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Modeling nutrient removal using watershed-scale implementation of the two-stage ditch

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ABSTRACT

Western Lake Erie Basin (WLEB) is the most intensively farmed region of the Great Lakes. Because of the flat topography and poorly-drained soils many farmers rely on drainage management practices (e.g., subsurface tile drainage, ditch channelization) to maintain productive agriculture. However, these practices also facilitate the delivery of excess nutrients and sediments to Lake Erie, which have been linked to recurring harmful algal blooms (HABs) and associated environmental degradation. Implementation of inset floodplains in formerly channelized waterways via the two-stage ditch can improve water quality but the efficacy has been tested using only implementation in short reaches. Watershed models are critical tools for assessing watershed-scale implementation and as such can guide effective management. We evaluated the effectiveness of the two-stage ditch in improving water quality in the River Raisin Watershed (RRW), a major subbasin in the WLEB, combining empirical measurements for nutrient reductions from two-stage ditches across the Midwest with output from a Soil Water Assessment Tool (SWAT) model. We modeled two-stage implementation in 25, 50, and 100% of headwater reaches in the RRW, and found that the practice could reduce total annual NO_3^--N export by 2, 5 and 10%, respectively. The two-stage was even more effective at reducing total phosphorus (TP) export, which was reduced by 12, 20 and 31%, respectively. Compared to other conservation practices, nutrient reduction efficiency for the two-stage ditch was good, both in terms of percent load reduction and cost, but watershed-scale adoption will be required in order to achieve significant nutrient reductions as called for by policymakers.
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1. Introduction

Western Lake Erie Basin (WLEB) is a highly productive and intensively farmed area of the Midwestern US cornbelt with over 70% of the region in row-crop agriculture. Much of this region is extremely flat (<2% slopes) with poorly-drained soils that can make it difficult or impossible for farmers to work these lands during the wetter spring planting and fall harvest seasons. These lands are also susceptible to surface pooling of water during the growing season, which can severely impact crop growth and production. Consequently, many farmers in the region depend on practices that facilitate drainage (e.g., subsurface tile drainage, channelized ditches and streams) to foster a more reliable and economically viable production of agricultural commodities. However, these drainage practices physically link agricultural fields to surface waters where excess inorganic nitrogen (N), phosphorus (P), and sediment can be rapidly transported to adjacent waterways (e.g., streams and ditches; Cooper, 1993; Vidon et al., 2012). Recent increases in seasonal harmful algal blooms (HABs) in Western Lake Erie (Conroy et al., 2014; Michalak et al., 2013) have been attributed

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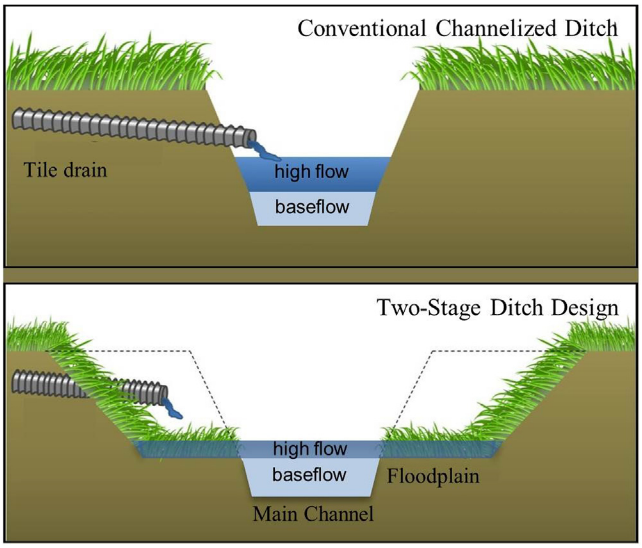

Fig. 1. Top: Typical cross section of a conventional trapezoidal ditch. Bottom: Typical cross section of a two-stage ditch.

to agricultural non-point sources (NPS) of excess nutrients and sediments from the surrounding agricultural watersheds (Dolan and McGunagle, 2005). There is a need for watershed-scale implementation of conservation practices that effectively manage excess nutrients and sediment (Carpenter et al., 1998; Jackson-Smith et al., 2010), while meeting the drainage needs of the agricultural community (Garcia et al., 2016).

The two-stage ditch is a conservation practice that has gained popularity as an alternative to the traditional trapezoidal ditch design. The two-stage ditch differs from channelized ditches in that it consists of both a main channel that conveys water during baseflow conditions, and an inset vegetated floodplain (the "2nd stage"; Fig. 1) that is inundated by surface water during higher flows (e.g., storms), thereby slowing water velocities and reducing bank stress and erosion potential (Powell et al., 2007a). Unlike the traditional trapezoidal ditch, a two-stage ditch requires little routine maintenance as was shown in 7 two-stage ditches in OH, IN, and MI, 3–10 years after construction (D'Ambrosio et al., 2015). A two-stage ditch is wider than a trapezoidal ditch due to the addition of the inset floodplain, which can be a concern for farmers. However, if the inset floodplain is constructed using land formerly in vegetated buffer strips, little or no land will be removed from agricultural production when a two-stage ditches is constructed.

In addition to improving channel stability, the two-stage ditch also provides increased bioreactive surface area and longer water residence times, which improve nutrient and sediment removal from both surface and subsurface sources. In tile-drained landscapes with trapezoidal ditches, nutrient-rich subsurface water is conveyed through tile drains that minimize interaction with soils and vegetation (Ducros and Joyce, 2003; Fennessy and Cronk, 1997). Conversely, when discharging to a two-stage ditch, water from tile drains can interact with soil and vegetation on the two-stage floodplains before entering the main channel. Recent reach-scale monitoring of two-stage ditch implementations has suggested that short reaches of the two-stage (<1 km) can improve water quality (Davis et al., 2015; Mahl et al., 2015; Roley et al., 2012a,b, 2014, 2016). For example, the two-stage ditch increased NO_3^--N removal via denitrification by 2–24 times relative to denitrification in channelized ditches (Mahl et al., 2015). The dominant mechanism for permanent NO_3^--N removal is denitrification, as other mechanisms such as plant assimilation provide temporary retention (Roley et al., 2012b; Vought et al., 1994). Using NO_3^--N loading rates and nutrient spiraling theory, Roley et al. (2012a) scaled denitrification rates and suggested that 1 km of two-stage could decrease NO_3^--N loads by up to 20%, even when NO_3^--N concentrations were high (Roley et al., 2012a). Furthermore, strong relationships between stream NO_3^--N and denitrification rates in the two-stage ditches are useful for predicting effects of the two-stage at larger spatial scales (Mahl et al., 2015).

Inundation of two-stage floodplains also decreases water velocity (Powell et al., 2007b), which can increase deposition of suspended sediment and total phosphorus (TP) associated with these particles (Grayson et al., 1996). Net reductions in water column soluble reactive P (SRP) concentrations were observed during both baseflow and storm flow conditions, but TP reductions could not be calculated during floodplain inundation due to limited sample collection during storms (Davis et al., 2015; Mahl et al., 2015). However, using permanently deployed datasondes, reductions in water column turbidity were documented at 8 of 9 Midwestern two-stage sites (Davis et al., 2015; Mahl et al., 2015). Given that water column turbidity has been correlated with TP and total suspended solids (TSS; Horsburgh et al., 2010), turbidity reductions associated with the two-stage ditch could be used to estimate reductions in TSS and TP export.

Reach-scale sediment and nutrient reductions achieved with the two-stage ditch could mitigate downstream nutrient and sediment export to sensitive downstream ecosystems like Western Lake Erie. However, unlike many other conservation practices (Muenich et al., 2016), the potential water quality benefits of the two-stage ditch have never been assessed at a watershed scale. Quantifying how the two-stage ditch could reduce nutrient export throughout a watershed with different levels of implementation (e.g., 25, 50, or 100% of current ditches) will be critical in demonstrating the potential contribution this practice could make toward addressing regional water quality issues. For instance, recurring HABs in the WLEB represents a regional water quality challenge that is being tackled through high profile government mandates. The US and Canada recently adopted targets to reduce phosphorus entering Lake Erie by 40%, a mandate stipulated in the 2012 Great Lakes Water Quality Agreement (GLWQA; International Joint Commission, 2012). The GLWQA also encouraged targeted implementation of a variety of agricultural conservation practices in order to achieve this reduction. The two-stage ditch is an in-stream conservation practice that could complement the many infield and edge-of-field practices that are being recommended and thus contribute to achieving these nutrient reduction goals for WLEB. However, it remains unclear how many km of streams and ditches would need to be modified in order to achieve these management outcomes.

Simulation models are critical tools for guiding and assessing watershed-scale conservation and management (Fohrer et al., 2002; Francesconi et al., 2016; Schilling, 2008; Van Rompaey et al., 2001), with models being used to determine preferred conservation practice scenarios for application in agricultural watersheds (Maringanti et al., 2009). Here we evaluate the watershed-scale efficacy of the two-stage ditch in improving water quality in the WLEB using a combination of empirical measurements for nutrient reductions applied to output from the most commonly used model for agricultural watersheds, the Soil Water Assessment Tool (SWAT, Arnold et al., 1998).

We used a fine resolution SWAT model (Yen et al., 2016) created for the WLEB that provided optimal resolution for inserting reach-scale conservation practices such as the two-stage ditch into a large agricultural watershed. We focused on one of the major subbasins of WLEB, the River Raisin Watershed (RRW) because analyzing the efficacy of conservation practices in the full WLEB SWAT was prohibitively and computationally intensive, and the RRW provided a sensible alternative that is still large (2736 km^2) and predominantly agricultural (>75%). First, we developed predictive relationships for

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