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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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A B S T R A C T

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