Statistical Relationship of Drainage Ditch Features to Watershed Characteristics, Probable Discharges, and Maintenance Practices[1]

Abstract

An understanding of fluvial processes might be used to make drainage ditches more self-maintaining and also enhance the ecology of these systems. Highly modified channels drain extensive portions of the United States. Maintenance practices remove or kill vegetation and typically deposited sediment is excavated out of the ditches periodically. Short term benefits due to improved conveyance are often offset by cycles of bank failures, accelerated scours, and the need to place rip-rap along the toe of the embankments. This manuscript presents the results of a study that tests the usefulness of river process concepts as a tool to understand drainage ditch design. The study is being conducted in a subwatershed of the Portage River that is located in Northwest Ohio. Drainage ditch form (pattern, profile, and dimension) has been measured on ditches exhibiting different levels of maintenance. Regression techniques were used to relate these properties to drainage area, channel slope, ditch width, and bed material particle size. A statistical analysis of precipitation data and regional stream discharges was used to determine the frequency of events associated with fluvial features in the ditches. Fluvial processes result in the formation of a small meandering main channel within the confines of the ditch, as well as benches, small flood plains, riffles and pools. The dominant main channel and benches are formed by discharges which occur much more frequently than discharges associated with natural channels – possibly influenced by high subsurface drainage flow. In the regression analysis, the drainage area was the most significant independent variable and in all cases accounted for more than 40% of the variability in the dependent variable. The d_{84} of the bed material was the second most useful variable but was not significant at a 5% level. The channel slope and the ditch width were also not significant in most cases and only accounted for a small amount of the variability in the dependent variable. However, the floodplain width (width of the depositional bench) was highly correlated with the constructed ditch width (measured at 5 ft. from the ditch bottom), with wider depositional benches being associated with wider ditch width.

We anticipate that the new knowledge resulting from this study will be useful in improving maintenance practices and in the design of future ditches.

Keywords: stream processes, bankfull dimensions, drainage ditches, regional curves.

Introduction

This manuscript presents preliminary results of a statistical analysis of the fluvial characteristics of drainage ditches in Northwest Ohio The goal of the work is to identify how knowledge of fluvial processes might be used to make highly modified channels in the Lake Erie Drainage Basin more self-maintaining while enhancing the ecology of these systems. Highly modified channels drain extensive portions of the U.S. In these productive agricultural areas, most natural channels have been deepened and straightened to facilitate the flow of water from agricultural subsurface drainage outlets and to maximize conveyance. The cost of maintaining these ditches is estimated to be more than $400/mile/year, with total maintenance costs in Northwest Ohio exceeding $1.7 million per year . Habitat modification, largely related to drainage improvement, is now the leading cause of aquatic life use impairment in Ohio. Ecological quality is dependent on fluvial processes that are a function of channel form and associated floodplain interactions.

The study has focused on agricultural drainage ditches with watersheds of 1 to 40 square miles. Typically, these large ditches (5-12 feet deep and 15-60 feet wide at the top) have over-steep side slopes. Bank slump and slope failure due to scour processes at the toe of the banks appear to account for some of the fundamental instability of the system. Periodically, maintenance practices remove or kill vegetation and/or excavate deposited sediments out of the ditches. Short term benefits due to improved conveyance are often offset by cycles of bank failures, accelerated scours, and the need to place rip-rap along the toe of the embankments.

Stable natural streams normally consist of a main channel with a particular pattern, width-depth proportion, and a floodplain connection. The size of the main channel is typically associated with the flow that is most effective at doing work; eroding and transporting sediment. This flow occurs 1-2 times annually and is often approximated as a

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1.5 year return period discharge as determined by the annual peaks method. Factors influencing the channel's shape and size include: geology, topography, flow velocity, discharge, sediment transport, sediment particle distribution, channel geometry. In natural stable streams these variables produce a channel in dynamic equilibrium, having a stable dimension, pattern, and profile such that, over time, channel features are maintained and the channel system neither aggrades nor degrades (Leopold, 1994).

Drainage ditch construction is often independent of the variables that give rise to the dynamic equilibrium observed in natural steams. Most notably, they lack a sinuous pattern and the two stage relationship between a main channel (bankfull channel) and floodplain. They often exhibit the characteristics of a Rosgen Type Gc or F stream system (Rosgen, 1996). However, with few exceptions (based on soil type) ditches in our study area develop fluvial features. Once an appropriate channel cross section dimension is achieved, increased sorting of material based on better sediment transport capacity should occur.

Objectives/Hypothesis

The primary goal of the study is to identify how knowledge of fluvial processes might be used to make drainage ditches more self-maintaining and also enhance the ecology of these systems. The concepts we plan to study are:

- Natural rivers, which are self-constructed and self-maintained, constantly seek their own stability (Leopold, et al, 1964). Drainage ditches in Northwest Ohio adjust their channels in predictable ways towards a state of dynamic equilibrium, even though they have been artificially constructed, periodically modified to maintain conveyance capacity, and often receive large discharges from subsurface drainage systems.
- Understanding how streams seek their own stability allows us to manage and construct ditches that in the long term might require less maintenance, while providing the required drainage capacity for agricultural production and better ecological function.
- Several decades ago, farmers reported that drainage ditches had substantially better ecological function than they do now. Maintenance practices that incorporate river geomorphology concepts might help to reestablish some of the prior ecological function of these systems and improve in-stream habitat.

The preliminary results presented in this manuscript will be used to address the first concept.

Research Approach

Site Selection

Thusfar the study has been conducted on an approximately 300 mi^2 subwatershed of the Portage River that is located in a flat (bed slopes generally less than 0.4%) region of Northwest Ohio with predominantly Lake Plain soils. Once an ancient lake bed surrounded by glacial moraines, the area was originally known as the Great Black Swamp, and was dominated by deciduous forest. Cleared and drained extensively in the last 150 years it is now dominated by row crop agriculture. Most fields have subsurface drainage as the silty clay soils are poorly drained. The region averages about 33 inches of rain annually.

An extensive reconnaissance was conducted of more than 200 ditch crossings in the Northwest Ohio Lake Plain area to identify what fluvial features were present in ditches and to select sites for the study. The initial fieldwork confirmed that throughout the region fluvial processes appeared to cause the formation of small meandering channels within the confines of the drainage ditch as well as the creation of benches (small flood plains), and some riffle-pool development. These features were particularly evident in Wood County. In order to prevent biasing the results by arbitrarily selecting ditches with very good or very poor fluvial features we decided to study all the ditches draining to the Portage River that have drainage areas of 1-40 square miles and intersected an east-west transect located at Cygnet Road. One ditch, the Rocky Ford, was omitted because a dam is located in its headwaters, it has a comparatively big drainage area, and the large size of the ditch dimensions make data collection difficult. Along most ditches additional research sites were selected upstream of the Cygnet Road transect in order to study the influence of drainage area on fluvial features and to evaluate the extent of fluvial features along each ditch system. These sites were located along east-west transects spaced every 2-3 miles upstream and extend into Hancock County. Overall there are 10 ditches and 21 sites.

Surveys of Fluvial Features

We surveyed selected reaches for channel materials, dimension, pattern and profile. Procedures used were generally consistent with the guidelines presented by Harrelson et al. (1994). The following features were measured along reaches that were much longer than the minimum recommended length of 20-30 bankfull widths: channel cross-section at several points along the reach; bed profile; water surface profile; azimuth; top of the bank; and bed material particle size distribution. Bed materials in the main channel were measured by conducting a Wolman Pebble Count using the zig-zag method. Survey data was assessed using the Reference Reach Spreadsheet (Mecklenburg, 2000).

Precipitation and Discharge Characteristics

Climatic Data is available from an Ohio Agricultural Research and Development Center (OARDC) experiment station located on the northwest side of the subwatershed. Current and historic electronic files for a period of 19 years can be readily obtained through the Internet. The analysis presented in this manuscript will determine the frequency of daily rainfall events greater than 0.1, 0.5, 0.8, 1.0, and 1.5 inches.

The subwatershed is ungaged but historically USGS gaging stations have been located downstream of the confluence of the Middle, North, and South Branches of the Portage River at Pemberville, Woodville, or Elmore. Discharge data for a 67 year period of record at the Woodville gage, which has a drainage area of 428 mi^2, was used to develop discharge-frequency relationships. This analysis used annual peaks, the USGS all peaks data, and also considered daily discharge data. The all peaks data set contains all the peaks larger than the lowest annual peak during the period of record. In addition, flow data for 39 gauges in northwest Ohio was used to develop regional discharge-drainage area relationships.

Several of the ditches have been instrumented with staff or crest gages or pressure transducers. In addition, a current meter will be used to periodically measure flow velocities. However, this type of data collection has only just been initiated. For this manuscript, bankfull discharges were calculated using Manning's equation with estimated Manning's roughness coefficients and measured bedslopes and channel dimensions. A study has been initiated to estimate discharges associated with different return periods using the Graphical Peak Discharge Method, the Rational Method, and a USGS Empirical Model for Ohio.

Analysis of Data

Statistical methods provided in Microsoft Excel were used for conducting the preliminary analysis. More comprehensive statistical software will be used for the final analysis when all data are available. Discharge-frequency relationships were developed based on modified Gumbel Type III procedures. Like most software, Excel does not provide Gumbel Probability scales. Therefore, we used a least square approach to fit a linear, power, or logarithmic trendline (regression line) to semi-log or log-log plots of discharge versus return period.

A multiple regression analysis was performed by using the Analysis ToolPak in Excel. Independent variables were added in a user defined stepwise approach. The dependent variables studied were: the bankfull cross-sectional area, mean depth, and width; the width of the flood plain at the bankfull stage, and the bankfull discharge. Independent variables available for consideration in the preliminary analysis were the drainage area (mi^2), channel slope (%), the width of the ditch at an elevation 5 ft above the bed, and the d_{50} or d_{84} of the bed material particles. At each reach measurements were made for 2-4 cross-sections. These included at least one representative cross-section which showed the dominant fluvial bench feature in a straight ditch section, a pool or point bar if one existed (normally on a bend), and in a few cases a cross-section which lacked any dominant fluvial features. For the purposes of this manuscript we used only cross-sectional data that was representative of fluvial features that were not associated with a bend in the ditch. – this was the majority of the data. Where more than one cross-section was available for a reach the mean dimensions were used in the analysis.

Results and Discussion

Ditch surveys and pebble counts have been completed for 18 sites and partial data are available for an additional 3 sites. All reaches exhibited 1-4 grade breaks up the side slopes (banks) of the ditches. In all but one reach the dominant grade break is between a small main channel and low depositional bench. In some of the smaller ditches the low bench was unstable and subject to scour during events which exceeded the bankfull discharge for the small main channel. In other cases, periodic maintenance and/or rip-rap resulted in the low bench only forming on alternating sides of the ditch and at bends in the ditch. In all cases the low benches are covered by dense grass during most of the year and the main channel meanders within the confines of the ditch. The main channel also exhibits some riffle and pool features. However, the pattern and profile characteristics of the channel are not as well defined as in natural streams and do not consistently fit the relationships with bankfull width that are reported in the literature.

In many of the ditches a second small grade break occurred higher up the bank and was usually associated with a distinct scour line. Estimates of the discharge at this elevation indicated that they corresponded to a 1-2 year return period flow for the region. A 1.5 year regional curve for Ohio is shown in Figure 1. Sometimes a third grade break occurred in close proximity to the second break. This break appeared to be associated with bank failure. In the large ditches there was often a bank failure line (4th grade break) near the top of the bank.

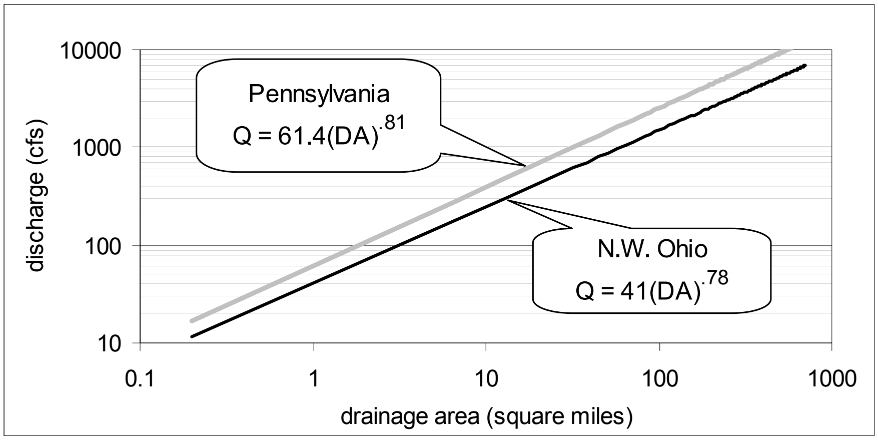

Figure 1. Regional Curves for N.W. Ohio and Pennsylvania.

The results of a linear multiple regression analysis that compares several of the bankfull channel features with drainage area properties, bed material size, and constructed ditch width are summarized in Table 1. The Drainage area was the most significant independent variable and in all cases accounted for 40% of the variability in the dependent variable of discharge and channel size. Large drainage areas are associated with greater discharge and channel dimensions. The d_{84} of the bed material was the second most useful variable associated with bankfull channel dimensions, but was not significant at a 5% level. The channel slope and the ditch width were also not significant in most cases and only accounted for a small amount of the variability in the dependent variables of the main channel itself. However, the floodplain width (width of the depositional bench) was highly correlated with the constructed ditch width (measured at 5 ft. from the ditch bottom), with wider depositional benches being associated with wider ditch width.

Table 1. Summary of the Regression Statistics

Independent variables	Discharge (cfs)		Bankfull Area (ft)		Bankfull Depth (ft)		Bankfull Width (ft)		Floodplain Width (ft)	
	R^2	F	R^2	F	R^2	F	R^2	F	R^2	F
Area	0.60	19.5	0.68	27.5	0.62	21.1	0.52	14.2	0.57	17.6
Area, D84	0.75	18.0	0.74	17.5	0.68	13.0	0.62	9.6	0.60	9.0
Area, D84, slope	0.75	11.0	0.76	11.9	0.70	8.4	0.63	6.3	0.64	6.6
Area, D84, slope ditch-width	0.76	8.0	0.76	8.2	0.75	7.5	0.66	4.8	**0.86**	**23.5**

Plots of the dimensions of the small main channel and the drainage area are reported in Figure 2. Non-linear regression equations are fitted to the data so the results can be compared to natural stream studies, which are reported in the literature. Comparing these results with those in Table 1 show that linear and non-linear regression equations seem to fit the data almost equally well. The results are greatly influenced by the relatively small dimension for the main channel at the site with the largest drainage area. When the study has been completed we will have more sites in the 15-35 mi^2 range.

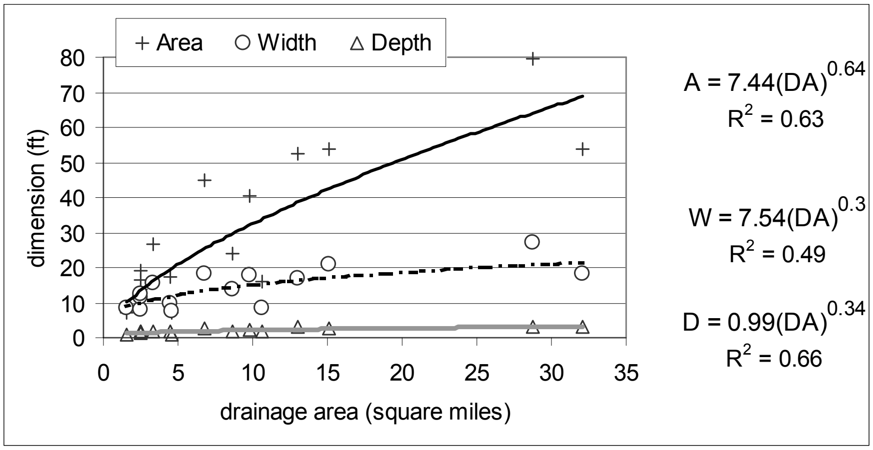

Figure 2 Dimensions of low channel

Estimated bankfull discharges for the small main channel are plotted versus drainage area in Figure 3. Comparing this plot with the regional curves shows that both the exponent in the equation and the coefficient (17.8) is less than 45% of the value of the coefficient in the regional curve (41.0). Therefore, the small main channel is associated with a lower discharge than the effective discharge that builds channels and benches in natural stream.

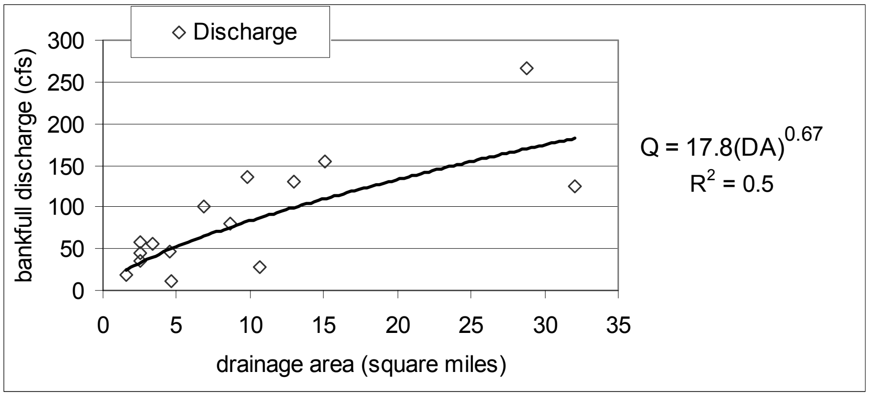

Figure 3 Discharge of low channel flowing full

While conducting the field surveys we speculated that the small main channel might be associated with high subsurface flows that occur a few times annually. Based on common drainage design system practices we anticipated that this discharge would be associated with about 0.3- 0.5 inches of runoff during a 48-72 hour period. An analysis of the precipitation records at the OARDC Experiment station showed that more than 0.8 inches of precipitation occurs on average 3.37 times annually (Table 2). During wet conditions rural land uses on the Hydrologic Soil Group C soils in the subwatershed would produce 0.3 to 0.8 inches of runoff for precipitation events greater than 0.8 inches. The NRCS curve number method was used to make these estimates. Some of these events would occur during dry summer conditions and others would be associated with snow. However late winter and early spring storms on thawing or saturated soils and/or snow melt will typically produce at least one large discharge event annually. It is reasonable to assume that on average there are 2-4 of these annual discharge events. This is also consistent with qualitative observations reported by farmers in the region.

Using the equation presented on Figure 3 the discharge for the 428 mi^2 drainage area at Woodville would be 1010 cfs or approximately 0.1 inches in 24 hours. However, the regression equation is influenced by the low discharge for the site on Needles Creek with the largest drainage area. This ditch is located on the western side of the subwatershed and has lower discharges than all of the other ditches. When data are available for other locations we anticipate that the predicted discharge will increase. Also, further discharge data are needed to establish the relationship between high sustained subsurface flows on small drainage areas and river discharges for the whole 428 mi^2 drainage area at the Woodville gage. Inspection of the regional curve for the Portage River (not shown) indicates that a mean daily discharge of 3000 cfs occurs about twice annually while a discharge of 2000 cfs occurs on average 10 times annually.

We speculate that the reason lower energy discharges, than those associated with a 1-2 year return period, are able to form the main channel and benches is because: (1) there is an available supply of very fine material at the bottom of the ditch –due in part to bank failures and also to the artificial conditions of the ditch (which is created independently of sediment supply unlike natural stream-valley formation); (2) a major part of the discharge entering the ditches is subsurface drainage which contains very little sediment so this flow picks up sediment in the ditch ; and (3) grass grows quickly on the benches and they then rapidly stabilize.

Table 2

Daily Rainfall Exceeding (inches)	Times Annual (number)	Total Discharge depth (inches)		
		CN=85	CN=90	CN=95
0.1	21.95	0.00	0.05	0.17
0.5	6.42	0.20	0.32	0.53
0.8	3.37	0.31	0.44	0.65
1	2.00	0.36	0.50	0.70
1.5	0.68	0.47	0.61	0.78

To isolate the many variables that form our study sites, we are looking at the county engineers maintenance records, the density of the tile mains, and the surrounding land use. We will also look at past aerial photographs to understand how our study sites might have changed over time. Specific morphologically and biologically detrimental events such as spike application and individual farmer dipping are also important. We will look at the relative extent of the low bench features in our study areas. We need to understand how consistent these features are and define which sites are anomalies and why.

Conclusions

These findings might add new insights to current definitions of channel stability and the importance of bankfull discharge. According to Dave Rosgen, “the bankfull stage and its attendant discharge serve as consistent morphological indices which can be related to the formation, maintenance, and dimensions of the channel as it exists under the modern climatic regime.” It appears that the low bench might serve a similar function to the stability of drainage ditches as the regional curve-derived bankfull elevation provides for natural streams. However, further research is needed to ascertain what combination of factors might be needed to establish and maintain each of these features. The low-flow channel has the potential to provide better habitat for biota in the same way that a bankfull channel is superior to an over-widened trapezoidal channel. It might also be useful in improving water quality particularly for nutrient assimilation in headwater streams (Schreiber, 2001).

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