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BEYOND THE FIELD: A LOOK AT AGRICULTURAL DITCH FLOODPLAINS AS A WATER QUALITY BMP

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ABSTRACT Agricultural fields, subsurface drainage, and a network of modified headwater systems dominate the landscape in the Midwest region of the United States. These systems are often the main conduits that export sediment and nutrients downstream, but very little is known about how these systems function. While most agricultural Best Management Practices (BMPs) focus on landscape measures to reduce sediment loss and water pollution little research has been performed on in-stream processes and channel system floodplains as agricultural BMPs. An important step in quantifying nutrient reduction capacities on floodplains is to predict discharges occurring on floodplains. This paper evaluates methods to predict the recurrence interval of discharges at ungaged sites and the annual exceedances of different discharge thresholds. Also presented is a study to evaluate the benefits of modifying channels to two-stage geometries that provide connection to floodplains and more bank storage. Preliminary results indicate that benches (small floodplains) should be located at elevations associated with about 25-35% of the 2-year discharge and they will usually flood about 10-60 days annually. Nitrate-N removal, in systems with flooded width ratios of 4 to 5 times the bankfull width, might be 5-20% of exports from fields if the treatment area (surface of the benches and inset channel) is about 1% of the watershed area. Results of this study are being used to develop a tool that quantifies the reduction in nitrate exports associated with different floodplain geometries and linear extent of the floodplains.

Keywords: Agricultural ditches, Benches, Flood frequency, Annual exceedances, Nitrate removal.

INTRODUCTION A water quality issue of particular concern has been the export of nutrients, pesticides, and sediment to the Great Lakes and the Gulf of Mexico. Agricultural drainage in the upper Midwest and other regions of the United States has been recognized as a major source of excess nitrogen (N) in these aquatic ecosystems (Turner and Rabalais, 2003). Intensely farmed landscapes export excess nutrients and sediments to streams, which leads to downstream turbidity and eutrophication problems, as well as potential community shifts to toxic species of algae, reduced fish and crustacean populations, human health risks, and aesthetic problems (Nolan and Stoner, 2000). Habitat modification, largely related to drainage improvement, is now the leading cause of aquatic life use impairment in Ohio.

Government programs on improving the water quality of agricultural runoff have focused on: sound land stewardship and the implementation of soil conservation practices; edge-of-field best management practices, including grassed waterways, riparian buffers, and constructed wetlands; and land retirement programs. An edge-of-field system that has garnered little research attention is the agricultural drainage ditch. Despite the extensive network of agricultural ditches that are found throughout the United States, and other regions of the world, relatively little research has been conducted on fluvial processes within these systems. Yet there is evidence to suggest that a significant portion of the sediment discharge from headwater systems is due to bank instability and in-stream processes (Trimble and Crosson, 2000). In contrast, headwater streams can reduce significant amounts of nitrogen in larger waterways (Kemp and Dodds, 2002).

In the Midwest Region, headwater systems usually contain more than two-thirds of the channel miles, have geometries that are small enough to be modified in a cost effective manner, and provide the most opportunity for water quality improvement. Agricultural channels are often deepened and straightened to facilitate the flow of water from subsurface drainage outlets and maximize conveyance capacity. The resulting modified channel geometries are incised trapezoidal channels with little or no connection to an active floodplain. Often, channel maintenance is necessary to remove woody vegetation and deposited sediment, stabilize bank slopes, and to address toe scour problems (Fausey et al., 1982). These routine maintenance activities are costly, disrupt the existing ecology, and adversely impact water quality. Figure 1 shows a ditch in Minnesota before (left) and after (right) a maintenance activity. Small stable fluvial benches at the bottom of the channel have been removed and runoff is already transporting high sediment loads.

Figure 1. A ditch in Minnesota with benches (left) and after maintenance to remove deposited sediment and benches (right).

Natural adjustments in unmaintained systems often establish fluvial channels, henceforth called inset channels, within the large modified or constructed ditch (Jayakaran and Ward, 2007; Powell et al., 2007). These inset channels have small stable floodplains, henceforth called benches that form by vertical accretions of deposited sediment that then vegetate with grasses. The formation of benches in a ditch is associated with an overwide geometry at the bottom of the ditch, sediment supply, cohesive soils that vegetate rapidly, and sufficient stream power to transport sediment through the system without excessive scour of the bed and banks.

Figure 2. Researchers from The Ohio State University and the University of Notre Dame collecting data in a two-stage ditch.

Channel-forming discharges in natural streams are often associated with the 1- to 2-year recurrence interval and are thought to exceed bankfull levels 10-15 times per year (Leopold, 1994; Simon et al., 2004); however, in agricultural ditches bankfull recurrence intervals can range as low as 0.3 years to 1.4 years in small headwater systems (Jayakaran et al., 2005), and can exceed bankfull levels more than 60 days annually. Therefore, common methods and assumptions to determine flow frequency distributions for natural streams are not always applicable to modified headwater systems. In these systems, bankfull flows are often associated with small and often sporadic bankfull features in the lower half of ditches.

We have developed detailed procedures for modifying a trapezoidal channel to establish a functional two-stage system (Powell et al., 2007; USDA-NRCS, 2007). The two-stage approach creates a first stage (bankfull stage) that is an inset channel associated with the channel forming discharge (Figure 3). The second stage is related to a minimum size to provide stability, the position of subsurface drainage outlets, and a desired conveyance capacity to prevent frequent flooding of adjacent areas. The approach is essentially a floodplain construction process.

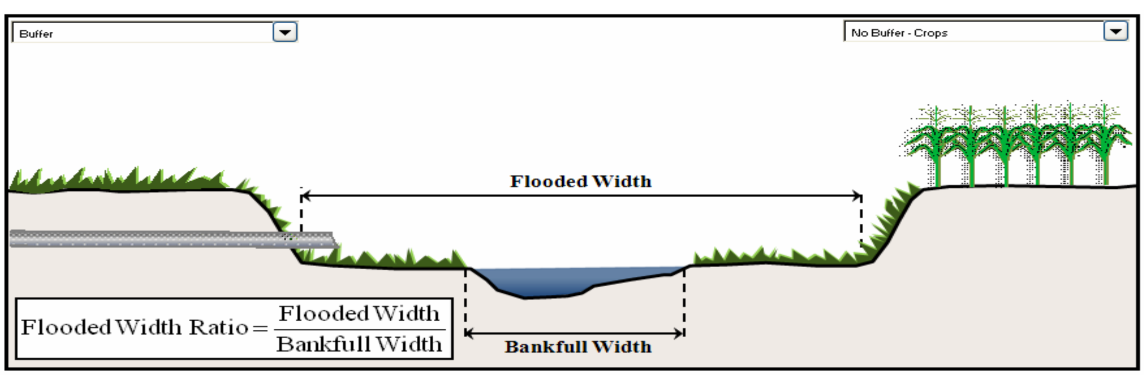

Figure 3. Two-stage ditch diagram showing bankfull conditions in the inset channel, benches with grass, a grass buffer on the left bank, a subsurface drainage outlet, and a field planted in corn on the right bank. Target flooded width ratios are usually 4 to 5.

The objectives of the study were to: (1) evaluate methods for developing relationships between discharge and recurrence interval - particularly for recurrence interval events more frequent than the 2-year; (2) determine the bankfull properties of modified headwater channels in central Ohio; (3) determine the recurrence interval of bankfull discharges in these systems, annual flow exceedances and the potential nitrate nitrogen reductions that might occur if two-stage systems with different size benches (floodplains) were constructed at the bankfull elevations.

METHODS The study was primarily conducted on modified headwater channels in the Upper Olentangy River watershed in central Ohio. Producers primarily use conventional tillage for corn, and no-till or reduced tillage for soybean production. The soils are predominately in hydrologic soil group C and much of the agricultural land has subsurface drainage. Although the focus of the study was 17 sites in the Olentangy River Watershed, regionalized flow exceedance relationships were also developed for other gages in Ohio (i.e., St. Joseph River, which also flows through part of Indiana and Michigan) to obtain a measure of how gage discharge signatures affect predicted flow exceedances. This analysis also provided input information for a simple Microsoft Excel-based tool for estimating nitrate-nitrogen removal associated with two-stage ditches.

Discharge versus Recurrence Interval Measured discharge data were obtained from long term records (42 to 83 years; http://waterdata.usgs.gov/usa/nwis/nwis) at the following USGS stream gages: Claridon (407 km^2, #3223000), White Oak (565 km^2, #328500); Worthington (1287 km^2, 3226800), St. Joseph (1401 km^2, #417800), Sandusky (3240 km^2, #4198000), Hocking (4224 km^2, #3159500), and Maumee (14361 km^2, #4192500). Annual series of instantaneous peaks were used to develop discharge versus recurrence interval relationships and daily series were used to develop flow duration curves. USGS discharge regression equations developed for rural areas in Ohio (Koltun, 2003) were used to predict discharges at the ungaged sites. The method is incorporated in the STREAM tools that were used to analyze the stream geomorphology data and are the approach incorporated in the USGS Streamstats tool for Ohio (http://water.usgs.gov/osw/streamstats/ohio.html). A comparison of the gage discharge and regression equation predictions was then used to develop a calibration factor. The calibration factor, together with ratios of n-year discharge to 2-year discharge at the gage, was then applied to the 2-year regression equation predictions for the ungaged sites.

To evaluate whether statistical methods for determining discharge versus recurrence interval have a significant effect on the results, the Weibull method (Thorne et. al., 1997), Pearson Type III (Abernethy, 2000), and Extreme Value Type I distribution (Natrella, 2005) were compared. The Weibull method has seen widespread application and is the most popular method globally of analyzing and predicting probability of exceedances of all types of data (Abernethy, 2000). The Log Pearson Type III distribution is recommended by the U.S. Interagency Advisory Committee on Water Data and is the default distribution used by the USGS for flood studies (http://www.dartmouth.edu/~renshaw/hydrotoolbox/). The Extreme Value Type I distribution was selected for its extensive use in the United Kingdom for calculating discharge recurrence intervals (Cunnane, 1988).

Measured gage data represent peak flows that occur within a watershed. To apply this gage signature to ungaged sites, a calibration factor was developed using three steps. Step one was to apply the Index method of the 2-year gage recurrence interval discharge to the all gage recurrence intervals. The Index method was developed based on the 2-year recurrence interval discharge because it is more predictable at sites within watersheds smaller than about 25 km^2 (Leopold, 1994). The Index method consists of dividing the 2-year recurrence interval discharge of the gage by all gage recurrence intervals creating a set of gage discharge ratios. The second step in developing a calibration factor was to divide the 2-year recurrence interval discharge at the gage by the 2-year recurrence interval discharge that was predicted by the USGS regression equation (other runoff methods could be used). The final step was to estimate the 2-year recurrence interval discharge at an ungaged site using the USGS regression equation (or some other method), multiply it by the calibration factor, and then apply it to the set of gage discharge ratios to obtain a set of discharge versus recurrence intervals at the site.

Developing a Flow Duration Curve A flow duration curve was developed at the gaged site after calibrated discharge recurrence intervals were calculated at the gaged and the study sites. The approach considers flow characteristics of the river throughout a range of discharges without regard to the sequence of exceedance. Typically, applications of the flow-duration method rely on the availability of discharge data from gaging stations, but none of the sites were gaged. Since these records were not available a regionalized flow-duration curve was selected to determine frequencies at all sites because it has proven to be more accurate for small watersheds than other methods. The non-dimensional discharge Index method, developed by Watson et al. (1997), was used to develop regionalized flow-duration curves. First, the entire daily-recorded peak for the gaged site was divided by the previously calculated 2-year recurrence interval making a data series that was dimensionless. This dimensionless data series was then multiplied by the calibrated n-year discharges to create a daily data series for each site. Once a flow duration curve was developed for a site, the number of days that the discharge for each recurrence interval was exceeded was determined from the flow duration curve. Regionalized flow exceedance relationships were then developed for other gages in Ohio, Indiana, and Michigan to obtain a measure of how gage discharge signatures affect predicted flow exceedances. This analysis also provided input information for a simple excel based tool for estimating nitrate nitrogen removal associated with two-stage ditches.

Stream Geomorphology A detailed geomorphic study was conducted at each site with procedures consistent with the guidelines presented by Harrelson et al. (1994). The following features were measured along reaches that were a minimum of 100 m long (a length that exceeded minimum recommended lengths of 20-30 bankfull widths): channel cross-section surveys at 2 to 3 points; bed profile; water surface profile; azimuth; and top of the bank elevations. Bed material size distributions were determined by conducting a Wolman pebble count at riffles using a zigzag pattern (Wolman, 1954). In this study, material finer than 1 mm was reported as sand or silt and clay based on feel. A pebble count was not conducted where most of the bed material was in this range. Studies have questioned the use of geomorphic bankfull concepts on unstable channels like agricultural ditches (Copeland et al., 2000). However, recent studies have shown that these disturbed headwater systems exhibit geomorphic features, such as a main channel system with a series of bars and benches (Jayakaran et al., 2005).

Data collected from the stream geomorphology surveys were entered into the Reference Reach Spreadsheet (Powell, 2006b). This tool provided a graphical plot of the profile, pattern, dimensions, and particle distribution. Manning's equation was used to calculate bankfull velocities at each site. Manning's roughness value *n* of 0.03 was assumed for all sites as they had similar clayey bank materials, gravel or smaller bed materials, and similar vegetation. Three regional curves were used to compare bankfull dimensions: Upper Scioto River watershed (Witter, 2006), the USGS Ohio Regional Curve (Sherwood and Huitger, 2005), and Northwest Ohio Ditches Regional Curve (Powell, 2006a).

RESULTS

Objective One The gage ratios and calibration factor developed with the instantaneous annual peaks series are reported in Table 1. Reported gage discharge estimates were determined using the Weibull Method. For this case, the calibration factor was 0.77.

A summary of the discharge versus recurrence interval results for all seven gages and the three statistical methods is presented in Table 2. Generally, there was only a small non-significant difference between results predicted by the different methods.

Objective Two Most of the agricultural headwater systems in this study were dominated by over-deep and over-wide incised channels that rarely exhibited out-of-bank flows onto a floodplain. At all cross-sections, bankfull elevations were associated with a noticeable feature within the cross-section (Figure 4). Profile slopes were estimated using the channel bed by selecting the start and end point of the survey.

Table 1. Calibration factors developed for the USGS gage in Claridon, Ohio.

Recurrence Interval	Gage Discharge (m^3/s)	Gage Ratio[1]	Predicted Discharge (m^3/s)	Calibration Factor[2]	Calibrated Discharge[3] (m^3/s)
0.2	8	0.09	28		8
0.4	21	0.25	48		21
0.8	45	0.51	74		45
1	47	0.54	80		47
2	87	1.00	112	**0.77**	87
5	240	1.79	169		240
10	207	2.38	209		207

1. Discharge divided by the 2-year recurrence interval discharge at gage.
2. Gage 2-year discharge divided by predicted 2-year discharge.
3. Predicted discharge times gage ratio times calibration factor.

Table 2. Summary of the discharge versus recurrence interval analysis.

	Claridon	**Worthington**	**Maumee**	**White Oak**	**Hocking**	**Sandusky**	**St. Joseph**
RI	Discharge (m^3/s)	Discharge (m^3/s)	Discharge (m^3/s)	Discharge (m^3/s)	Discharge (m^3/s)	Discharge (m^3/s)	Discharge (m^3/s)
				Weibull			
1	47	109	840	191	204	291	71
2	87	167	1224	273	340	412	116
5	155	247	1732	381	521	572	176
10	207	306	2116	462	658	693	221
				Log Pearson			
1	33	82	44	63	87	59	15
2	87	172	1364	288	353	443	123
5	137	235	1826	388	510	592	178
10	181	283	2044	453	628	680	214
				Extreme Values			
1	14	90	686	161	154	244	55
2	90	178	1293	288	354	423	119
5	141	246	1758	385	511	564	171
10	175	291	2066	450	615	658	206

A summary of the bankfull properties is presented in Table 3. The recurrence intervals of the mean bankfull discharges at each site ranged from about 0.4 years to 1.0 years. This high frequency of discharges associated with benches in ditches is consistent with our earlier findings and suggests that equilibrium in these headwater systems is often associated with a discharge that occurs more frequently than the 0.8 year event. Ditchfull discharges ranged from 0.4 years to more than 400 years, with five of the more natural sites having ditchfull discharges with a recurrence interval less than 2 years.

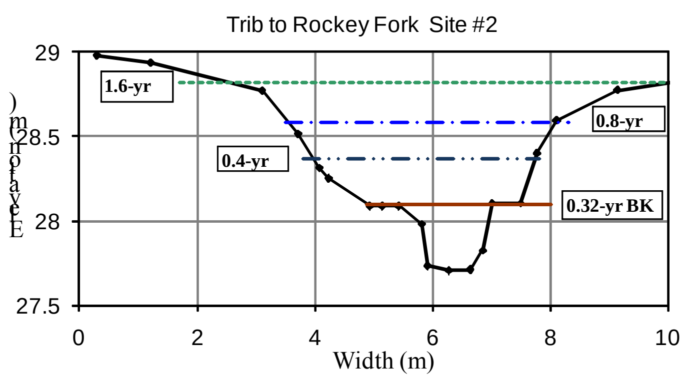

Figure 4. Cross-section with benches at a bankfull elevation that corresponds to the 0.32-yr discharge.

Table 3. Summary of mean bankfull properties of each study site.

SITES[1]	**DA**[2] **km**^{2}	**MBD**[3] **ft**	**BW**[4] **ft**	**Bed slope %**	**TPS**[5] **mm**	**d50 mm**	**d84 mm**	**BQ**[6] **years**
1	1.6	0.2	1.5	1.10	17.7	-	-	0.4
2	8.5	0.4	3.2	0.48	16.0	17.0	60.0	0.5
3	13.2	0.5	4.3	0.19	7.7	-	-	0.4
5	22.5	0.6	6.6	0.26	15.0	4.6	18.0	0.6
6	4.9	0.2	2.3	0.22	3.3	-	-	0.4
7	3.6	0.3	2.5	0.46	10.3	9.0	21.0	0.4
8	11.1	0.4	4.3	0.53	19.0	18.0	38.0	0.5
9	4.9	0.4	2.7	0.04	1.7	-	-	0.4
10	9.6	0.5	4.1	0.22	9.0	9.6	28.0	0.4
11	4.4	0.3	3.4	0.21	5.3	-	-	0.4
12	11.1	0.5	3.9	0.20	8.0	7.8	15.0	0.4
13	1.6	0.2	3.2	0.35	7.7	-	-	0.5
14	6.7	0.4	4.5	0.39	13.7	31.0	74.0	0.5
15	3.1	0.3	2.4	0.55	13.5	1.2	7.7	0.4
18	36.3	0.7	8.6	0.21	13.3	-	-	0.7
19	14.5	0.4	4.3	0.22	8.7	-	-	0.4
20	9.3	0.5	5.8	0.18	9.0	5.1	17.0	1.0

1) Sites 4, 16, 17 insufficient data – all values are means of 2 or three cross-sections; 2) drainage area; 3) bankfull depth; 4) bankfull width; 5) threshold particle size; 6) recurrence interval of bankfull discharge.

Nine of the sites (1, 2, 3, 6, 7, 9, 10, 12, 15) had bankfull widths that deviated by less than 20% from values predicted by the Northwest Ohio regional curves for ditches. A logistic regression analysis (not reported) showed that whether a site did or did not satisfy the 20% threshold could be predicted (15/17 correct predictions) based on a ratio of the channel width at the stage of the 1.2-year recurrence interval discharge divided by the bankfull discharge.

Estimates of the range of mean annual number of days an *n*-year discharge would be exceeded are summarized in Table 4. From Tables 3 and 4 it can be seen that many of bankfull stages correspond to a discharge that is about 25% of the 2-year discharge and will be exceeded many times annually – 10 to 50 times for most of the sites.

Objective Three The tool used to address this objective is in the early stages of development so we have not presented details on the methods incorporated in the tool. While the results reported are for illustrative purposes only we feel they are

Table 4. Recurrence interval (RI) versus exceedance ranges based on the 7 gages.

RI (years)	**2-year Q (%)**	**Exceedance Ranges (days/year)**
0.2	1 to 9	50-170
0.4	7 to 32	7-140
0.8	48 to 61	2−23
1	54 to 71	1−13
2	100	0.03−3
5	139 to 179	0−0.5
10	169 to 238	0−0.22

representative of probable nitrogen removal rates in modified agricultural ditches. Based on user provided ranges for the inputs a Monte Carlo simulation (3,000 runs) was conducted. An example analysis was conducted for a hypothetical 10 km^2 watershed with the following attributes: 2.5 m wide bankfull width for the inset channel, annual exceedances of 10-20 days (flow on to benches), and 190-230 days annually when nitrate-N removal might occur in the inset channel. About 50% of the watershed was assumed to receive nitrogen fertilizer applications of 130-180 kg-ha/year and 20-30% of the applied amount was assumed to discharge to the surface ditch system. In poorly drained agricultural areas in this Midwest region of the United States a 10 km^2 watershed might contain at least 10 km of surface ditches (about 0.6% of the surface area of the watershed). If the nitrate-N removal rates in the ditch systems were 0.35 $gN/m^2/day$ (Birgand et al., 2007), and all 10 km were modified to two-stage ditches with a flooded width ratio of 5 (flooded width divided by bankfull width), then about 11-19% of the exported nitrate-N would be removed by the system and it would occupy about 1.7% of the watershed. Results from this example should be used with caution as both lower and higher nitrate-N removal rates have been reported in the literature; and the number of days benches will be saturated will vary from location to location as will the number of days when conditions in the inset channel are favorable for nitrate-N removal. Preliminary results from an ongoing study we are conducting with the University of Notre Dame indicate that removal rates of nitrate-N per unit area might be larger than rates used in this example.

CONCLUSIONS Each of the statistical methods gave similar discharge versus recurrence results except in the tails of the distribution. A calibration method based on using data for the nearest upstream gage data was used to develop discharge versus recurrence interval and exceedance values at ungaged sites and gave results consistent with previous studies. Bankfull discharge was associated with recurrence intervals more frequent than 1 year and were associated with flows that occur many times a year that are about 25% of 2-year discharges. Preliminary results indicate that nitrate-n removal associated with two-stage ditches might be 10% or less of exported loads.

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