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Chapter 10 Two-Stage Channel Design

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Cover photo: Low gradient, nonincising channels and ditches may be modified by creating a narrow flood plain, thereby creating some ecological benefits, while minimizing the need for maintenance (clean-outs).

Advisory Note

Techniques and approaches contained in this handbook are not all-inclusive, nor universally applicable. Designing stream restorations requires appropriate training and experience, especially to identify conditions where various approaches, tools, and techniques are most applicable, as well as their limitations for design. Note also that product names are included only to show type and availability and do not constitute endorsement for their specific use.

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Chapter 10 Two-Stage Channel Design

654.1000 Purpose

Constructed channels are part of extensive portions of productive agricultural land in the United States. These channels provide important drainage and flood control functions. However, these agricultural channels are often constructed as traditional trapezoidal ditches using threshold design techniques. While this approach is suitable in some areas, channels of this design can require frequent and expensive maintenance in other parts of the country. In addition, natural ecological functions are normally not a consideration in the design of these channels. This chapter presents an alternative design to the conventional trapezoidal drainage channel. This two-stage channel system incorporates benches that function as flood plains and attempts to restore or create some natural alluvial channel processes. However, these two-stage channels are not an exact copy of natural streams, as the width of the benches is often small due to the confining geometry of the constructed channel. This chapter 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. Although this chapter focuses primarily on an alternative design for constructed ditches, the technique may also have application in natural streams that have undergone incision or in streams where boundary constraints restrict restoration designs such as in urban or developed areas. A case study is also presented for a constructed two-stage ditch in Michigan.

This two-stage channel design approach is applicable to low gradient ditches and channels that are not undergoing incision.

Figure 10–1 Trapezoidal cross section of a constructed drainage ditch

654.1001 Introduction

Agricultural ditches and channels have long been used to provide important drainage and flood control. Historically, many of these drainageways are designed following threshold design techniques and result in a large, trapezoidal cross section. The primary purpose of the constructed channel is to convey water from agricultural fields.

Figure 10–1 illustrates the basic design configuration for a trapezoidal channel, and figure 10–2 is an example of one in Iowa. In many situations, the waterway does behave as a threshold channel, so this is an appropriate approach. However, when the waterway behaves as an alluvial channel, the ditch can be too entrenched and have overwidened bed widths. While the large section of a traditional agricultural drainage channel may provide sufficient flood conveyance, the more frequent discharges may not flow at a depth and velocity sufficient to move sediment through the reach. Deposition results, requiring maintenance to maintain the design flow capacity. As deposition occurs, bank stability may also become an issue as sediment deposits may force flows into one bank or the other. In addition, baseflows in this wide channel may have a depth which does not provide adequate aquatic habitat.

Figure 10–2 Drainage ditch constructed in north-central IA

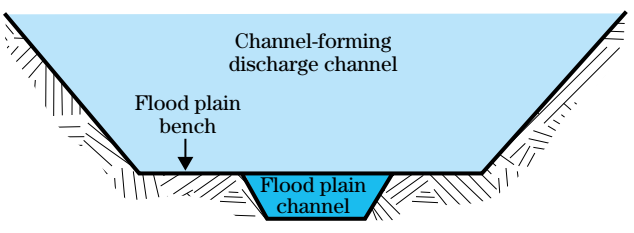
Fluvial processes at work in agricultural ditches functioning as alluvial channel systems often try to develop a flood plain that consists of low benches. While this deposition reduces flood capacity, these ditches show improved stability and improved habitat quality. This chapter presents a two-stage approach to design stable agricultural drainage channels (fig. 10–3). Specifically, the two stages are the:

- dominant discharge or channel-forming discharge channel
- flood plain bench or flood plain channel

This two-stage approach provides improved physical, as well as ecological performance. The channel-forming discharge channel provides the necessary sediment conveyance, while the flood plain channel provides for the design flood conveyance. By nesting the channel-forming discharge channel within the larger channel, the entire waterway is more stable.

The technique described herein uses bankfull discharge as representative of the channel-forming discharge. Therefore, the channel-forming discharge channel is referred to as the bankfull channel. The bankfull channel has also been referred to as the effective discharge channel. However, this is not necessarily accurate. There are no calculations made to define the effective discharge. Rather, this lower stage is assumed to be the bankfull discharge of a low-flow channel formed in a typical constructed ditch. The distinctions between bankfull, channel-forming, and effective discharge are addressed in more detail in NEH654.05. The differences between alluvial and threshold channels are addressed in NEH654.07.

Figure 10–3 Conceptual design for two-stage channel system



654.1002 Background

Highly modified channels drain extensive portions of productive agricultural land in the United States. Headwaters are typically the most modified. 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 maximize water conveyance. Work is done periodically to maintain the drainage function, which typically includes removal of woody vegetation, weeds, and deposited sediment. Ancillary work includes stabilizing bank slope failures and toe scour. Ditch form is a result of not only construction and maintenance, but also to verifying degrees, due to fluvial (flowing water) processes.

Ditch maintenance typically restores the ditch to a trapezoidal shape designed to transport large storm events (fig. 10–4). 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 channel relatively wide and shallow. Therefore, the constructed ditch channel is often oversized for small flows and provides no flood plain for large flows.

In contrast to trapezoidal agricultural drainage ditches, integral parts of many natural stream channels are the flood plains. The flood plains of natural 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 flood plain to dissipate the energy of high flows and to concentrate the energy of low flows to effectively create a balance in sediment transport, storage, and supply. In natural alluvial streams, fluvial processes work to size and maintain the dimensions of the bankfull channel based on the effective discharge (Ward and Trimble 2004).

In response to the construction of an oversized trapezoidal channel, alluvial channel processes often work to create a small bankfull channel by building a flood plain or bench within the confines of the ditch (fig. 10–4). If conditions allow, these benches can reach

a stable size, thickly vegetated with mostly grasses. This results in a two-stage channel. The small bankfull channel will often meander slightly within the ditch. The bankfull channel will usually have steep (1H:1V) sides and a bed consisting of material coarser than that of adjacent reaches where benches have not formed. Further details on fluvial processes in ditches are available form Landwehr and Rhoads (2003) and Ward, Mecklenburg, and Brown (2002). It is important to note that these deposits within a constructed trapezoidal ditch reduce the overall flood conveyance. As a result, the channel may no longer provide the designed flood protection.

(a) Advantages of a two-stage channel

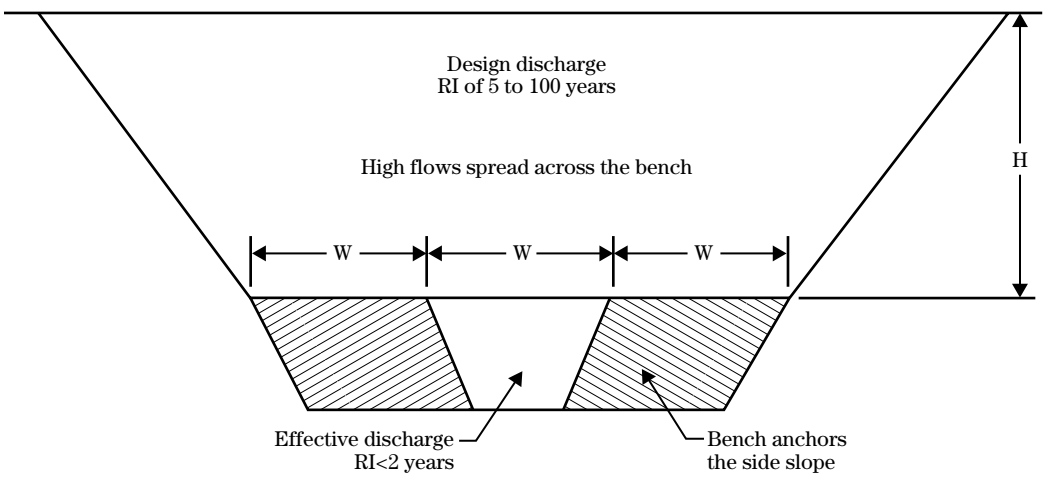
Benefits of a two-stage ditch over a conventional trapezoidal ditch are potentially both improved drainage function and ecological function. Drainage benefits may include increased ditch stability and reduced maintenance. Evidence and theory both suggest that ditches prone to filling with accumulated 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 (fig. 10–5).

Figure 10–4 Ditch before maintenance and after maintenance (MN)

(a) Before

(b) After

Figure 10–5 Two-stage ditch geometry with minimum sized benches



Stability of the ditch bank should be improved where the toe of the ditch bank meets the bench, rather than the ditch bottom. Here the water depth is effectively reduced, and the shear stress (erosive force) on the toe of the bank is less. Also, not being in contact with low flow, this bank material will be dryer and can be stabilized with vegetation using threshold design techniques as described in NEH654.08. Since a two-stage channel in an alluvial system will be more likely to retain its design shape, it is easier to predict its flood protection performance.

The biggest advantage of these two-stage channels is the ability to transport sediment more effectively. However, the two-stage ditch also has the potential to create and maintain better habitat than a conventional trapezoidal ditch. The narrow, deep bankfull channel provides better water depth during periods of low flow. Grass on the benches can provide some instream cover and shade. The substrate in the bankfull channel is improved as the two-stage form increases sediment conveyance and sorting, with fines deposited on the benches and coarser material forming the bed.

(b) Design of a two-stage channel

Design and construction of two-stage channels is different than that of traditional trapezoidal channels. The design of a two-stage agricultural ditch in an alluvial channel system involves correctly sizing the bankfull channel and minimum bench widths for the flood plain bench. The dimensions of the bankfull discharge or fluvial channel dictate the two-stage channel design. If properly sized, the bankfull channel will be maintained by fluvial processes and will reduce or possibly even eliminate large-scale channel maintenance. The flood plain bench serves as a flood plain for the smaller bankfull channel, but it acts more as a threshold channel. The upper stage must convey the channel-forming discharge and must have an adequate size to prevent design flood flows from overtopping the ditch banks and flooding surrounding land.

654.1003 Field measurements

Initial reconnaissance of the site area is recommended to establish a base knowledge of the project characteristics, surrounding area, and regional environment. The unique characteristics of the project site will generate the criteria for regional measurements. If searching for a reference reach, the watershed area, vegetation, soil, land use, and slope should correspond to the site in question.

Where a modification will be made to an existing channel, detailed measurements should be made of the channel profile and the dimensions of the bankfull channel and benches that have formed within the channel system. Often, the bankfull channel will be overwidened, and the benches will be intermittent and sloping. Guidance on performing such investigations is provided in NEH654.03. Conducting an onsite geomorphology study is a simple and reliable method, but is only adequate if:

- a bankfull channel and benches have formed
- the project length is short; the drainage area is relatively constant

A detailed survey along the reach of interest, or a reference reach, consists of measuring the profile, pattern, and dimension of the channel. The profile is the slope of the bed surface including all pools, riffles, and runs. The undulating elevations of the channel bed leads to questions of the true channel profile. To compensate for the bed slope variability, the water surface is also measured to represent the slope of the channel. The pattern of a reach measures the sinuosity of the bankfull channel. This is obtained using a compass and measuring the azimuth from magnetic north. The dimensions of the channel are obtained by surveying cross sections, either at increments along the reach or at representative cross sections. A laser level and survey tape, or a total station instrument, are often used. The distance from the left channel bank and the change in elevation are measured for each grade break across the channel cross section. A pebble count should be performed to estimate the mean bed particle size. Guidance for performing pebble counts is provided in NEH654 TS13A.

654.1004 Bankfull channel design

The first step in developing a two-stage design is determining the probable dimensions of the bankfull channel. This channel will carry most of the sediment in the channel. The width of the bankfull channel is a key design characteristic. It will determine the success in achieving the intended drainage effects, as well as ecological benefits. Channel design dimensions are determined by measuring the bankfull discharge features or calculating the effective discharge at the project site and then by creating a watershed specific regional curve for the project.

(a) Regional curve development

The probable dimensions of the bankfull channel can be empirically determined based on regional studies similar to those that are conducted for natural streams. Typically, for natural streams this knowledge is acquired by developing regional curves that relate the bankfull channel dimensions to drainage area. Traditional regional curves are created by performing numerous profile and cross-sectional surveys at locations with different drainage areas, which often include U.S. Geological Survey (USGS) stream gage sites as described in NEH654.05 and NEH654.09. The regional sites should be selected to provide fluvial information over a range of drainage areas that can be plotted to show channel dimension relationships to drainage area.

Measurements can be taken at the water surface and the bankfull fluvial features. Each gage station has a unique rating curve, which is a relationship between the gage reading and the streamflow rate. The bankfull height at each gage can be obtained by the measurements at bankfull and the waters surface along with the USGS real-time gage value. However, it is important to note that while each gage station may have a unique rating curve, the relationship between gage height and discharge is not necessarily unique. The rating curve may shift over the long term as the cross-sectional shape and/or elevation changes, and it may shift over the course of a hydrograph due to the unsteady loop effect or changing bedforms. If the rating curve is applicable, these values, combined with the width, will provide an additional point when creating a regional curve. An applicable and complete regional curve can be a valuable tool for two-stage channel design, as well as many other stream design activities.

Care must be taken with the use and development of the regional curves. The data used to develop a curve needs to be from physiographically similar basins. Drainage network patterns and the relative location of the channel site with respect to uplands are significant characteristics. The bed and bank characteristics used in the regional curve development should be the same as those at the project site. Issues related to the development and use of regional hydraulic geometry curves are described in more detail in NEH654.09.

Small watersheds that are drained by agricultural ditches can present particular challenges in the development of traditional regional curve data. In most parts of the Nation, there are a limited number of small-gaged watersheds, and these typically have short records or have been discontinued. Some additional difficulties associated with developing regional curves are that gages are often located at road crossings or the reach within the vicinity of the gage is highly modified.

(b) Rapid regional curve development

For two-stage channel design in many agricultural watersheds, an abbreviated rapid regional curve may be adequate. The method consists of finding ditches or streams with well-developed benches/flood plains and measuring at least the width and depth of the naturally formed bankfull channel. The selected channels must have reached a state of equilibrium and must be stable. Sites for any regional curve should also have similar characteristics to the project site and should come from physiographically similar watersheds. Several measurements should be taken for each range of drainage areas to verify that the measured feature is consistent with those across the watershed. Whenever possible, precision surveying instruments should be used to make the elevation and distance measurements.

Traditional regional curves are created by performing numerous detailed surveys at locations with different drainage areas. In contrast, a rapid regional curve channel dimension measurement consists of quickly

measuring visual fluvial features with a 100-foot tape and a telescoping leveling rod. The channel dimensions taken at a complementary range of several drainage areas should provide a sufficient spread for each log cycle. The bankfull dimensions of width and depth are measured where visible fluvial features are noticed. The drainage area for each measurement is acquired from a variety of methods such as calculating the area by hand using a planimeter or computer GIS software. The measured dimensions can be the plotted area versus drainage area, and a power regression equation can be fitted to the data. This equation can be used to estimate the bankfull channel design dimensions for a ditch, given the drainage area.

This rapid regional curve approach has been used on several watersheds in Ohio. Reportedly, this approach typically provides relationships between the bankfull channel and drainage areas with r^2 values of 0.8 or greater (Ward 2005; Ward et al. 2003).

(c) Reference reach

Measurements from a reference reach can provide valuable design guidance for the design of the bankfull channel. Typically, for natural streams this knowledge is acquired by conducting detailed surveys along a reach of interest and by conducting a detailed survey of a reference reach along the same stream or a similar nearby stream system. However, finding reference reaches can be a time consuming, costly, and frustrating activity. The attributes of the local subwatershed, such as the topography, soil and bedrock properties, vegetation on the banks and adjacent riparian zone, and size and characteristics of the active flood plain, can result in a variety of different stable channel dimensions for similar-sized drainage areas within a watershed or region. For a reference reach to be directly applicable, it must have similar climate, history, drainage area, and watershed conditions. More information on the identification and use of reference reaches is provided in NEH654.09 and 654.12.

654.1005 Flood plain channel design

The formation of benches in constructed ditches is the natural result of fluvial processes in most alluvial systems. The bench acts as a flood plain within the ditch to dissipate energy, reduce the erosive potential of high-flow volumes, and reduce the shear stress on the bank toe. In establishing two-stage geometry, it is often not cost effective or practical to form a flood plain as wide as fluvial processes would form under natural conditions. Large, deep agricultural ditches have often already been constructed to handle discharges from subsurface drainage systems. Making these large ditches even wider would result in extensive earth moving, high cost, and substantial losses in productive agricultural land. Therefore, the ability of these small flood plains (benches) to aid in developing a self-sustaining system is dependent on the establishment of dense grass cover on the benches and banks of the ditch. Also, the side slopes and depths of the ditch above the benches must satisfy geotechnical engineering requirements to provide bank stability.

In a designed two-stage channel, the elevations of the flood plain channel benches are dependent on correctly determining the size of the bankfull channel. The flooded width is defined as the total width across the ditch at the stage elevation where benches have formed and/or are anticipated to form. The two-stage width ratio is defined as the flooded width divided by the top width of the bankfull channel. Based on visual observations and modeling bed-load transport, two rules of thumb have been established:

- If the total width, when out-of-channel flow is initiated, is less than three times the top width of the bankfull channel, the benches might not fully develop, the benches are more likely to be unstable, and shear stresses on the bed and banks of the ditch will be high during large events.
- If the total width, when out-of-channel flow is initiated, is more than five times the top width of the bankfull channel, the channel will begin to exhibit a natural meander pattern that, at places in the ditch, is likely to cut into the banks of the ditch.

Therefore, when out-of-channel flow is initiated, the designed target total width should be between three to five channel widths (total bench sizes that are two to four times the channel width), if the objective is to provide adequate conveyance capacity and a more self-sustaining system, while maintaining a relatively straight ditch geometry. If the project goals or the stability requirements of the channel design require the development of a sinuous channel, a wider bench may be required. However, channel alignment design elements, such as are described in NEH654.12, will need to be addressed so that a stable planform is chosen.

654.1006 Flood conveyance

The overall conveyance capacities of the two-stage systems can be sized based on the probability of out-of-ditch flooding into adjacent areas. This probability is based on the recurrence interval storm event that the entire ditch can transport. Where possible, stream gage data should be used to determine the discharges associated with a prescribed recurrence interval. However, in most parts of the Nation, there are limited numbers of small watershed gages. Typically, these gages have short records or have been discontinued. Therefore, measured streamflows at locations without gages are determined from hydrologic models or from regional discharge curves. One source of regional discharge information is the National Flood Frequency (NFF) Program. The NFF Program includes 2,065 regression equations for 289 flood regions nationwide. These equations are contained in a Windows® program for estimating the magnitude and frequency of peak discharges for unregulated rural and urban watersheds. This program can be obtained at the following Web site:

http://water.usgs.gov/software/

Since most two-stage channels are of fairly uniform section and constant slope, a resistance equation, such as Manning's equation, can be used to calculate the depth corresponding to the design flow recurrence intervals.

654.1007 Spreadsheet tools for data analysis and design

Many of the calculations for two-stage channel assessment and design can be performed with the help of computer spreadsheets. One set has been developed by the Ohio Department of Natural Resources (ODNR). This suite of spreadsheet tools can be obtained from the following Web site:

http://www.ohiodnr.com/soilandwater/streammorphology.htm

These spreadsheets aid in designing a new bankfull channel together with various size benches, based on the following:

- a regional curve for the area
- cross-sectional data for a ditch or channel reach
- profile data for the reach that can include bed, water elevation, bench, and top of ditch data
- the D_{50} fraction of the bed material
- user-defined adjustments to the channel, bench, and ditch geometry

The channel width, depth, and cross-sectional area associated with the bankfull discharge at each location surveyed are entered into the spreadsheet to develop a regional curve. The calculated drainage area and bankfull discharge at each location are also entered into the same spreadsheet. A log-log plot is then made of each bankfull discharge dimension versus drainage area. A least-squares analysis is then used to fit a power regression line (a trend line) through each set of data and calculate the coefficients of the regional curve.

In the spreadsheet, stage-discharge relationships for each site are obtained based on Manning's equation. A separate Manning's n value is used for the bankfull channel and the vegetated benches and banks of the ditch. The roughness of the bed, banks, and benches vary seasonally based on winter conditions, vegetation growth, maintenance, and scour or deposition on these features. Therefore, the approach used only provides a general representation of roughness conditions. User-defined discharge versus recurrence interval data, or estimates based on the USGS Urban Method for Ohio, are used together with Manning's equation to calculate the flow stage associated with each recurrence interval. The ODNR channel design spreadsheet is programmed to obtain coefficients for recurrence intervals of 0.25, 0.5, 1.0, and 1.5 years.

In the spreadsheet, bed-load transport in the bankfull channel is calculated based on the probable discharges that will occur during a 100-year time period, the D_{50} of the bed material, and based on estimates obtained from the Meyer-Peter and Müller bed-load transport equation (Ward and Trimble 2004). Estimates are obtained for the bed load, recurrence interval of the bankfull discharge, and probable stage of the bankfull discharge.

While these spreadsheet tools have been developed to aid in the analysis of stream form and processes, they are best applied to alluvial stream systems that are a function of the bankfull discharge.

(a) Site selection and reconnaissance

Potential sites for regional curve measurements were marked on Michigan, Indiana, and Ohio State Gazetteers published by DeLorme. Sites were selected to provide data for several sized drainage areas within each log cycle. Due to the remoteness of the area from Columbus, Ohio, no preliminary reconnaissance was conducted. At each site, the widths and depths associated with grade breaks were measured using a 100-foot tape and a telescoping surveying rod. A more detailed and accurate survey was conducted at the Hillsdale ditch using a laser level, 100-foot tape, and a telescoping rod with a laser receiver. At that site, cross-sectional information was obtained every 100 feet, and the location of the thalweg was noted. On November 16, just prior to construction of the two-stage geometry, a pebble count was conducted for reaches 600 to 800 feet, 800 to 1,000 feet, and 1,000 to 1,200 feet.

(b) Regional curve

Data were obtained at 14 locations within a 600-square-mile drainage area. A regression analysis of the data (fig. 10–7) indicates that the bankfull discharge dimensions are highly correlated with drainage area.

The poorest correlation is with channel depth, perhaps because some of the channels were associated with streams that were highly connected to the flood plain, while others were associated with grade breaks and small bench formation in ditches. The Hillsdale ditch has a 4.5-square-mile drainage area, and its measured channel dimensions are located almost exactly on the regression lines.

(c) Discharge data

The regional curve analysis was extended to the USGS gage on the St. Joseph River near Newville, Indiana. Streamflow data for this gage was obtained from the following Web site:

http://water.usgs.gov/oh/nwis/rt

At this site, a laser level was used to determine the bankfull discharge and water surface elevation. Real-time gage data were available at the time the survey was performed and downloaded from the Internet. Due to deep flow conditions, it was only possible to estimate the width of the river by making a measurement on the road across the bridge.

(d) Discharge versus recurrence interval

An annual series of peak flow data for the period 1947 through 2002 were available for the gage on the St. Joseph River near Newville, Indiana. The Weibull method (Ward and Trimble 2004) was used to develop a plot of discharge versus recurrence interval data resulting in a high correlation (r^2=0.96) between peak discharge and recurrence interval.

Example 10–1: Hillsdale County case study

The Hillsdale County, Michigan, case study was conducted as part of a demonstration project for The Nature Conservancy, Upper St. Joseph River Project Office, and is funded with a grant from the Great Lakes Commission. The survey was conducted in July 2003, and an existing ditch was modified to a two-stage geometry in November 2003 (fig. 10–6). The project site is located in Hillsdale County, within the St. Joseph Watershed (MI). In 1997, the ditch was cleaned out as part of a maintenance action and in July 2003, had 0.5 to 2.0 feet of sediment deposits on the bed and had formed small intermittent benches.

Figure 10–6 Ditch before construction at location 1,000–1,200 ft, and after widening of small benches at location 1,600–2,100 ft (Hillsdale County, MI)

(a) Before

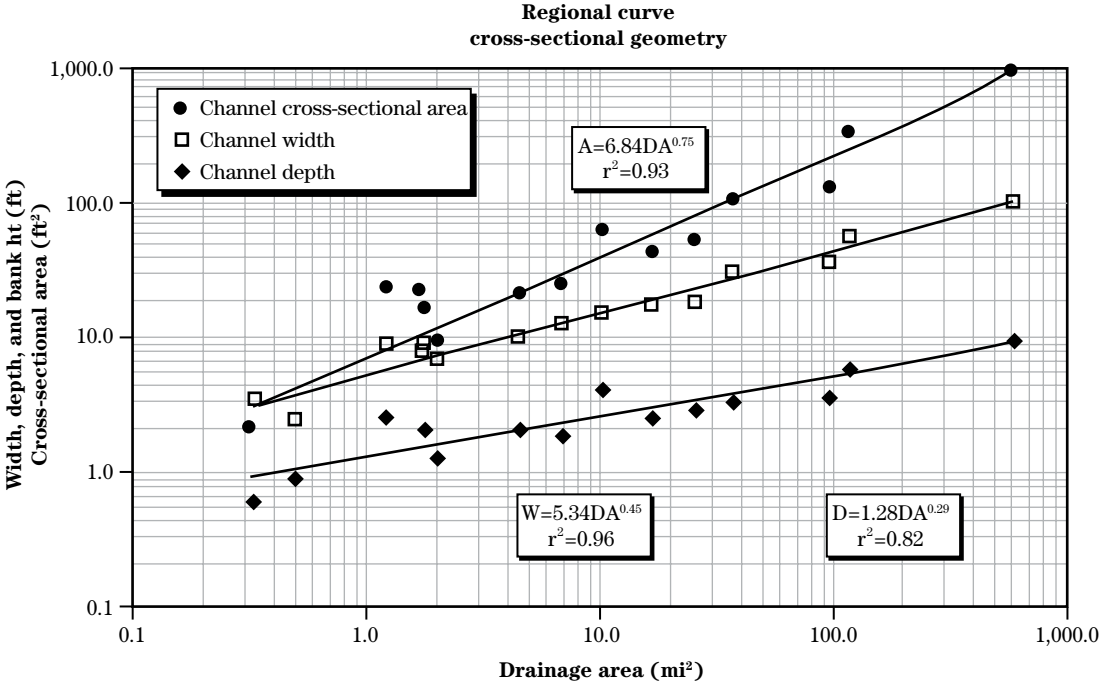
(b) After

On the day of the survey, the water depth at the gage was about 3.7 feet (based on the real-time measurement from the USGS NWIS Web site), and the bankfull discharge dimensions were measured on both banks at about 3.7 to 5.4 feet above the water elevation. The most dominant feature was a continuous approximately 20-foot high bench that was located on the left bank. A shorter bench at a similar elevation was located on the right bank. Therefore, it was estimated that the bankfull stage was 7.4 to 9.1 feet.

An approximate rating curve for the gage was created using data from the USGS Web site. The bankfull discharge was estimated from the survey data, and the rating curve to be between 740 and 1,330 cubic feet per second. While this is a wide range, an analysis of the recurrence interval curve indicates that this corresponds to a recurrence interval that is much more frequent than 1 year. This frequent occurrence is not surprising. In flat, poorly drained areas in the Midwest, where subsurface drainage is widely used, the bankfull discharge occurs frequently and primarily due to subsurface drainage discharges. Since this bankfull discharge is associated with high subsurface flows, it is usually associated with a recurrence interval that is much more frequent that one year (Ward 2005; Ward et al. 2003).

An analysis of the daily flow records shows that discharges within this range or larger occur on average 40 to 80 days annually. This range of flow seems to be too frequent to correspond to the bankfull or channel-forming discharge. However, an analysis of the daily flows exceeding 1,330 cubic feet per second revealed that, on average, they are associated with 1 to 13 discharge events annually, and the duration of these flows ranged from 1 to 49 days. High flows lasting many days typically occurred between November and April. On

Figure 10–7 Bankfull discharge channel dimensions for the St. Joseph River (OH) upstream of the gage near Newville, IN



average, annually, there are slightly more than five events, with an average duration of 8 days that exceeded 1,330 cubic feet per second.

A bankfull channel associated with very frequent flows is consistent with observation by Ward, Mecklenburg, and Brown (2002) in Wood County, Ohio. However, in a recent study, they noted that typically, only about 10 percent of the sediment is transported by flows that are less than double the mean discharge. For most of the gages, less than 25 percent of the sediment load is transported by flows that are 3 to 5 times the mean discharge. (Ward et al. 2003). For example: the mean annual discharge for the St. Joseph gage is about 540 cubic feet per second, so it is probable that a discharge of 1,330 cubic feet per second or higher corresponds to the bankfull discharge at the gage.

At the gage, the river was very entrenched the top of the bank corresponded to a stage of at least 16 to 18 feet (not measured). From further analysis, it was estimated that the out-of-bank discharge is 6,000 to 9,000+ cubic feet per second and corresponds to a 4- to 20-year recurrence interval flow. Therefore, at this location, the behavior of the river is similar to that of a ditch.

The results of discharge versus recurrence interval estimation analysis are presented in table 10–1 for this example. The gage data results were obtained from the regression equation. At the gage, the USGS Rural method gave similar results to the gage data. However, the USGS Urban method greatly overestimated the discharges, even though an annual precipitation of only 32 inches was used, rather than the 34 to 35 inches suggested by the annual precipitation map for Ohio (Ward and Trimble 2004). For the rural equation, a slope of 0.1 percent (5.2 ft/mi) and a storage value of 3 were used. At the Hillsdale ditch, the urban method also gave much higher estimates than the rural equation. However, if the urban method were calibrated based on the ratio of the urban to gage data results, the urban and rural methods gave similar results, except for a recurrence interval of 2 years. It was decided to base the analysis on the rural equation results. For this ditch, knowledge of the actual discharge versus recurrence interval has little influence on the design. The ditch is extremely large, and regardless of what estimates are used, the out-of-bank discharge is associated with a recurrence interval greater than 100 years.

Table 10–1 Discharge vs. recurrence interval results at the gage and the Hillsdale ditch

	St. Joseph gage			Hillsdale ditch		
Recurrence interval (years)	**Gage data**	**USGS Urban method**	**USGS Rural method**	**USGS Urban method**	**Urban calibrated**	**USGS Rural method**
2	4160	4902	5261	176	149	110
5	6337	9735	7365	302	197	171
10	7984	13920	8635	373	214	205
25	10162	22495	10148	546	247	246
50	11809	30121	11141	663	260	274
100	13456	37488	12148	786	282	301

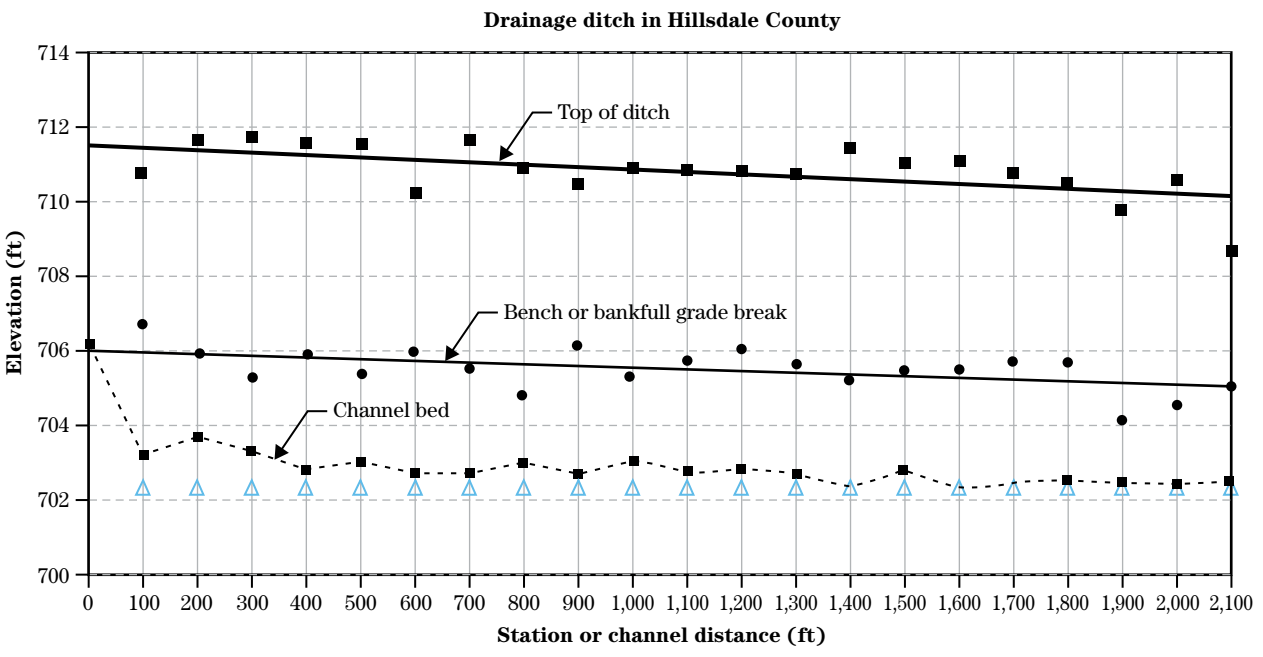
(e) Ditch geometry

A survey of a 2,100-foot length of ditch was performed on July 17, 2003. Station 1+00 is located 100 feet south of the upstream bridge, and station 21+00 is located near the southeast corner of the field on the right bank. This location is close to the Michigan-Ohio state line and the point where the ditch enters a wooded area.

Working conditions in the ditch were difficult because of steep slopes, dense vegetation, and deep deposits of fine sediment in the bottom of the ditch. Therefore, cross-sectional data were obtained by locating a person with a rod and receiver on each side of the ditch and stretching a tape between the two people. Each person took elevation and position data on their side of the ditch and part of the bankfull channel. Notes were made indicating the location of the thalweg in the bankfull channel, and the water depth. Thalweg data were then used in place of conducting a separate profile survey. Also, grade-break data and top-of-bank data were extracted from the cross-sectional data to obtain profiles of these features. Profiles of the various features are shown in figure 10–8. All elevation data are relative to an arbitrary datum. For most of the ditch, the bed slope varied from 0.05 to 0.2 percent.

A typical cross section is shown in figure 10–9, with a possible new design with a 4:1 overtopped width to channel-width ratio. For a 4:1 ratio, the total width of the benches is three times the width of the bankfull channel. The top width of the bankfull channel is 10 feet, the mean depth is 1.8 feet, and the maximum depth is 2.3 feet. Based on an analysis of the data, the maximum stable size of this channel might be 12.3 feet wide, with a mean depth of 2.2 feet, and a maximum depth of 2.8 feet. The channel has a 0.1 percent slope, the channel dimensions estimated from the regional curve (top width of 10 ft and maximum depth of 2.3 ft), and an over bench flow width to channel width ratio of 4:1. The 0.2-year recurrence interval discharge almost fills the small channel, the 1.6-year recurrence interval discharge fills the channel to a depth of about 4.5 feet, and the stage for the 100-year discharge is just over 5.5 feet. For these conditions, fine sediment will be flushed from the bankfull channel, and substrate with a mean size of about 3 to 4 millimeters will be established.

Figure 10–8 Profiles of the bed, bench, and top of ditch



This ditch was cleaned out about 6 years prior to this survey and only exhibited intermittent small bench formations along much of its length. There was up to 2 feet of sediment deposited on the bed in the first few hundred feet, perhaps because of the culvert configuration and a rapid change in bed elevation. Further downstream from the bridge, the bench formations improved, the depth of the sediment deposits decreased, and in places (1,000 to 1,400 ft), clean, coarse substrate was observed in the bottom of the bankfull channel.

(f) Bed material and bed-load transport

The measured D_{50} and D_{84} for reaches 600 to 800 feet, 800 to 1,000 feet, and 1,000 to 1,200 feet were <1 millimeter, <1 millimeter and 12 millimeters, and 3 millimeters and 10 millimeters, respectively. More than 80 percent of the bed material was clay and silt where there were only small intermittent benches (600–800 ft). In the next two reaches, the bench development was more pronounced, and the main channel was narrower, resulting in the coarse substrate sizes. Pebble counts for the last 200 feet (1,000–1,200 ft, fig 10–6a) had the coarsest substrate, widest benches, and narrowest bankfull channel.

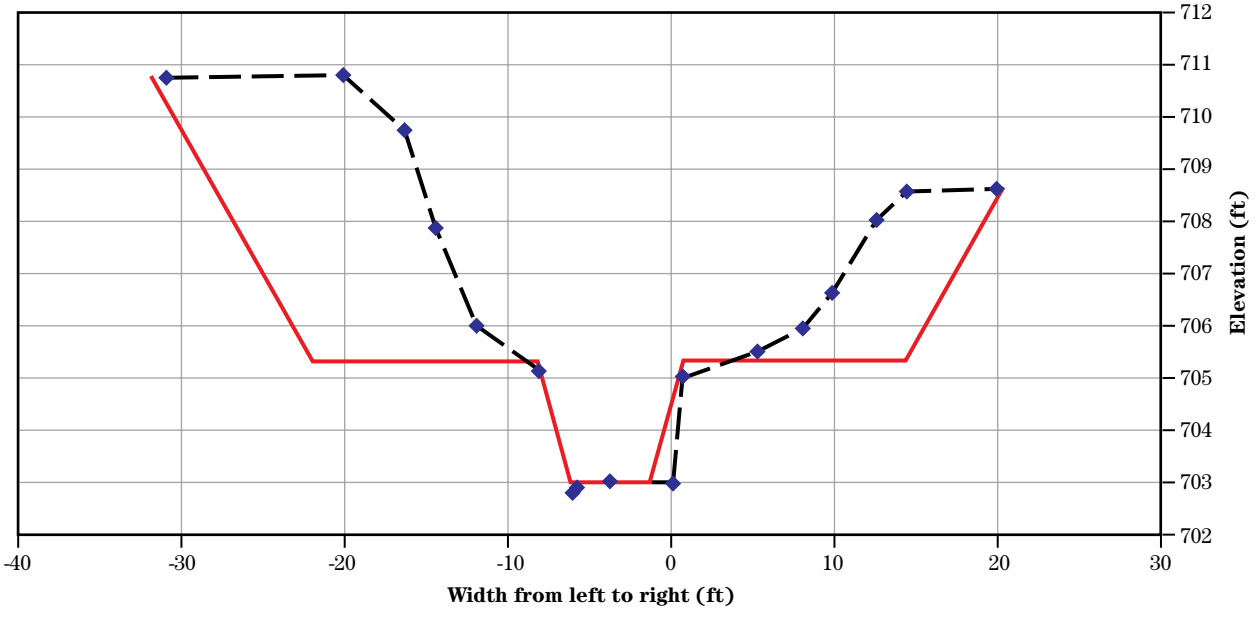
The mean bed-material size is associated with the tractive force (mean shear stress) on the bed and can be estimated as (Ward and Trimble 2004):

$$D_{50} = 1000ds$$

where:
D_{50} = particle size (mm)
d = flow depth (m)
s = bed slope (ft/ft)

Therefore, a 0.6-meter (2.0 ft) bankfull discharge depth in a channel with a bed slope of 0.1 percent might result in a D_{50} of 6 millimeters. The bed slope varies from 0.05 to 0.2 percent, and the bankfull discharge depth is 1.8 to 2.5 feet, so the probable D_{50} is about 3 to 13 millimeters. This is in good agreement with the measured D_{50} and D_{84} of 3 millimeters and 10 millimeters in the channel at reach 1,000 to 1,200 feet, where fluvial benches have formed.

Figure 10–9 Pre- (dashed line) and post- (solid line) maintenance geometries at a location with a grade break, but weak bench formation at the elevation where it was determined that a bench would naturally form. The existing main channel has a similar geometry to the projected geometry.



While this equation is readily applied, it should be noted that it contains some inherent assumptions. Its use assumes that sufficient coarse material is available to form the armor layer. If sufficient coarse material is not available, then this approach may not be advisable.

Actual bed-load transport is difficult to quantify because of the complexity of the system and the lack of any sediment transport data. Relative bed-load estimates were obtained by relating bed-load transport to the current channel conditions: a bed slope of 0.1 percent and a D_{50} of 2 millimeters. The geometry for current conditions was approximated as a cross-sectional area that is three times the area predicted by the regional curve and an over-bench flow width to channel width ratio of 1.5. The results of the bed-load transport analysis results are summarized in table 10–2. It is anticipated that fluvial processes will establish a coarse substrate with a mean particle size of 4 to 8 millimeters, and bed-load transport will be less than half current rates. Following the flushing of deposited fines, and bench building by fluvial processes, the total sediment export will primarily be a function of conservation practices on the landscape and ditch instability problems upstream of this reach.

(g) Discussion

In establishing two-stage geometry, the ditch is widened at the elevation that corresponds to existing bench features or the elevation at which these benches are predicted to form from fluvial processes. Vegetation is left along the fringe of the existing channel, and no work is done to reshape or narrow the current channel. The benches will vegetate quickly, and it is anticipated that the channel will adjust its shape as a function of fluvial processes.

A much debated and often controversial issue is the type of vegetation that should be established on the benches and at the top of the ditches. Trees provide many benefits in natural stream systems and are particularly important for the aquatic biota. However, in straightened, channelized systems, grass might provide better overall benefits. Often trees will affect the ability of nature to establish stable benches, as much of the stability of these systems depends on the dense grass cover that quickly establishes, in the absence of trees. A way of viewing these systems is to think of the small bankfull channels as meadow streams (Rosgen type E channels) that lack the sinuosity that occurs in natural systems. Therefore, trees will often provide the most benefit if they are set back from a grass buffer at the top of the two-stage system or at locations where there is a wide, well-attached flood plain—something that is rarely found in watersheds with extensive networks of agricultural ditches. Constructing wide benches with a 10:1 or larger flood-width ratio might be considered, but that approach will be very expensive in locations where the main function of the ditches is primarily to convey discharges from subsurface drainage systems. In those situations, the ditches must be more than 5 feet deep and sometimes are more than 10 feet deep.

Table 10–2 Relative bed-load transport for various channel conditions

Geometry	Bed slope 0.05%		Bed slope 0.1%		Bed slope 0.2%	
	Relative bed load	D_{50} (mm)	Relative bed load	D_{50} (mm)	Relative bed load	D_{50} (mm)
Current	0.36	2	1	2	2.45	2
3:1 bench ratio	0.06–0.18	4–6	0.28–0.49	6–8	1.03–1.38	8–10
4:1 bench ratio	0.04–0.16	4–6	0.25–0.45	6–8	0.96–1.30	8–10

The primary costs of two-stage ditches are associated with the increased ditch width required. This increased width requires additional initial earthwork. Costs for construction increase with both watershed size and ditch depth and might range from $5 to $20 per linear foot.

Creating a low bench typically requires the top width of the ditch to be greater than what would be required for a traditional trapezoidal channel. It is important to note that the wider ditch top width results in the surrendering of surrounding agricultural production land. To offset landowner costs, the potential for including the bench width in buffer conservation programs should be considered. Buffers have typically been measured from the top of the ditch. Alternatively measuring from the top of the small channel to include the bench and the main side slope of the ditch is preferable from a water-quality perspective and profitability perspective.

In many locations, a do nothing approach might be considered. Removing benches will only provide an increase in the conveyance capacity of the ditch. However, this improvement might only be temporary. If subsurface drains are free flowing and not blocked by bench formations, constructing wider benches may provide limited benefit and could disrupt a functional system that currently provides aquatic and terrestrial habitat and water quality benefits.

654.1008 Conclusion

In channelized ditches and streams that are entrenched and have overwidened bed widths, alluvial channel processes try to develop a flood plain that consists of low benches. Often, these ditches show improved stability. The techniques presented in this chapter are based on observations and analysis of the behavior and evolution of traditional trapezoidal earth channels.

The elevation of the benches and size of the bankfull channel can be determined from regional curves that relate channel dimensions to drainage area. The design approach considers the magnitude and design frequency of discharges for both stages of the channel. It is anticipated that total bench widths that are two to four times the bankfull channel width will result in a stable geometry and a channel with low sinuosity. The overall conveyance capacities of these two-stage systems can be sized based on the probability of out-of-ditch flooding into adjacent areas.

Construction of a two-stage channel system requires a significant capital investment to create a wider design top width. However, it is anticipated that two-stage systems will have improved conveyance capacity, be more self-sustaining, and create and maintain improved aquatic habitat.