is relatively straightforward to implement. Here, we assume that the pothole could be simulated as a small wetland. To our knowledge, this model has not been evaluated for its ability to simulate the inundation of potholes. Thus, the objective of this study is to evaluate the AnnAGNPS model for simulating the inundation behavior of drained farmed potholes in Prairie Pothole Region (PPR) of Iowa. Specifically, we attempted to simulate the occurrence, depth, and duration of ponding in two potholes within a farm field in Central Iowa, USA.

2. Methods

2.1. Site description

Two potholes located in a single conventional farm field straddling adjacent Hydrologic Unit Code (HUC-12) watersheds in the Prairie Pothole Region of Iowa, known as the Des Moines lobe, just outside of Ames, IA, were monitored for water level (as described below). The pothole positions in relation to the Walnut Creek and Worrell Creek HUC-12 watersheds are presented in Fig. 1.

The field is managed in a corn-soybean rotation with conventional tillage. Detailed records of the management schedule at this site were not available, so we assumed a typical schedule for Story County, Iowa in which the site is located. Table 1 gives the land management schedule we assumed for this project, spanning a total period of two years.

According to the USDA NRCS Soil Survey, the field is 10% Okoboji silt clay loam, 25% Nicollet loam, 7% Harps clay 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; these soils are formed in saturated conditions and could support wetland vegetation species when not drained. Relevant properties for each soil type are presented in Table 2.

The potholes, which are located in two different HUC-12 watersheds (Fig. 1), have different drainage areas and depression volumes, and thus the potential to receive and 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. The locations of the subsurface drainage lines are largely unknown, except where they connect to the surface inlets. Bunny has two surface inlets connected to the drainage system in the west portion of the pothole; the eastern depression in the pothole does not have a surface inlet. The pothole located in the Walnut Creek watershed is referred to as "Walnut" and has a single surface inlet (Fig. 1).

2.2. Observed data

During the growing seasons of 2010 and 2011, a pressure transducer was installed at the bottom of each pothole (Fig. 1), and the depth of ponded water was derived from the hourly transducer data (Logsdon, 2015). Transducers were installed after planting, and removed just prior to harvest. The water depth was monitored for 85 days (12th June to 4th September) in 2010 and 121 days (8th June to 6th October) in 2011 in the Walnut pothole, and 86 days (11th June to 4th September) in 2010 and 121 days (8th June to 6th October) in 2011 in the Bunny

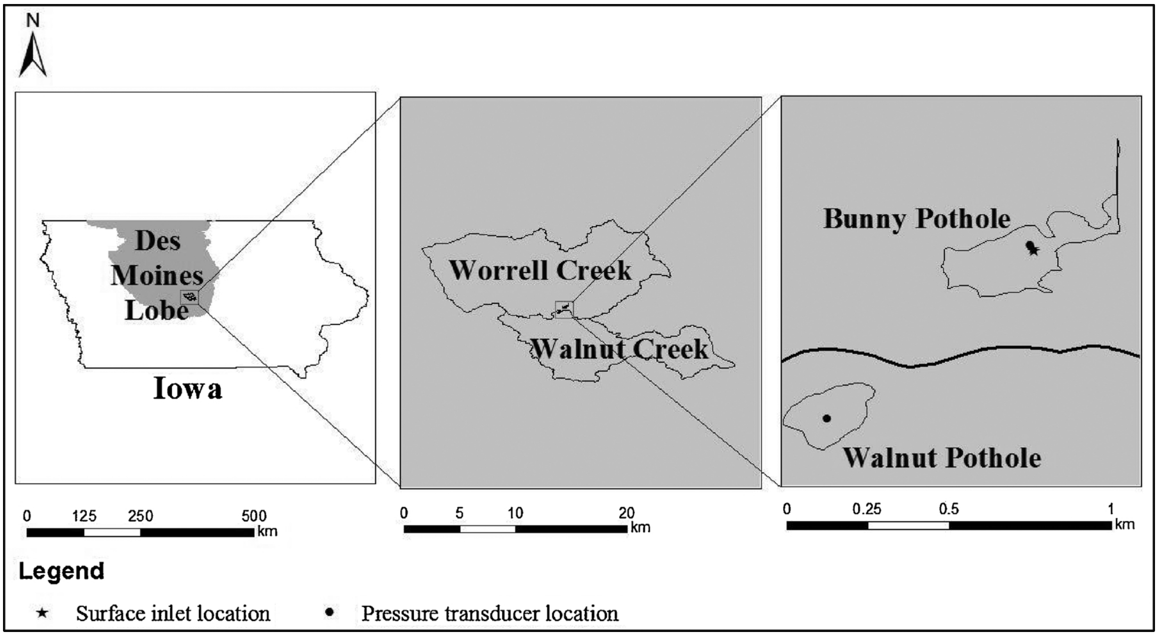

Fig. 1. Locations of Walnut and Bunny potholes in central Iowa, USA.

Table 1
Management practice information for the corn-soybean rotation field.

Date	Operation	Vegetation
Nov. 1	Fertilizer application	
May 1	Cultivator	
May 2	Sprayer pre-emergence	
May 3	Planter	Corn
Jun. 7	Sprayer; post emergence	
Oct. 20	Harvest	
Nov. 1	Chisel plow; disk	
Apr. 28	Disk; tandem light	
May 1	Cultivator	
May 10	Sprayer; pre-emergence	
May 11	Planter; double disk	Soybean
Jun. 7	Sprayer; post emergence	
Aug. 1	Sprayer; insecticide	
Oct. 10	Harvest	

pothole. Additionally, the water depth was monitored for 143 days (20th May to 9th October) in 2016 in both the potholes. However, the 2016 data for Walnut is not included in this study, because additional subsurface drainage was added beneath this pothole in 2015, such that we would not expect the pothole's hydrologic response to be the same as in 2010–11. In order to compare the observed data to the model output, which is generated for the end of each simulated day, the last hourly record in the observed data was considered to be the water depth for that day.

Depth-volume relationships for each pothole were developed from the site topography data in order to translate the observed depth data into estimates of pothole water volume. A high-resolution Digital Elevation Model (DEM) of the site was generated from Light Detection and Ranging (LiDAR) data available from the Iowa LiDAR Consortium (available at archive http://geotree2.geog.uni.edu/lidar/). The raw data in point cloud format, at 1.4 m average bare-earth data spacing, were in a LASer file format (LAS) containing X and Y coordinates (UTM Zone 15N nad83), orthometric elevation Z (NADV88), return level (1, 2, or 12), and intensity (0–255). The DEM was generated according the procedures proposed by Gelder (Gelder, 2015), using ArcGIS 10.4.1 (ESRI, 2016).

To delineate the pothole extent in the DEM, we identified depressional areas using the fill tool in ArcGIS, which identifies depressions in the surface and fills them to facilitate delineation of basins and streams. Pothole extents were then estimated by subtracting the filled DEM from the original DEM. The result of this subtraction is a layer of only the filled areas, which we assumed were potholes (confirmed with a visual check of the results). Pothole volume and surface area were computed for each 0.1 m rise in elevation from the bottom (lowest elevation) of each pothole respectively. Maximum depth, volume, and flooded area for each pothole are given in Table 3. The area and volume data presented for the Bunny pothole is for the union of both depressions together. We assumed that the water surface elevation was the same for both depressions in this pothole. When the measured water depths was below the elevation of the bottom of the shallower depression, the depth-volume relationships for the deeper depression was used; when the measured depth was above the bottom elevation of the shallower depression, volumes for the two depressions were combined based on common elevation intervals of 0.1 m

Table 2
Characteristics of the top soil layer for the soils in the microwatershed*.
*Source: Web Soil Survey; $^{+}$drained.

Soil	Soil texture	Slope (%)	Saturated conductivity (mm/h)	Hydrologic soil group
Nicollet loam^{+}	Loam	1 to 3	5.1 to 50.8	B
Canisteo clay loam, Bemis moraine^{+}	Clay loam	0 to 2	5.1 to 50.8	C
Clarion loam, Bemis moraine	Loam	2 to 6	5.1 to 50.8	B
Harps clay loam, Bemis moraine^{+}	Clay loam	0 to 2	5.1 to 50.8	C
Okoboji silty clay loam^{+}	Silty clay loam	0 to 1	1.5 to 50.8	C
Webster clay loam, Bemis moraine^{+}	Clay loam	0 to 2	1.5 to 50.8	C
Clarion loam, Bemis moraine (moderately eroded)	Loam	6 to 10	5.1 to 50.8	B

Table 3
Depth and storage capacity of the two potholes in the study area.

Pothole	Max Depth, m	Max Area, m^2 (ha)	Max Volume, m^3 (ha-m)
Walnut	0.76	25,441 (2.54)	11,571 (1.15)
Bunny	1.0	50,753 (5.08)	28,068 (2.81)

2.3. AnnAGNPS model setup

We used the AnnAGNPS model, version 5.44. AnnAGNPS is a watershed scale, continuous simulation, daily time-step model designed to simulate water movement and non-point source pollution from agricultural watersheds (Bingner et al., 2015). As such, it 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). In the model, a user-specific CN is an input parameter, and the model modifies those CNs on a daily basis during the running of the model based on tillage operations, soil moisture content, and crop stage. For purposes of runoff generation and soil water storage, the soil profile is divided into two layers. The top 200 mm are used as a tillage layer whose properties can change (bulk density, etc.). The remaining soil profile comprises the second layer whose properties remain static. A daily soil moisture water budget considers applied water (rainfall, irrigation, and snow-melt), runoff, evapotranspiration, and percolation (Bosch et al., 1998). 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 handled using the potential ET, and when there is no water in the wetland, then ET is handled as the amount coming from the soil of the cell. The model also considers precipitation to the wetland as a primary water source.

Preliminary water quality sampling (Serrano, 2015) indicated relatively high sediment and phosphorus concentrations paired with relatively low nitrate concentrations, suggesting these potholes were predominantly filled by overland flow rather than by a rising water table (or in the pothole with surface inlets, backflow from the tile drainage system). Amado et al. (2016) also determined that their study potholes were primarily filled by surface flow rather than water table rise. This suggests that the CN approach is appropriate for modeling the hydrology of the potholes, as it estimates surface and shallow subsurface runoff.

The first step is to assess the watershed topography of the drainage area for each pothole to generate the hydrological units or cells and the reaches between cells. AnnAGNPS considers the cells to be independent units where generated runoff will load into the reaches. A conceptual map of the cell and reach framework of AnnAGNPS is shown in Fig. 2. Development of the cells and reaches is automated through the Topographic Parameterization program (TOPAZ) within AnnAGNPS. As in most watershed models, TOPAZ will fill surface depressions in the DEM. However, in this study, all the load generated by the cells is delivered into the pothole, as the wetland feature is the outlet of the last reach of the pothole watershed. The runoff generated from all the cells in a microwatershed will contribute to the potholes, and therefore we treated each pothole as a subwatershed outlet that can be represented by a wetland. The advanced wetland technology AgWET (AGNPS WETland feature) within AnnAGNPS is used to characterize the pothole in a microwatershed (Momm et al., 2016).

After the cells were generated, they were populated with soil, management, and weather information. The precipitation data is downloaded from Parameter-Elevation Regressions on Independent Slopes Model (PRISM) datasets, PRISM Climate Group gathers climate observations from a wide range of monitoring networks, applies sophisticated quality control measures, and develops spatial climate datasets which can be downloaded at any point location or in gridded format for larger areas. The other weather parameters (maximum temperature, minimum temperature, dew-point temperature, wind velocity, wind direction and solar radiation) data is 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 United States Department of Agriculture (USDA). The STEWARDS weather station used in this assessment was located approximately 5 km from the field site.

The model allows the user to enter the minimum AnnAGNPS cell area that will be treated as a homogeneous unit, and the minimum reach length for uniform surface flow. These mechanisms, denoted as "Critical Source Area" (CSA) and "Minimum Source Channel Length" (MSCL), allow the user to study spatially variable watersheds of various sizes, and the number and division of generated cells is determined by the hydrology patterns suggested by the topography. For each cell, parameter values describing soil, land cover and climate are attributed according to input data described below. Here, CSA and MSCL values were reduced until a detailed stream network was generated. Suitable CSA and MSCL values were selected to generate a small number of cells to characterize the area since the entire drainage area of the potholes was under the same management and comparatively little variability is expected. The CSA selected was 1 ha and the MSCL was 10 m. Because these values correspond to 10% of the default value, we use the term "microwatersheds" to refer to the drainage area of the potholes in this paper. The final delineation resulted in microwatersheds with approximately 9.5 and 40 ha of area for Walnut and Bunny potholes, respectively, and the generation of 13 cells and 6 reaches for Walnut; and 52 cells and 22 reaches for Bunny.

AnnAGNPS computes runoff, percolation, evapotranspiration, lateral subsurface flow, and tile drainage flows separately, then updates daily soil moisture estimates using a water balance approach. When there is rainfall, surface runoff is computed using the CN method (Cronshey et al., 1985). The CN for average conditions (CN_2) is defined by the user, and, based on soil moisture conditions, the value for dry (CN_1) and wet (CN_3) conditions is computed internally by the model, as a function of soil moisture content for that day. The remaining soil moisture can be lost by evapotranspiration (ET) or be added to soil moisture for the next day computation. Reference evapotranspiration (ET_O) is computed on a daily basis with the Penman-Monteith equation, and is then adjusted for crop evapotranspiration (ET) through a crop coefficient procedure (Allen et al., 1998). One limitation of AnnAGNPS is that it considers all the load generated in a given day to be delivered to the outlet. While this may not be reasonable for larger watersheds, given the small scale of the pothole watersheds this may be more consistent with reality (Das et al., 2008).

Subsurface flow consists of the sum of lateral subsurface flow and tile drain flow. This will only be simulated when either an impervious layer or a subsurface tile drainage system is indicated by the user. Because of the limitation that AnnAGNPS assumes surface runoff and subsurface flow produced by the cells will merge before being loaded into the reaches, it is not possible to simulate scenarios with artificially drained cells that represent reality, since the water load in the potholes would increase instead of decrease. To address this limitation, we accounted for the amount of water that is flowing out of the pothole by increasing the infiltration (I) rate.

The AnnAGNPS wetland component models the pothole as a cuboid pool with a fixed surface area, height, and weir properties, as well as constant infiltration throughout its extent. The outflow consists of the water leaving the pothole through a weir, going to the downstream reaches. The user determines the properties of the weir, and its height in relation to the bottom of the pothole, according to observed conditions. This conceptualization, however, does not account for common features of farmed potholes, such as subsurface drainage systems and surface inlets, and a surface area that varies with depth. To address the

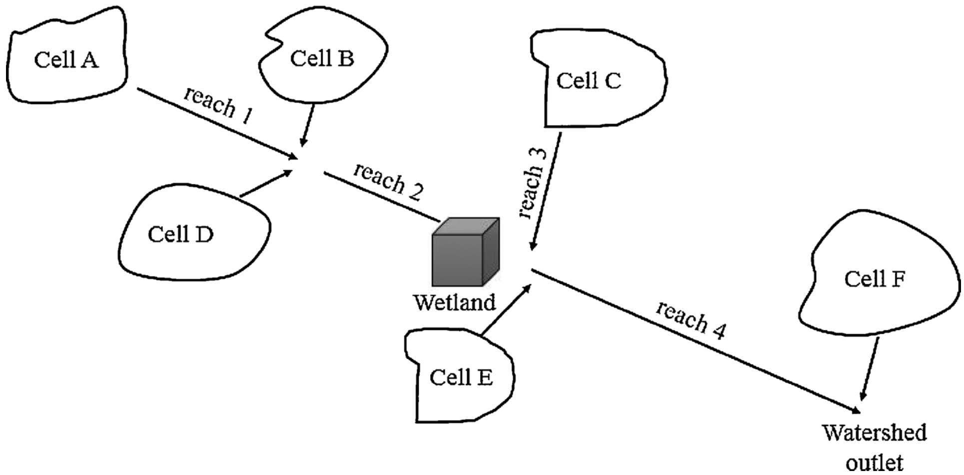

Fig. 2. Cell hydrology simulation in AnnAGNPS. For this simulation, the wetlands are located in the reach before the outlet to capture all the load generated by the watershed.

shape limitation, we simulated depth and volume variations separately in two different model calibrations.

2.4. Model parameterization and calibration

The parameters adjusted during calibration were the CN, which regulates the water load produced by the cells, and therefore the load into the potholes; and the wetland infiltration rate, which influences the rate at which water leaves the system. The initial CN considered in the assessment was the "Straight Row Crop" for poor conditions; from there the CN was adjusted upwards. Evaluation metrics, discussed below, were computed for the delivery of water to the pothole only, and a final calibrated CN was determined based on the best performing CN value.

Once the water load into the potholes was determined by the calibration of the CN, then the water retention time was regulated by calibrating the infiltration rate. The initial infiltration rate was the default value for loam soils, and from there was increased until the model output best matched the drop in observed water depth as the inundation receded.

Because the AnnAGNPS representation of potholes assumes that the depth of potholes is linearly related with its volume, it is not possible to model both depth and volume variations with a single calibration. Therefore, for the assessment of depth and volume, different calibrated values for infiltration rate and CN were determined. In the case of the volume-based simulation, the model output is water depth in the wetland pool, simulated depths were converted to simulated volume by multiplying the model depth output by the model wetland area; observed depths were converted to observed volume using the lidar-based depth-volume relationships described above.

Weir height was set as the maximum depth of the potholes, weir width and maximum water depth comes into play when the pothole in the model overflows. A default value of 10 m was selected for weir width of both the potholes. For the depth-based simulations, wetland area was equivalent to the pothole surface area as determined by using the LiDAR data. For the volume-based simulations, the area was determined by dividing the LiDAR-derived pothole volume by the maximum water depth. Table 4 presents model wetland parameters adopted for the calibrations of depth and volume variations in the potholes.

2.5. Statistical assessment of model performance

In the absence of long-term records of pothole inundation, we used the split sample technique for model calibration and assessment, where we divided the observed data collected in 2010 as one part and the data collected in 2011 as another part. For the Bunny pothole only, we also performed leave-one-out cross-validation using 2010, 2011 and 2016 data. Performance analyses were based on two schemes: one used the entire growing season (GS), corresponding to the span in which there was observed data, with zero values when there was no inundation; the other considered only days in which water storage (WS) was observed or simulated. Furthermore, we restricted the calibration process to exclude (or treat as zero, for the GS analysis) days when observed or simulated depth was below 0.05 m for non-consecutive days. We used four evaluation metrics, each providing different insights into model performance, to evaluate the calibration against the validation data. Table 5 describes these metrics and their interpretation.

Table 4
Wetland properties adopted for the calibrations of depth and volume variations in the potholes.

	Wetland ID	Wetland Area (ha)	Max Water Depth (m)	Weir Width (m)	Weir Height (m)
Depth Calibration	Walnut	3.0	0.76	10	0.76
	Bunny	5.0	1.00	10	1.00
Volume Calibration	Walnut	1.5	0.76	10	0.76
	Bunny	2.8	1.00	10	1.00

3. Results

3.1. Observed data

During the observation period 2010–2011, standing water occurred for 32 days in 2010 and 11 days in 2011 in the Walnut pothole, and 35 days in 2010 and 14 days in 2011 in the Bunny pothole. In 2010, there were four to five inundation events, whereas in 2011 there were only two. These data are also presented in Logsdon, 2015, in which the Walnut and Bunny potholes are referred to as South and North, respectively. During the observation period 2016, standing water occurred for 10 days in the Bunny pothole, over three events.

3.2. Volume simulation

For the volume simulation, calibrated CN values were generally outside the range of published CN values for these land use and soil types, and calibrated infiltration rates were very high. Furthermore, the evaluation metrics indicated that the model performance in validation was poor. We attempted another calibration approach in which we calibrated distinct CN values for cells inside the pothole extent and

Table 5
Selection of evaluation criteria, their corresponding formulation and specific values.

Criterion	References	Mathematical formulation	Range of values	Interpretation
NSE	(Nash and Sutcliffe, 1970)	$NSE = 1 - \left[\frac{(\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim})^2)}{(\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{m-o})^2)}\right]$	(-∞,1]	NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. Values between 0.0 and 1.0 are generally viewed as acceptable levels of performance, with 1 being the optimal value.
PBIAS	(Moriasi et al., 2007)	$PBIAS = \left[\frac{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^{n}(Y_i^{obs})}\right]$	(-∞, ∞)	(PBIAS) measures the average tendency of the simulated data to be larger or smaller than their observed counterparts. The optimal value of PBIAS is 0.0, with low-magnitude values indicating accurate model simulation. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias.
RSR (RMSE-sd)	(Moriasi et al., 2007)	$RMSE - sd = \frac{\sqrt{\frac{\sum_{i=1}^{n}(Y_i^{sim} - Y_i^{obs})^2}{n}}}{STDEV_{obs}}$	[0, ∞)	RSR incorporates the benefits of error index statistics and includes a scaling/normalization factor. The lower RSR, the lower the RMSE, and the better the model simulation performance.
R^2	(Krause et al., 2005)	$R^2 = \left[\frac{(\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{m-o})(Y_i^{sim} - Y_i^{m-s}))}{\sqrt{\sum_{i=1}^{n}(Y_i^{obs} - Y_i^{m-o})^2}\sqrt{\sum_{i=1}^{n}(Y_i^{sim} - Y_i^{m-s})^2}}\right]^2$	[0,1]	R^2 describes how much the observed dispersion is explained by the prediction. A value of zero means no correlation at all whereas a value of 1 means that the dispersion of the prediction is equal to that of the observation.

Y_i^{obs} = observed data, Y_i^{sim} = simulated data, Y_i^{m-o} = mean of observed data, Y_i^{m-s} = mean of simulated data and n = number of events.

those outside the pothole extent, and these results were also poor. For this reason, we conclude that the model is not capable of simulating pothole inundation based on volume. The rest of the results will thus focus in greater detail on the depth-based simulation.

3.3. Depth simulation

3.3.1. Calibrated CN and infiltration rates

The values for the final calibrations of the CN and infiltration according to the depth analysis are illustrated in Tables 6 and 7 for the one-year and two-year calibration, respectively. For both potholes, calibrated values of CN were the same as or close to published values for straight row crop in poor hydrologic condition (81 and 88 for soil groups B and C, respectively) when 2010 and 2011 were validated against each other. Calibrated values of infiltration rate were higher at Bunny, presumably because the observed data reflects the influence of the surface inlets.

For the two-year calibrations at Bunny in which the 2016 data were included, calibrated infiltration rates were similar or identical to those of the one-year calibrations. Calibrated CN values, however, varied by which year was left out, and did not correspond as well to standard CN values for this land use.

Fig. 3 illustrates observed and simulated flooded depth for both potholes for the depth calibration and validation, according to pothole properties, CN and Infiltration values available in Tables 4 and 6, respectively.

3.3.2. Model evaluation

Tables 8 and 9 show the model evaluation metrics for the various models: the two one-year calibrations at both Walnut and Bunny, and the three two-year calibrations at Bunny.

Table 6
CN and infiltration values determined in the depth calibration of the potholes. Parameters are listed by calibration year.

Pothole	Walnut		Bunny	
Calibration Year	2010	2011	2010	2011
Daily infiltration (mm/day)	33	33	79	75
CN Hydr. Soil Group B	81	81	81	82
CN Hydr. Soil Group C	88	88	88	88

Table 7
CN and infiltration values according to depth calibration in the Bunny pothole, calibrated using two years.

Calibration years	2010 and 2016	2011 and 2016	2010 and 2011
Daily infiltration (mm/day)	79	79	79
CN Hydr. Soil Group B	78	71	71
CN Hydr. Soil Group C	85	79	79

Nash-Sutcliff Efficiency values were higher when the entire observation period (GS), including all days in which neither the model nor the observations indicated water in the pothole, than when the data were restricted to only days in which there was water observed and/or simulated (WS). For the one-year calibrations, the validation NSEs were all greater than zero, and in some cases, greater than 0.5 for GS data. Using WS data only, several NSE values were less than zero. The differences between the GS and WS results suggest that the model is better able to simulate when there is or is not standing water in the pothole than it is at precisely simulating how deep the standing water is. For the two-year calibrations at Bunny, that same trend holds, but the NSE-GS results tend to be lower. Moriasi et al. (2007) suggest NSE > 0.5 for satisfactory model performance at monthly streamflow simulation. While pothole depth and streamflow are quite different, using this benchmark we would conclude the model performance is often unsatisfactory at depth simulations when using NSE as the metric, depending on the calibration and validation data.

RSR values in validation ranged from 0.42 to 0.87. In the case of RSE, higher values indicate lesser model performance. Unlike with NSE, the RSR-WS values were lower and thus more favorable than the RSR-GS values. Using the streamflow recommendations of Moriasi et al. (2007) that RSR ≤0.7 is satisfactory, and RSR < 0.5 is very good, we would conclude that when used to simulate non-zero inundation depths (WS), the model performance is very good, whereas it is often satisfactory when considering all the data (GS).

PBIAS values, representing a percentage over- or underestimation, indicate that the model tends to underestimate pothole water depth. Depending on the calibration and validation data used, PBIAS values

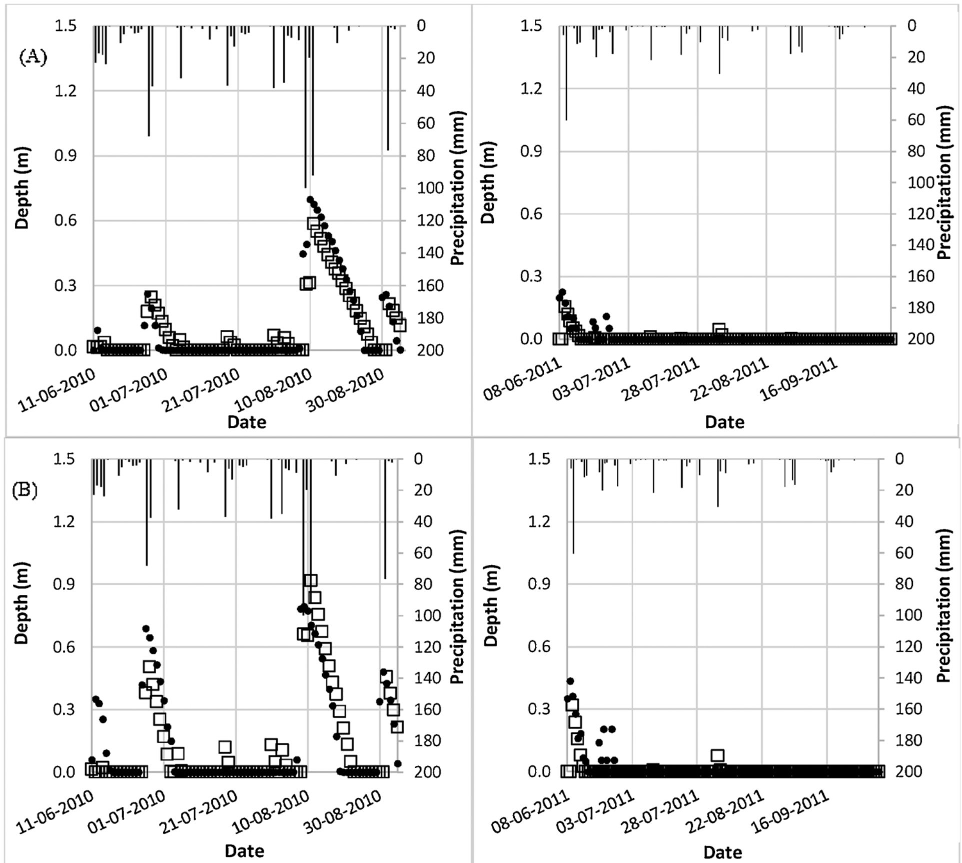

Fig. 3. Simulation of water depth variation (2010–calibration and 2011–validation) in Walnut (A) and Bunny (B) potholes during the growing season.

Table 8
Simulation performance of potholes considering the NSE, PBIAS, RSR and R^2 efficiency models for the whole growing season (GS) and for days in which water storage (WS) was observed.

	Calibration				Validation			
	Walnut		Bunny		Walnut		Bunny	
	2010	2011	2010	2011	2011	2010	2011	2010
NSE − GS	0.77	0.24	0.56	0.31	0.24	0.77	0.30	0.55
NSE − WS	0.71	−0.41	0.34	−0.47	−0.41	0.71	−0.49	0.34
PBIAS − GS	11.41	54.15	15.58	60.34	54.15	11.41	65.22	9.54
PBIAS − WS	11.41	54.15	15.58	60.34	54.15	11.41	65.22	9.54
RSR − GS	0.48	0.87	0.66	0.83	0.87	0.48	0.84	0.67
RSR − WS	0.42	0.44	0.60	0.45	0.44	0.42	0.46	0.61
R^2 − GS	0.79	0.27	0.60	0.34	0.27	0.79	0.34	0.59
R^2 − WS	0.73	0.05	0.46	0.14	0.05	0.73	0.16	0.45

NSE- Nash-Sutcliffe Efficiency, PBIAS- Percent bias, RSR- Ratio of the root mean square error, R^2- Coefficient of determination, GS- Growing season, WS- Water storage.

Table 9
Simulation performance of the Bunny pothole considering the NSE, PBIAS, RSR and R^2 efficiency models for the whole growing season (GS) and for days in which water storage (WS) was observed.

	Calibration			Validation		
	2010 and 2016	2011 and 2016	2010 and 2011	2011	2010	2016
NSE − GS	0.53	0.23	0.51	0.28	0.46	0.24
NSE − WS	0.28	−0.39	0.04	−0.87	0.05	−0.16
PBIAS − GS	0.89	21.16	39.57	71.64	31.27	−31.71
PBIAS − WS	0.89	21.16	39.57	71.64	31.27	−31.71
RSR − GS	0.69	0.88	0.70	0.85	0.73	0.87
RSR − WS	0.49	0.44	0.52	0.48	0.68	0.42
R2 − GS	0.56	0.31	0.55	0.34	0.52	0.40
R2 − WS	0.37	0.06	0.38	0.15	0.36	0.12

NSE- Nash-Sutcliffe Efficiency, PBIAS- Percent bias, RSR- Ratio of the root mean square error, R^2- Coefficient of determination, GS- Growing season, WS- Water storage.

were frequently greater in magnitude than the ± 0.25 recommended for satisfactory model performance, and always positive, indicating observed values higher than the simulated values. Using the streamflow modeling criterion we would conclude that the model in general has unsatisfactory underestimation of ponded depth.

However, given the sparser nature of pothole inundation data, it is reasonable to use less stringent criteria for determining satisfactory model performance than those for streamflow modeling. On the whole, we conclude that AnnAGNPS has potential in this application, but will require further study to determine when and where modeling failure occur. Some of the reasons for lower model performance are known; for one, given the interannual variability in precipitation, and the very small size of the watersheds being simulated, some years generate standing water in the potholes more frequently than others, and indeed in some years there may be only one or two occasions where the potholes fill with any observable standing water. This makes it difficult to generate a sufficient dataset for model calibration and validation.

There are also difference between potholes; in general the AnnAGNPS model gives better performance in the simulation of Walnut compared to Bunny. The probable reason for the better performance in the simulation of Walnut pothole is the presence of just one surface inlet, which allowed it to be modeled more precisely through infiltration. Bunny pothole has two surface inlets through which water leaves the pothole. Another cause might be the size of the microwatersheds, and the shape of the potholes. Walnut microwatershed was smaller than Bunny microwatershed, and the water load coming to Walnut is lower than Bunny; given the model's tendency to underestimate water depth, this underestimation may be more pronounced when the watershed and pothole are larger.

An example of AnnAGNPS performance was assessed in a 45-month simulation in two Kansas watersheds. AnnAGNPS underestimated the extreme runoff generation in comparison to the observed data and another watershed model (Parajuli et al., 2009). This situation was also observed in another study in Ontario, which investigated the occurrence of high peaks of runoff generation (Das et al., 2008). In this study, 2010 was a wet year with recorded rainfall of 1214 mm, which is 42.7% more than the average annual rainfall (850.9 mm, 1992–2016). Given the evidence that AnnAGNPS underpredicts runoff under very wet conditions, our assessment of the model performance may be complicated by the fact that our dataset, particularly WS, is dominated by wet conditions because those are the more likely cases for the pothole to fill to a substantial depth.

In general, the model is able to capture the occurrence of ponding, as well as the initial depth of ponding in the potholes. The model simulated the duration of ponding better than the depth, it is likely due to the observed data reflecting the influence of short-duration, high-intensity events, whereas the model operates on a daily basis and will assume less intense rainfall events over a 24-h period, and potentially divides the rainfalls across multiple days when a single event lasts more than a day.

Taken in total, we conclude that AnnAGNPS is a useful tool for the determination of inundation and water-depth in the potholes, but further research is necessary for a better estimation of the runoff generation from the microwatershed.

4. Conclusions

AnnAGNPS was capable of simulating inundation of the drained and farmed potholes in this study, when comparing model output of ponded depth to observations of the same, but was not capable of simulating potholes on a volume basis. This suggests that the model may be used for applications such as assessing occurrence of crop failures associated with standing water, or investigating agricultural management strategies that would reduce potholes' tendency to flood. The model cannot, however, be readily used in applications such as assessing downstream streamflow effects, or estimating pollutant loads from spillover or drainage fluxes, which rely on accurate estimates of water volumes. In such cases, water volumes may be estimated by simulating the pothole depth, and using terrain data to convert pothole depth to water volume. To expand model application to volume-based scenarios, further development of the AnnAGNPS wetland component could include expanded options for wetland or pothole topography, so that the depth-volume relationship might better represent site characteristics of the pothole. This may allow for simultaneous simulation of both depth and volume, with a single calibration.

The variable performance of the model with different calibration data and for different evaluation metrics indicates that longer-term datasets will be beneficial in understanding the model's limitations. There are a number of factors influencing model performance, many of which are areas for further study. For example, some of our observed data and the work of others eg. Amado et al. (2016) suggests a need to more effectively distinguish between surface runoff and shallow subsurface flow; both appear to be influential in filling potholes, but the percentages of ponded water deriving from these two pathways, with different travel times, is not known. Likewise, the role of subsurface drainage, and the variability of drainage conditions − including extensively drained with multiple surface inlets, extensively drained without surface inlets, somewhat drained with older drainage lines nearby but perhaps not directly underneath the pothole, and not drained at all − are largely unknown in terms of their effect on filling and draining the pothole. Accurately modeling unknown pathways is a significant challenge.

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. Finally, further research is needed to expand the simulations to other potholes, and in other locations, to determine if similar trends are observed.

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