XVII[th] World Congress of the International Commission of Agricultural and Biosystems Engineering (CIGR)

Hosted by the Canadian Society for Bioengineering (CSBE/SCGAB)
Québec City, Canada June 13-17, 2010

A DECADE LATER: THE ESTABLISHMENT, CHANNEL EVOLUTION, AND STABILITY OF INNOVATIVE TWO-STAGE AGRICULTURAL DITCHES IN THE MIDWEST REGION OF THE UNITED STATES

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CSBE100209 – Presented at ASABE's 9th International Drainage Symposium (IDS)

ABSTRACT Much of the landscape in the Midwest region of the United States has been converted to agricultural use and with this conversion has come greatly altered hydrologic functioning. The elimination of wetland storage and installation of subsurface drainage systems and agricultural ditches has caused water to drain from agricultural watersheds at greatly accelerated rates. In some cases, these hydrologic alterations have led to severe water quality problems, including stream bank erosion, sedimentation, and inadequate processing of nutrients, each of which pose dire consequences for aquatic biota. Research by the authors has led to the modification of some trapezoidal agricultural ditches to two-stage geometries that are sized based on geomorphic concepts. A procedure for sizing these systems has been developed by the authors. Most of these innovative systems are located in Indiana, Michigan and Ohio. The main objective of the paper is to present details on how these systems have evolved since construction. The paper addresses issues that require further consideration. Channel evolution, determined by the assessment and analysis of physical condition, includes tracking changes in form by repeated surveys of channel dimension, pattern and profile. Pre-construction and post-construction properties are compared. Channel dimensions are also compared to regional curves. Analysis will include computing the hydrology and hydraulics for the range of recurrence intervals using the computer simulation models HEC-HMS, HEC GeoHMS, and HEC-RAS. All systems that have been studied have been stable, exhibited small adjustments on the constructed floodplains (benches), and have required little or no maintenance.

Keywords: Geomorphology, Two-stage, Agriculture, Water quality, Channel evolution, Hydrology.

INTRODUCTION An environmental issue of particular concern in the Midwest region of the United States has been the export of nonpoint source (NPS) pollutants such as nutrients, pesticides, and sediment to downstream receiving systems. Runoff from intensely farmed agricultural landscapes in the upper Midwest and other regions is recognized as a major source of excess nitrogen (N) in these important aquatic ecosystems. Excess nutrients and sediments to streams 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 reduced aesthetics (Carpenter et al., 1998; Nolan and Stoner, 2000). Agricultural nonpoint source runoff in the upper Midwest not only influences local lakes and rivers, but also contributes anthropogenic nitrogen to the Great Lakes and the Gulf of Mexico, where excess nutrients fuel a seasonal hypoxic zone (Turner and Rabalais, 2003).

Research on reducing the adverse water quality impacts of agricultural runoff, land management practices, and government programs primarily 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 found throughout the United States and other regions of the world -- which often times are headwater streams modified to enhance drainage and discharge capacity and reduce flooding -- relatively little research has been conducted on fluvial processes within these systems.

In the Midwest, headwater systems usually contain more than two-thirds of the channel miles and have geometries that are small enough to be modified in a cost effective manner. 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). Routine maintenance activities are costly, disrupt the existing ecology, and adversely impact water quality (Figure 1).

Figure 1. An agricultural ditch in Minnesota before (left) and after (right) a maintenance activity.

The two-stage ditch is a type of best management practice (BMP) that sustains original drainage function, increases channel stability, attenuates peak flooding, produces a self-flushing/self-sustaining system, and does not disrupt in-stream biota. The two-stage approach creates a first stage (lower stage) that is an inset channel associated with the channel forming discharge (Figure 2). The second stage is related to a minimum size to provide stability, the position of subsurface drainage outlets, and a desired conveyance capacity to pre-vent frequent flooding of adjacent areas. The approach is essentially a floodplain construction process.

Figure 2. A constructed two-stage channel in Hillsdale County, Michigan.

Successful implementation of the practice has lead to its incorporation in the Part 654 Stream Restoration Design, National Engineering Handbook (USDA-NRCS, 2007). Additionally, it has been included in Indiana's CREP program and is being considered as the only in-stream agricultural BMP for Indiana's EQIP (Personal Communication with Joe Draper of The Nature Conservancy). Approximately 20 two-stage ditches have been implemented in Ohio, Indiana, Michigan, and Minnesota and 10 more are in the planning phases.

Although these systems have been relatively successful, there has been little monitoring or research on how the constructed two-stage channel evolves over time. Many of these systems have been designed to be self-sustaining and require little, if any, maintenance but a dearth of information exists how they are actually performing. At the reach and watershed scale little is known about the influence of these systems on water quality Furthermore, for two-stage channels that are currently implemented, it us unknown what the significance is of their contribution to changing watershed hydrology.

This study is part of a larger study on watershed-scale evaluations of the water quality benefits of two-stage channel systems in a tri-state region if the upper Midwest USA. To examine the effect of a two-stage channel best management practice on watershed functionality, the overall objectives of this study are to:

1) Determine the evolution, sediment transport and stability of two-stage ditches in the tri-state region in the upper Midwest, USA.

2) Determine the extent to which two-stage channel must extend through watershed to provide beneficial impacts hydrology and channel stability.

METHODS

Site Description Five constructed two-stage ditches in the Ohio River and Lake Erie basins were selected to address the objectives (Figure 3). Study sites include: Creel Ditch (Site 4) and Crommer Ditch (Site 1, Upper Maumee River Watershed), a tributary to Bull Creek (Site 2; Portage River Watershed), Klase Ditch (Great Miami River Watershed), and Shatto Ditch (Tippecanoe River Watershed). Table 1 summarizes the attributes of each site. The two-stage ditches were sized and constructed with the 9-step procedure outlined in Powell et al. (2007).

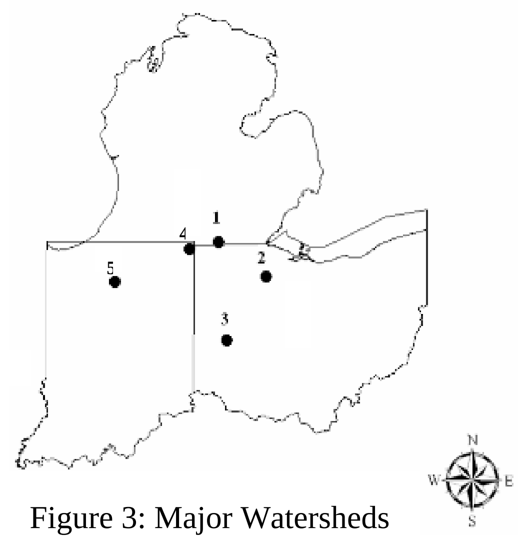

Figure 3: Major Watersheds of the study site locations.

Table 1. Site location, drainage area, year of two-stage construction, receiving river system, major watershed, and percent agricultural land use of each study site.

Site ID	Site Name	Drainage Area km^2	Construction Year	Receiving system	Ag. Land Use (%)
1	Crommer Ditch	13	2005	Ohio River	80+
2	Bull Creek	9	2001	Lake Erie	80+
3	Klase Ditch	7	2006	Ohio River	80+
4	Creel Ditch	12.3	2008	Lake Erie	80+
5	Shatto	12	2008	Ohio River	80+

Assessment and Analysis of Physical Condition To meet Objective 1, we assessed the pre--construction and post---construction geomorphology and hydrology for each of the study sites.

Data Collection Geomorphology measurements were consistent with Harrelson et al. (1994) and Ward and Trimble (2004). Transects were established every 30.5 or 61 meters (depending on site constraints and previous surveys) to capture cross-sectional area and relative slope (Figure 4). Data were collected using a laser level, telescoping rod with receiver, 30.5-m tape, compass, and a ruler with millimeter graduations. Not all study sites had geomorphology data for each consecutive year post-construction. Table 2 provides the years in which the data were collected. Bed material particle sizes were collected at each project site, whenever possible, using the Wolman Pebble Count procedure (Wolman, 1954).

Table 2. Geomorphology data available for each of the project sites.

Site	Pre- Construction Survey	Post-- Construction Survey(s)
Crommer Ditch	2003	2004, 2005, 2009
Bull Creek	2001	2004, 2009
Klase Ditch	2005	2009
Creel Ditch	2007	2009
Shatto Ditch	2006	2009

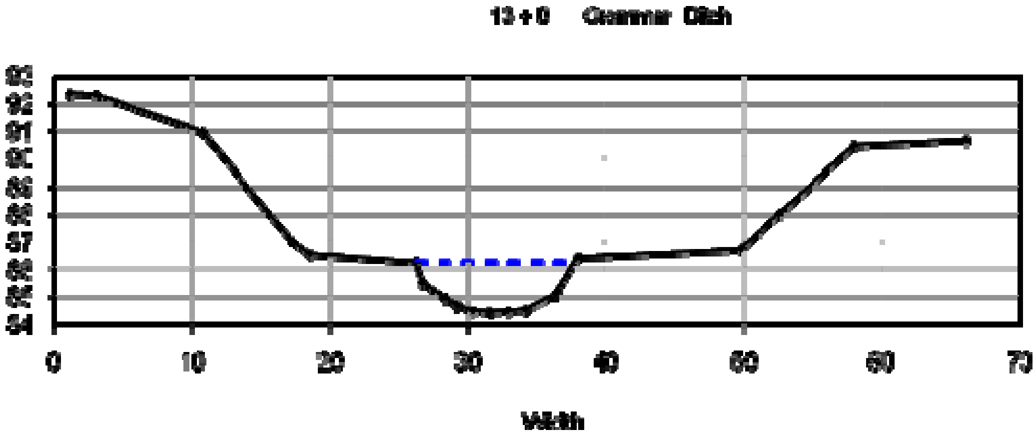

Figure 4. An example of a surveyed transect from Crommer Ditch, Michigan, in 2009.

Regional geometry curves were developed for Klase Ditch, Crommer Ditch, and Bull Creek (Powell, 2006). No regional curve had been developed for the Tippecanoe River watershed; therefore, the regional curve for Crommer Ditch was used.

Drainage areas in Ohio and Indiana were estimated using the web-based StreamStats tool (http://water.usgs.gov/osw/streamstats/ssonline.html). StreamStats is unavailable for Michigan; therefore drainage area for the Crommer Ditch was estimated using the Digital Watersheds tool (http://www.iwr.msu.edu/dw/). Recurrence interval to discharge relationships were developed using U.S. Geological Survey (USGS) instantaneous peak stream flow data from a stream gage located downstream of the project site (Ward et al., 2008; Table 3). The gage information was used to calibrate the USGS Rural Peak Discharge equations for Ohio (Koltun and Roberts, 1990) and the Indiana Peak Discharge Regression Equations for Indiana (Glatfelter, 1994).

Table 3. USGS stream gage number, location, and drainage area at the gage.

Site	Site Number	Location	Drainage Area (km^2)
Crommer Ditch	4178000	St. Joseph River near Newville, IN	1600
Bull Creek	4198520	Portage River near Elmore, OH	1274
Klase Ditch	3261950	Loramie Creek near Newport, OH	394
Creel Ditch	4177720	Fish Creek at Hamilton, IN	96
Shatto Ditch	3331500	Tippecanoe near Ora, IN	2123

Data Analysis Once bankfull widths, depths, and cross sectional areas were determined for each transect, the mean and standard deviation were calculated for each parameter over the entire reach. The program Statview v. 1.0 (BrainPower, Inc., 1985) was used to perform a paired t-test analysis at each site on mean bankfull width, mean bankfull depth, and mean bankfull cross-sectional area for pre-construction and post-construction conditions. Velocity, unit stream power, and threshold grain size means and standard deviations were calculated over the entire reach to determine sediment transport potential for pre-construction and post-construction conditions. A paired t-test also was performed for these parameters at all of the sites. A confidence level of 95% was used to determine statistical significance. At Klase Ditch, Bull Creek, Creel Ditch, and Shatto Ditch a paired t-test also was done to compare geometry and unit stream power within segments of the reach. The segment analysis may elucidate the effects of small geomorphic changes that are occurring, which could help predict future evolution of the reach.

RESULTS An image of Shatto ditch in the summer of 2009 is shown in Figure 5A. Dense tall grass grows on the benches that, on average, are flooded more than 60 days annually. Figures 5B, 5C, and 5D show the tributary of Bull Creek just before construction, just after construction, and 7 years post-construction, respectively. There is dense vegetation on the benches that hide the inset channel in Figure 5D. The benches are flooded many times annually but during summer months the ditch can be virtually dry.

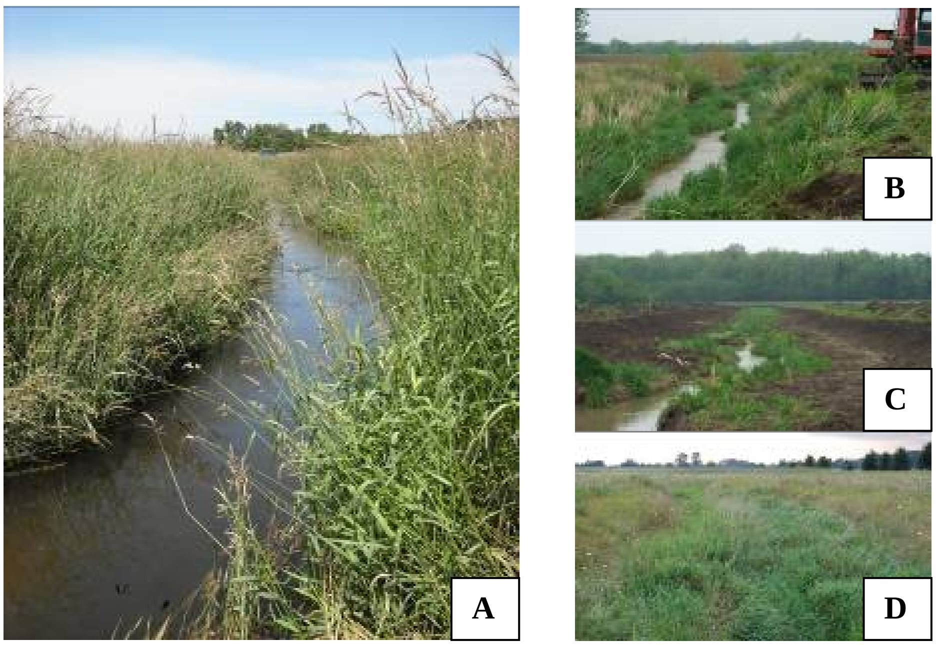

Figure 5. A: Shatto Ditch, Indiana – grass growing on the benches. B: Bull Creek, Ohio pre-construction; C: just after construction; and D: 7 years after construction.

Measured cross-sectional area data were obtained at the same stream length location for each data collection year and were superimposed on to one another to provide a visual reference of how the channel geometry might be changing over time (Figure 6).

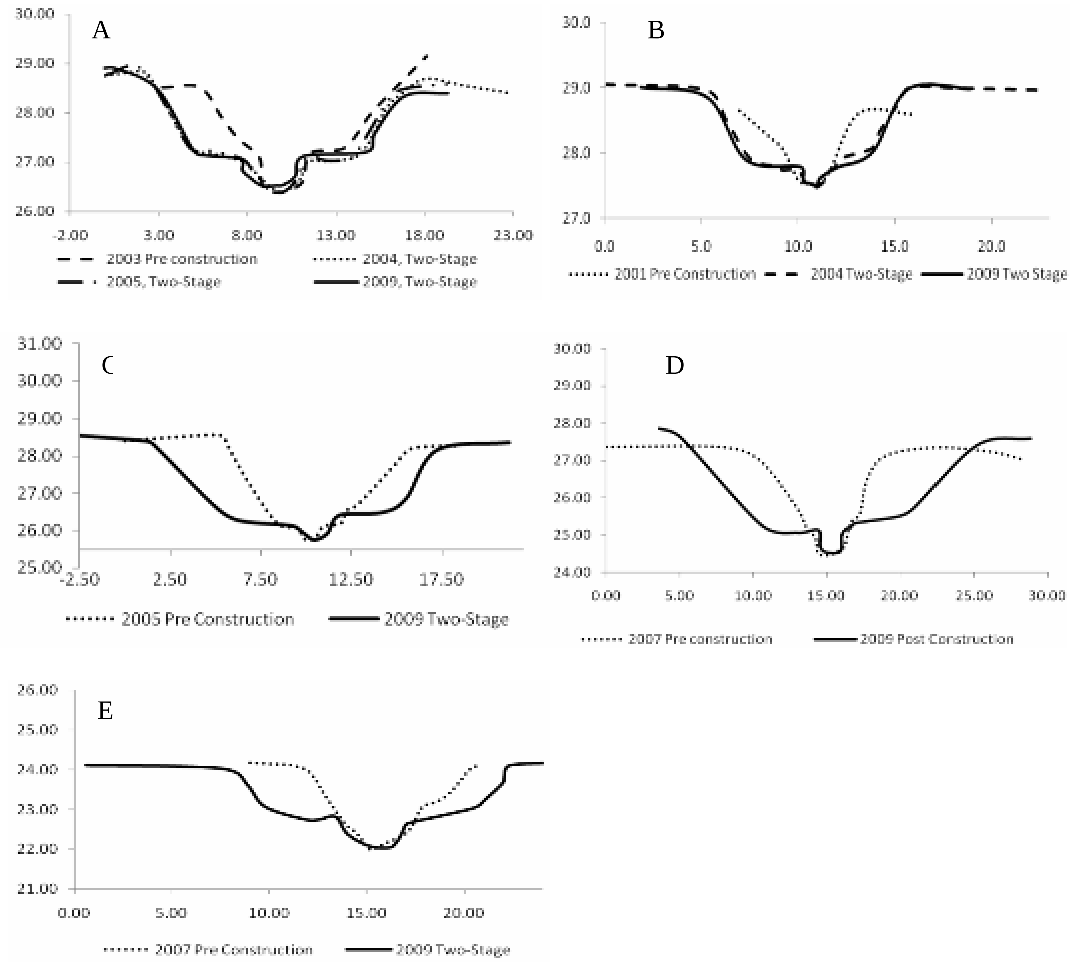

Figure 6. Superimposed measured cross-sections for pre-construction and post-two stage construction years at A) Crommer Ditch, B) Bull Creek, C) Klase Ditch, D) Creel Ditch, and E) Shatto Ditch. The graphs report elevation (meters) versus distance (meters).

Mean bankfull depth, width, and cross-sectional area at each site for pre-construction and post-construction years were compared (Table 4). Results of a paired t-test at Crommer Ditch indicated no statistically significant change in the geometry from the pre-construction and year 1, year 2, and year 5 post-construction (Table 5). At Creel Ditch, there was no statistically significant difference between pre-construction and year 1 post-construction for mean bankfull cross-sectional area. Results for Klase Ditch indicate a statistically significant change in mean bankfull cross-sectional area ($p=0.021$) and mean bankfull depth ($p=0.031$) between the pre-construction and post-construction condition. The change in mean bankfull width was not significant ($p=0.563$). The statistically significant change in cross-sectional area primarily was a result of the decreased mean bankfull depth, which may be an indication that the system is aggrading. At Bull Creek, mean bankfull cross-sectional area for pre-construction and year 3 post-construction were statistically different ($p<0.001$) as was mean bankfull cross-sectional area between pre-construction and year 8 ($p=0.034$). However, there was not a significant change in bankfull cross-sectional area between year 3 and year 8. Additionally, mean bankfull width and depth were not statistically different between all years.

Shatto Ditch showed a statistically significant decrease in mean bankfull depth from the pre-construction to post-construction condition (p=0.013), but no significant change in mean bankfull width (p=0.563) or mean bankfull cross-sectional area. The small reduction in mean bankfull depth might be an indicator that the system is aggrading.

Table 4. Summary of data for each site used in the paired t-test statistical analysis.

Site	Time	n	Area (m^2)	Width (m)	Depth (m)	Velocity (m/sec)	Unit Stream Power (Kg/m/sec)	Threshold Grain Size (mm)
Crommer Ditch	Pre-Construction	21	1.68	3.96	0.43	0.32	0.04	1
	Year 1	19	1.53	3.79	0.40	0.12	0.05	1
	Year 2	20	1.52	4.07	0.39	0.12	0.04	1
	Year 5 (2009)	16	1.51	3.61	0.42	0.31	0.04	1
Bull Creek	Pre-Construction	6	0.90	3.46	0.26	0.51	0.24	4
	Year 3	9	0.90	2.56	0.35	0.68	0.53	6
	Year 9 (2009)	7	0.65	2.50	0.26	0.62	0.38	5
Klase Ditch	Pre-Construction	15	0.80	2.50	0.30	0.09	0.25	4
	Year 4 (2009)	11	0.46	2.27	0.22	0.07	0.18	3
Creel Ditch	Pre-Construction	9	0.92	2.47	0.37	0.82	1.07	9
	Year 2 (2009)	9	1.04	2.76	0.36	0.92	1.27	11
Shatto Ditch	Pre-Construction	5	1.57	3.40	0.47	1.16	2.17	16
	Year 1 (2009)	9	1.27	3.67	0.35	1.12	2.03	16
All sites	Pre-Construction		1.17	3.16	0.37	0.58	0.75	6.8
	2009		0.99	2.96	0.32	0.61	0.78	7.2

A paired t-test was performed to compare the current (2009) mean post-construction dimensions to the pre-construction dimensions for the five sites. It was determined that, across all sites, there was statistically significant change in the cross-sectional area from 1.17 m^2 to 0.99 m^2 (p=0.042). Most of this change was due to the mean bankfull depth decreasing from 0.37 m to 0.32 m. This result indicates that some of these systems might aggrade to form linear wetlands. An analysis was performed on stream sediment transport potential to better understand what was contributing to Klase Ditch becoming shallower and why the four other ditches exhibited no change. Sediment transport potential explains a ditch's ability to move sediment and shape the channel. The three variables used to define that potential were velocity, unit stream power, and threshold grain size. The mean of the three different parameters was calculated over the entire reach for each sample year. A summary of results are shown in Table 4. The four ditches that experience no change in geometry did not have a change in velocity, unit stream power, or threshold grain size. We hypothesized that, at Klase Ditch and Shatto Ditch, the decrease in mean depth could have been contributed to a decrease in unit stream power; however, results indicate that stream power had not changed over sampling years and the geometric change these two locations could not be explained using this analysis.

To better predict the potential for change in the future at each site, the reaches were broken into segments. Bull Creek was divided into three segments based on trends observed in the 2009 geometry data. The segments included an upstream section, a midstream section, and a downstream section. A paired t-test between the upstream, midstream, and downstream segments indicated that there was no statistically significant change between the mean bankfull cross-sectional area, mean bankfull width, or mean bankfull depth. The paired t-test result for unit stream power indicated a statistically significant change between the upstream segment and the midstream segment ($p=0.026$). This may be attributed to the midstream section being a bend in the ditch. No statistical difference in unit stream power was found between the upstream and downstream segments or between the midstream and downstream segments.

Klase Ditch was divided into an upstream segment and a downstream segment based on 2009 data. The segments are separated by a section of one-sided bench construction. Paired t-test results indicate no statistical difference between the upstream and downstream mean bankfull cross-sectional area, mean bankfull width, or mean bankfull depth; however, there was a statistical difference in unit stream power ($p=0.015$). Three factors may be attributed to this difference: a change in geometry between the two segments from two-sided to one-sided two-stage construction; a small tributary enters the ditch between the upstream and downstream segments that may alter the discharge regime of the downstream segment; or a difference in bed slope between the upstream segment (0.17%) and the downstream segment (0.29%).

Creel Ditch was divided into an upstream segment and downstream segment based on 2009 data. This division of segments was selected because of a tile drain located on a bend between the two segments. A paired t-test on the mean bankfull cross-sectional area, mean bankfull width, and mean bankfull mean depth indicated no statistically significant difference between the upstream and downstream geometries. Similarly, there was no statistically significant difference in unit stream power.

Shatto Ditch was divided into an unconstructed upstream segment, a constructed one-sided two-stage midstream segment, and a constructed two-sided two-stage downstream segment based on 2009 data. A paired t-test analysis on the mean bankfull cross-sectional area and mean bankfull width indicated no statistical difference between the segments. Mean bankfull depth was statistically different between the upstream and downstream segment ($p=0.049$) but not between the other segments. A paired t-test analysis on unit stream power indicated a significant difference between the upstream and midstream segments ($p<0.001$) and between the downstream and midstream segments ($p<0.001$). There was no statistical difference between the upstream and midstream segments.

CONCLUSIONS To date, all systems that have been studied have been stable, exhibited small adjustments on the constructed floodplains (benches), and have required little or no maintenance. Bankfull widths are narrowing and there are small reductions in bankfull cross-sectional areas, but these changes are not statistically significant based on a paired t-test analysis. Some reaches (i.e., Klase Ditch) have undergone some degree of aggradation of the channel bed. It is unclear as these systems evolve whether this is a trend that might occur due to limited stream power and a supply of sediment or whether the channels will evolve as theory suggests being self-flushing and exporting the aggraded material downstream. Preliminary results presented in this paper suggest that construction of a two-stage channel may result in either a linear wetland or self-forming channel condition depending on an as yet unknown threshold of unit stream power relating to hydrology, slope, drainage area, and land use. Results of field studies are leading to development of new assessment techniques for small streams, and anticipated end outcomes will have the potential to recommend new Best Management Practices (BMPs) for small watersheds in highly productive agro-ecosystems.

Acknowledgements : This research was funded by: the USDA-CSREES (Integrated Research, Education, and Extension Competitive Grants Program); the Ohio Agricultural Research and Development Center (OARDC); OSU Extension (Ohio NEMO Program); and the Department of Food, Agricultural and Biological Engineering and the College of Food, Agricultural and Environmental Sciences at OSU; through collaboration and support from local, state and federal organizations including The Nature Conservancy, the USDA-ARS, the University of Notre Dame, and the Ohio Department of Natural Resources as well as assistance from county engineers and surveyors, and landowners.

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