Creating Ditches with Floodplains*

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Abstract

Two-stage channel systems incorporate benches that function as floodplains. In comparison to floodplains in natural streams, the width of the benches is often small due economic and land loss considerations. This manuscript outlines measurement and analysis procedures that can be used to size two-stage channel systems that are more self-sustaining than conventional one-stage constructed channels. The analysis procedures are incorporated in the STREAMS spreadsheet tools that have been developed by the Ohio Department of Natural Resources and the Ohio State University. Construction of a two-stage channel system requires a significant capital investment to create a wider surface width.

KEYWORDS. Drainage Ditch, Design Procedures, Ditch Stability, Fluvial Processes

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Introduction

The Problem

Highly modified channels drain extensive portions of productive agricultural land in the U.S.A. In some areas virtually all of the natural channels have been deepened and straightened to facilitate the flow of water from agricultural subsurface drainage outlets and to increase conveyance. Work is done periodically to maintain the drainage function, typically including removal of woody vegetation, removal of weeds, and "dipping out" deposited sediment. Ancillary work includes stabilizing bank slope failures and toe scour.

Ditch maintenance typically restores the ditch to a trapezoidal shape designed to transport large storm events (Figure 1). To facilitate drainage, and reduce the frequency of over bank flows, trapezoidal ditches are designed to accommodate large flows (5 to 100+ year recurrence interval) within the ditch. Also the width of the ditch bottom is constructed wider than the channel bottom that would form by fluvial processes, thus making the effective discharge relatively wide and shallow. Therefore, the constructed ditch channel is often oversized for small flows and provides no floodplain for large flows. Despite the tradition of ditch maintenance and current majority mind set, ditch dimensions are a result of fluvial (flowing water) processes and current practices are antitheses to the natural processes.

Figure 1. A Minnesota ditch (left) before maintenance, and (right) after maintenance.

Nature's Solution

In contrast to trapezoidal agricultural drainage ditches, an integral part of natural stream channels are the floodplains (Figure 2). The floodplains of high quality streams (except for those with steep bed slopes) are characterized by frequent,

extensive over-bank flow. In dynamic-equilibrium, a stream system depends on both the ability of the floodplain to dissipate the energy of high flows and concentrating the energy of low flows to effectively create a balance in sediment transport, storage and supply. In natural streams, fluvial processes work to size and maintain the dimensions of the main channel based on channel-forming discharge concepts (Powell et al., 2006).

Figure 2. An Ohio stream with an active floodplain.

Like other physical systems, streams try to be in a state of equilibrium. Many factors influence the system but the movement of water and sediment are the two primary influences on the equilibrium of the system. Lane's classic description of channel stability states that dynamic equilibrium exists between stream power and the discharge of bed-material sediment (Ward and Trimble 2004):

$$Q_s d \propto QS$$

where Q_s is the sediment discharge, d is the mean or median sediment size, Q is the discharge and S is the bed slope. The force that flowing water exerts on the bed and banks of a stream channel is called the shear stress. It is proportional to the product of the depth of flow of the water and the slope of the bed of the channel. The deeper the depth of flow, or the steeper the bedslope, the greater the force. For every place in a stream there will be some combination of water depth and bedslope that will cause the bed or banks to scour.

If the geometry of the main channel is in equilibrium it must over a long period of time have a maximum stream powers and shear stresses on the bed and banks that are not greatly exceeded. In order to accomplish this flows larger than the channel-forming discharges need to spread across an active floodplain so the maximum flow depths, discharges and sediment loads in the main channel stay within the equilibrium threshold and the bed and bank materials do not scour.

In response to the construction of an oversized trapezoidal channel, fluvial processes work to create a small effective discharge (inset) channel by building a floodplain or bench within the confines of the ditch. If conditions allow, these benches can reach a stable size, thickly vegetated with mostly grasses. The inset channel will often meander slightly within the ditch and will usually have steep (1:1) sides and a bed consisting of material courser than that of adjacent reaches where benches have not formed. Further details on fluvial processes in ditches are provided by Landwehr and Rhoads (2003), Jayakaran et al. (2005), Jayakaran and Ward (2007), and Powell et al. (2007a).

Sizing Approach

This paper outlines a strategy to size a channel system (see Figure 3) that has a compound cross section consisting of: (1) a channel that is sized to convey the effective discharge, (2) a bench to serve as a floodplain for the smaller effective discharge channel, and (3) a stage of adequate width to prevent flow overtopping the ditch banks and flooding surrounding land. The design procedure will create a channel system that based on our qualitative experience will then maintain the compound form.

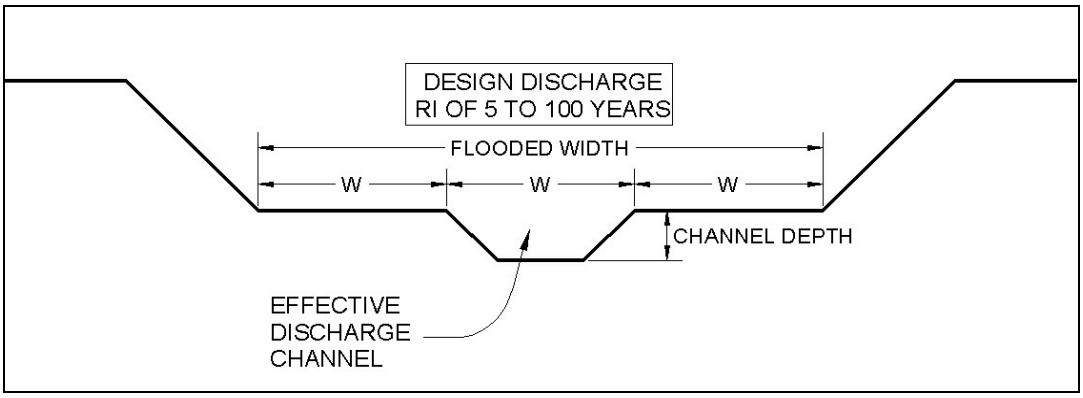

Figure 3: A two-stage channel geometry with minimum sized benches.

This section is based on Powell et al. (2007a). Similar information is also presented in USDA-NRCS (2007). Reference should be made to those publications to obtain complete details on sizing a two-stage system. Two-stage channel sizing, construction, and assessment procedures include nine steps: 1) project identification; 2) data collection; 3) data analysis; 4) hydrologic evaluation; 5) conceptual channel sizing; 6) project assessment; 7) final sizing and design; 8) construction; and 9) monitoring and performance evaluation.

Step 1: Problem Identification

The initial step for any design project is to evaluate the situation and identify problems and potential solutions. Identifying channel problems involves evaluating physical, hydrological, ecological, and chemical aspects of the channel and watershed. Streams are part of a complex system. Failure, recovery, and sustaining dynamic equilibrium might depend on upstream, downstream, and/or watershed and stream characteristics, as well as factors in the vicinity of the point or reach of interest.

Consideration must be given to land use changes on the watershed. Land use changes, such as urbanization or conversions of forests to agriculture, will usually increase peak discharges, the frequency of discharges, and the volume of runoff (Ward and Trimble, 2004).

Step 2: Data Collection

Following project identification, geomorphic data should be collected at the project site, at a reference site if possible, and throughout the watershed. A detailed study of the project site is always required. Measurements throughout the watershed provide information regarding the channel dimensions based on drainage area. It is recommended that channel geomorphology measurements be made using procedures that are consistent with those presented by Harrelson et al. (1994). Collecting data at the project site includes measuring the inset channel width and depth, and any associated benches. Bed slope, water surface slope, and floodplain slope should all be measured. A pebble count of the bed material should be conducted to estimate the median bed particle size. If the project site does not have an inset channel and benches, detailed measurements of the project site should still be performed. In addition, a reference site can be selected to provide additional information on similarly-sized stable channels.

Regional curve measurements should be taken at drainage areas that are smaller, larger, and similar to the project's drainage area that range through several magnitudes (Ward and Trimble, 2004). If a USGS gaging station is located within the project watershed, it is recommended that regional curve measurements be extended to include the gage station.

Step 3: Data Analysis

The following site specific data are needed to size a channel system: 1) drainage area; 2) channel slope; 3) inset channel dimension; 4) regional curve; 5) d_{50} and d_{84} bed material; and 6) bankfull discharge and an index of the frequency of out of bank discharges. Drainage areas are required for the project site, reference reach, and all locations where measurements were made for the regional curve. Determination of a representative channel cross-section aids in estimating the channel bankfull discharge and provides the framework necessary for any channel modification project.

A Wolman pebble count provides information on the particle size distribution of the bed material (Ward and Trimble, 2004). Channel systems that are in equilibrium should have a d_{50} or a d_{84} bed material size that falls within the upper and lower limits shown on Figure 4.

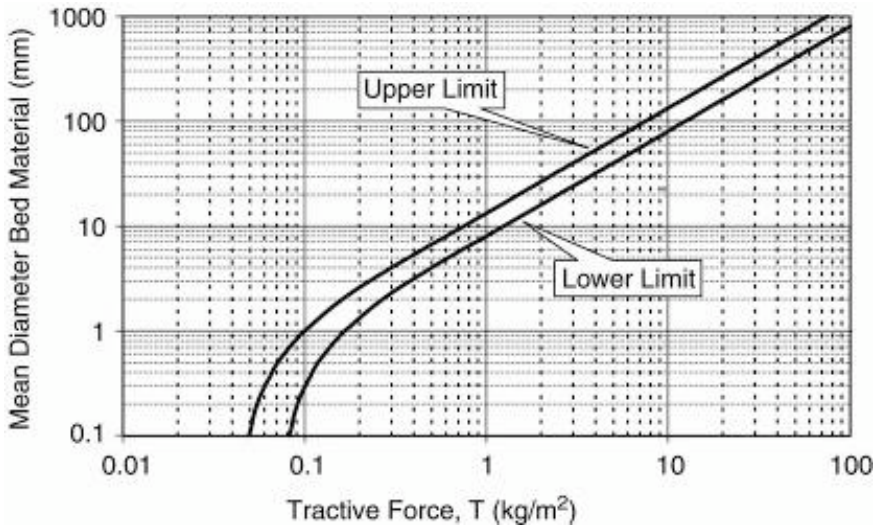

Figure 4. Mean bed material moved by tractive forces on a streambed (based on Lane, 1955; upper and lower limits by Ward; *Source: Ward and Trimble, 2004*)

The authors have developed the STREAM spreadsheet tools to assist in data analysis by reducing the number of hand calculations required and providing a uniform presentation of all collected data (Powell et al., 2006; www.dnr.state.oh.us/soilandwater/). These tools allow users to input measured data, including: meander pattern, bed and water profile, channel cross sections, pebble count, regional curves, and hydrology estimates, and then provide information on most of the factors that are needed to size a two-stage channel design.

Step 4: Hydrologic Evaluation

Included in the STREAMS spreadsheet tools are USGS empirical regression models for predicting peak discharges in urban and rural ungaged watersheds in Ohio. Other hydrologic estimates can be entered into the spreadsheet in place of the Ohio USGS estimates. Regardless of location, pertinent gage data should be used to first calibrate the hydrology method that is used. If actual flow data are not available for a location near the project site we recommend calibrating the hydrology method with data from the nearest USGS gage.

In Ohio, the bankfull channel usually conveys a discharge exceeding the average annual flow but not large enough to convey the two-year recurrence event (Powell et al., 2006). However, in ditch systems with low stream power and dominated by herbaceous vegetation the bankfull discharge for the inset channels is often much smaller. Sizing fluvial channels should never be based solely on a discharge associated with a specific recurrence interval.

In addition to providing adequate bench width, the second stage of the channel system should be able to transport a design flow that will prevent frequent flooding of adjacent areas. The maximum design flow is typically based on economic

criteria, including a cost-benefit analysis such as loss of crops, flooding, or maintaining capacity flow. Modification of a channel system to a two-stage geometry will usually provide a greater increase in conveyance capacity than maintenance activities to remove sediment deposits on the bed and benches.

Step 5: Conceptual Channel Sizing

A conceptual geometry is developed based on the weight-of-evidence collected through the previous sizing steps and flooding considerations. Sizing a two-stage channel involves first determining the inset channel geometry, which defines the bench height, then sizing the flooded width at the bankfull elevation of the inset channel, and finally determining the channel side slope for the second stage. The flooded width includes the width of the fluvial benches and the channel width.

The project drainage area is applied to the regional curves developed in step 3 to provide estimates for bankfull width, depth, and cross-sectional area. Estimates from the regional curve need to be compared with the actual measured fluvial features at the project site, the reference reach, the hydrologic estimates, the shear stress depth, and the depth associated with the channel forming discharge. If there is good agreement between all factors then the likelihood of success is high and the project should proceed.

The design of the new flooded width in the channel is a function of the top width of the inset channel (Figure 3). In systems with cohesive bank materials that can readily be vegetated with grass our experience is that the ratio of the flooded width to the inset channel width should be at least three. The bench elevation corresponds to the height above the channel bed as estimated by the inset channel depth; the existing bank will be excavated at the bench elevation. The second stage can also be sized to accommodate the maximum design flow rate used for the existing trapezoidal channel. Typically, provision of adequate floodplain will result in a second stage with more available conveyance capacity than existed prior to channel modification. The Contrasting Channel spreadsheet that is part of the STREAM spreadsheet tools includes a procedure to estimate effective discharge and depth of flow associated with the effective discharge (Powell et al., 2006).

Step 6: Project Assessment

Results from the previous five steps need to provide sufficient detail to obtain a cost-benefit estimate of the project. Each aspect of the two-stage design should be examined in the context of the specific project conditions. The two-stage channel concept involves widening the existing channel; the land owner must be willing to permanently have a small width of potentially farmable land excavated or agree to compensation for the loss of this land. An integral part of project assessment is the establishment of a post-construction management plan that should address landowner, engineering, and environmental concerns.

Step 7: Final Sizing and Design

If the decision in Step 6 is to move forward with the project then a final design will need to be developed based on the weight-of-evidence collected through the previous sizing steps. Depending on the client and legal requirements, this might require the preparation of engineering drawings that are approved by a licensed professional engineer.

The stability of two-stage systems is highly dependent on the quality and extent of vegetation on the benches. In our experience, grasses provide excellent protection for the two-stage channel. Woody vegetation as the dominant vegetation type on benches is not recommended because it often shades portions of the benches and limits the growth of necessary stabilizing grass cover.

Step 8: Construction

Construction of two-stage channel systems uses similar equipment to other types of ditch projects. It is recommended that an engineer provide oversight to the construction work. Of particular importance is that the benches be constructed at the correct elevation and with the correct dimensions. The low bank and channel bed can be left undisturbed (Figure 5). Existing vegetation on the inset channel bank can provide stability and facilitate the narrowing process. Timely establishment of grass on the disturbed surfaces is also important. During construction, consideration should be given to all drainage discharge pipes. Drainage pipes should be extended from the second stage channel bank across the benches or the benches should be stabilized if the pipes discharge directly on to them.

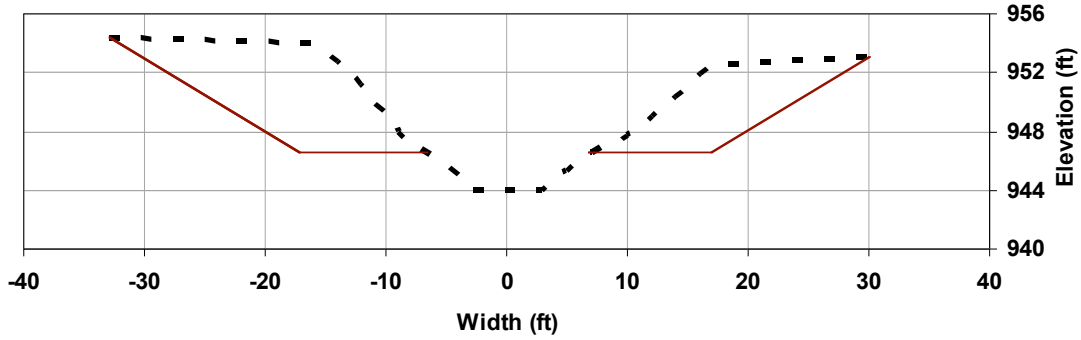

Figure 5. Construction of the Creel Ditch in Indiana. Top: Original geometry (dashed line) and constructed geometry (solid line) with no inset channel modification. Bottom: Construction of the bench and new side slope on one side of the ditch.

Step 9: Monitoring and Performance Evaluation

Very few agricultural Best Management Practices (BMPs), storm water management projects, and stream projects are evaluated following construction and, therefore, we have very little knowledge of how well or poorly any practice performs. To evaluate the implementation of management practices on river restoration projects, Palmer et al. (2005) presents five criteria for measuring success of river restorations.

Ideally, pre- and post-construction monitoring would consider ecology, geomorphology, and water quality. In Ohio, water quality is related to aquatic life use attainment and assessed using the Index of Biotic Integrity (IBI; Karr, 1981), the Invertebrate Community Index (ICI; Ohio EPA, 1987) and the Qualitative Habitat Evaluation Index (QHEI; Rankin, 1995). As these assessment methods are used in many parts of the United Stated it is recommended that, in addition to the data needed to size a two-stage system, pre-construction monitoring include making IBI, ICI, and QHEI assessments. Following construction, similar assessments together with geomorphology measurements should be made at least once annually for several years.

Discussion

The design procedures outlined earlier have been used for several applications in Ohio and Michigan (Powell et al., 2007b). While the procedures were initially developed for application in rural settings they are starting to see application as a storm water management strategy in urbanizing watersheds.

In the approach we have proposed the second stage (geometry between the benches and the top of the ditch) might be designed based on the recurrence interval of the discharge it can convey. Alternatively, it might be designed as a function of the bankfull width of the inset channel. A flooded width that is 3 to 5 times the bankfull width of the inset channel is recommended. Larger widths will provide more function and increase the likelihood of the inset channel establishing a more natural meander pattern. How cost considerations, the large loss of agricultural land, and the huge amount of earth moving will usually make it impractical to establish wider widths. Attempting to size the inset channel based on a recurrence interval will probably result in an oversized channel. Our experience with low gradient ditches in the Midwest region of the United States suggest that the effective discharge is associated with high flows from subsurface drainage systems and that these flows occur many times annually.

Potential benefits of a two-stage ditch over a conventional ditch are improved drainage function, better water quality and improved ecological function. Drainage benefits may include increased ditch stability, increased capacity and reduced maintenance. Evidence and theory both suggest that ditches prone to filling with accumulated sediment may require less frequent "dipping out" if constructed in a two-stage form. Second, channel stability may be improved by a reduction in the erosive potential of larger flows, as they are shallower and spread out across the bench. Stability of the ditch bank should be improved where the toe of the ditch bank meets the bench rather than the ditch bottom. This should result in less sediment from the channel system.

A two-stage channel system has the potential to create and maintain better habitat and improved water quality. The narrow deep fluvial channel provides better water depth during periods of low flow. Grass on the benches can provide quality in-stream cover and shade. The substrate in the fluvial channel is improved as the two-stage form increases sediment conveyance and sorting, with fines deposited on the benches and courser material forming the bed. As two-stage systems create a self-flushing system, reductions in suspended sediment loads might only occur in some cases if the establishment of a two-stage geometry is coupled with landscape soil conservation BMPs. Two-stage ditches might also be useful in improving water quality particularly for nutrient assimilation. A recently funded project will evaluate nutrient movement in channel systems with different geometries (Ward et al, 2008).

The primary costs of two-stage ditches are associated with the increased ditch width required. Wider ditch top width requires surrendering of surrounding agricultural

production land. The increased width requires additional initial earthwork. Costs for construction increase with both watershed size and ditch depth and might range from $5 to $20/linear foot for many agricultural ditches in the Midwest region of the USA.

To offset landowner costs the potential for including the bench width in buffer programs is being explored. Buffers have typically been measured from the top of the ditch. Alternatively measuring from the top of the small channel thus including the bench and the main side slope of the ditch is preferable from a water-quality perspective and profitability perspective.

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