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Impact of a two-stage ditch on channel water quality

Andi Hodaj[a,*], Laura C. Bowling[b], Jane R. Frankenberger[a], Indrajeet Chaubey[a]

[a] Agricultural and Biological Engineering Department, Purdue University, 225 S University St., West Lafayette IN 47907, United States
[b] Agronomy Department, Purdue University, 915 West State St., West Lafayette, IN 47907, United States

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ABSTRACT

A two-stage ditch involves modifications of a conventional, trapezoidal drainage ditch to better replicate the features of a natural stream through the addition of adjacent floodplains or benches. Previous research in Indiana and Ohio has shown that two-stage ditches offer the potential to reduce sediment load and extend the interaction time between water, bench vegetation, and bench soil allowing larger uptake of nutrients by the vegetation and increasing the denitrification rates. A two-stage ditch was constructed that drains an area of approximately 267 ha of farmland used for corn and soybean production. Discharge, nitrate-N (NO3), total phosphorus (TP), soluble reactive phosphorus (SRP) and total suspended sediment (TSS) were monitored in the two-stage ditch and a control reach immediately upstream. The two-stage ditch was found to significantly decrease TP, SRP and TSS concentrations and loads. Although the two-stage ditch decreased NO_3 concentrations significantly, it did not have a significant impact on NO3 loads. More specifically, the two-stage ditch reduced the loads of TP by 40%, SRP by 11% and TSS by 22–40% depending on the stage of vegetation establishment on its floodplain benches, compared to an increase in load of 78%, 2% and 1%, respectively in the control reach.

1. Introduction

Agricultural activities are a major source of nitrogen (N) and phosphorus (P) to aquatic systems (Alexander et al., 2007; Baker and Richards, 2002; Carpenter et al., 1998). Since the Midwestern part of the United States is a major agricultural area, the nonpoint source runoff from this region affects not only local rivers and lakes but is also a major contributor of N and P to the Gulf of Mexico and the Great Lakes, where excess transport of these nutrients fuels seasonal hypoxic zones (Turner and Rabalais, 2003).

Agricultural drainage ditches are the main conduit of these nutrients to downstream water bodies (Sharpley et al., 2007). Whether natural channels that have been dredged and managed as ditches or artificially constructed channels, these ditches help convey and remove the excess water from poorly drained agricultural land in the Midwest in order to enhance crop production. In fields that are not artificially drained through tile drains, nutrients such as P and N are conveyed to ditches almost exclusively via surface runoff and/or erosion, both in dissolved form and adsorbed to sediment particles. Natural or constructed vegetated buffers may help reduce the amount of nutrients delivered to ditches by slowing and infiltrating the runoff and allowing for more plant uptake and settling of sediment-bound nutrients (Palone and Todd, 1998). In contrast, in subsurface drained fields subsurface runoff travels into the ditches without going through the vegetated buffers, resulting in the transport of nutrients directly to the aquatic system (Greenan et al., 2006).

Several mechanisms within agricultural streams and ditches can affect the transport of nutrients to downstream water bodies. Nitrate load can be reduced in three ways: uptake by organisms, utilization by plants, and through denitrification, in which NO3 is transformed into N gas by denitrifying bacteria under anaerobic conditions (Bernot and Dodds, 2005). For P, the three reduction mechanisms are uptake by organisms, utilization by plants, and adsorption on the stream sediment (Needelman et al., 2007). Both nutrients can also be temporarily stored in water in interstitial spaces and pools.

Several studies have found an increase in TP concentrations from upstream to downstream in agricultural ditches (Dorioz et al., 1998; Hill, 1982; House and Warwick, 1998). Higher discharge during flow events increases the resuspension of particulate P and helps transport it further downstream (Svendsen et al., 1995). In contrast, McDowell and Sharpley (2001) observed dissolved P retention during high flow storm events in an agricultural stream. They observed

* Corresponding author at: 3618 N Hoyne Ave., #3, Chicago, IL 60618, United States.
E-mail addresses: ahodaj@purdue.edu, hodajandi@gmail.com (A. Hodaj), bowling@purdue.edu (L.C. Bowling), frankenb@purdue.edu (J.R. Frankenberger), ichaubey@purdue.edu (I. Chaubey).

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that average dissolved P concentrations were higher at the watershed outlet than in the headwaters during baseflow while the inverse occurred during high flow events.

For NO3, various factors affect its retention in streams including oxygen concentration, organic matter content, residence time and discharge. High levels of dissolved oxygen increase the nitrification process which converts ammonia to NO3 in stream benthos and decreases denitrification rates (Bernot and Dodds, 2005). The organic matter content of benthic sediment enhances the denitrification process (Bernot and Dodds, 2005; Roley et al., 2012) while water residence time or, travel time, affects the amount of time that N has to interact with the water-benthos system and for the retention mechanisms to be effective. Stream discharge determines the load of N transported through the stream and in turn affects the retention mechanism's success. Increased stream velocity can also cause scouring which reduces the impact of the retention mechanisms in a stream (Bernot and Dodds, 2005). Thus, practices that affect oxygen concentration, organic matter content, residence time and discharge will have a direct impact on the ability of ditches to process, retain and release N (Alexander et al., 2009; Arango et al., 2007).

Ditch management practices can also have a significant effect on these systems' ability to retain or export nutrients. The most common management practice is periodic dredging to increase conveyance capacity and avoid flooding of the surrounding fields. Previous research has shown that immediately after dredging, ditches exhibit reduced capacity to retain and reduce the nutrient loads in the water column (Smith and Pappas, 2007; Smith et al., 2006). There could be several reasons for this, including the removal of vegetation and other biota in the ditch that can uptake nutrients (Smith and Huang, 2010) and the changes in the hydrology of the channel with increased stream velocities and decreased residence times (Sharpley et al., 2007).

An in-stream management practice that has been used in states like Indiana, Ohio, Michigan, and Minnesota in recent years is the two-stage ditch. The practice has been promoted mainly as an alternative management practice for agricultural drainage ditches that enhances the conveyance capacity of the ditch, while requiring little maintenance and improving ditch bank stability (Powell et al., 2007b). Early research on two-stage ditches focused on their stability, through geomorphic studies (D'Ambrosio et al., 2015; Biske, 2007; Kallio et al., 2010; Powell et al., 2007a) and/or denitrification rates on the benches of the two-stage ditch. The two-stage ditches that have been surveyed so far have been stable and have required little or no maintenance (D'Ambrosio et al., 2015; Biske, 2007; Kallio et al., 2010; Powell et al., 2007a). This supports the use of the two-stage as a reliable practice that provides stability for the drainage system.

The role of two-stage ditches in reducing nutrient loads is less certain. Although denitrification rates are generally enhanced, given the limited area of the benches and the magnitude of denitrification rates, denitrification alone may not be sufficient to remove a large percentage of NO3 from the water (Powell and Bouchard, 2010; Roley et al., 2012). Powell and Bouchard (2010) observed that denitrification rates increased significantly (almost double) in the benches of the two-stage ditch compared with the side-slopes of the traditional ditch. The accumulation of organic matter on the benches of the two-stage ditch appears to enhance the denitrification rates on these benches (Roley et al., 2012). The retention time of the water on or in the benches might be more important than the denitrification process. Increased retention time enhances plant (and other biotic and abiotic) uptake of the nutrients which along with increased denitrification rates is necessary for the two-stage system to have a practical impact in reducing NO3 loads.

NO3 concentrations were reduced in three out of ten two-stage ditches studied in Indiana, Michigan and Ohio with no significant reductions in loads (Davis et al., 2015; Mahl et al., 2015). Reductions were also found in Turbidity and SRP concentrations for all four ditches in the Davis et al. (2015) study, when compared to a reference ditch, while TSS and TP concentrations were reduced in only one of the ditches that the lowest bench height.

The main objective of this study was to quantify the impact of a newly-constructed two stage ditch on concentration and load of TSS, NO3, SRP and TP in the channel water. The two-stage and an upstream control reach were compared for their ability to reduce nutrient and sediment levels. The hypothesis was that the two-stage ditch would reduce the mass transport of sediments and nutrients downstream relative to the mass transport through the control reach or that the increase in sediment and nutrient loads through the two-stage ditch would be less than the increase that occurs through the upstream control reach.

2. Methods

2.1. Site characteristics

The two-stage ditch was constructed on September 26, 2012 at the Purdue University Throckmorton Purdue Agriculture Center (TPAC), in north-central Indiana (86.898 W, 40.299 N) (Fig. 1). Benches were constructed on both sides of the treatment reach, with an average width of 3 m and a design elevation approximately 0.38 m above the channel bottom (Fig. 2). The design capacity was calculated for a two-year storm event at 10 m^3/sec and flow velocity of 0.06 m/sec. Wetted area and perimeter were 6.6 m^2 and 21.7 m respectively for a channel depth of 1.13m. A 183 m control reach was upstream of the 200 m treatment reach, which drains an area of approximately 2.7 km^2 of farmland (all the area that drains to the downstream cross-section of the two-stage ditch) used mainly for corn and soybean production. Mean annual precipitation in the area is about 914 mm (36 inches), and mean annual temperature is about 11 °C (51 °F) according to 20 years of data (1986–2014) from GHCND:USC00124715 (Lafayette 8 S, IN US) of the National Climatic Data Center (Menne et al., 2012). Monitoring occurred from January 2012–September 2015. During the monitoring period, there were five months with mean temperatures below 0 °C, January of 2012, 2013, 2014 and February and December of 2013.

2.2. Monitoring setup

To determine the two-stage ditch effectiveness, flow and water quality were monitored upstream and downstream of both the control reach and the treatment reach. Three monitoring stations were established, CS1, CS2, and CS3 (Fig. 1). Each of these stations consists of one ISCO 3700 Standard auto sampler, one Campbell Scientific CS410 shaft encoder that records continuous water level in each cross-section, a CR1000 Campbell Scientific data logger, a radio and antenna for remote communication. Two multi-parameter YSI sondes were installed upstream and downstream of the two-stage reach that continuously measure water quality parameters every 15 min including: temperature, turbidity, dissolved oxygen and chlorophyll concentration. Turbidity values were used to estimate TSS concentrations at each of the cross-sections. Base flow was monitored using grab samples, while the auto sampler was used to sample storm events. To efficiently utilize the 24-bottle capacity of the typical auto sampler over hydrographs of various magnitudes, the autosampler was triggered to take samples five times during the rising limb of a hydrograph, using the equation derived from Gall et al. (2010) for sampling during the recession limb of the hydrograph. To identify the water level at which to start sampling for storm events, baseflow stage was separated from storm stage using the Web-based Hydrograph Analysis Tool (WHAT) (Engel