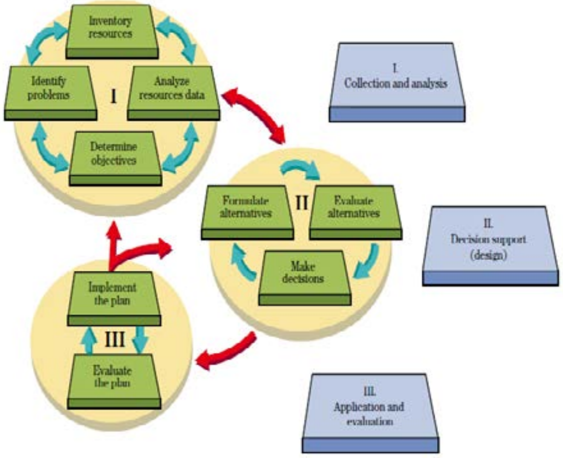
Alternative Design Options for Open Channels: Two-Stage Ditches and Self-Forming Channels



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Deliverables:
1) Technical Support Document on Alternative Channel Design Options
2) Identification of Resource Concerns for Channels
3) Decision Aids and Guidance for Local-Level Decision Makers
4) Spreadsheet Design Tools for Alternative Channels
5) Educational Materials to Facilitate Technology Transfer
6) Workshop Opportunity
7) Post-Project Presentation

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Executive Summary

Alternative channel designs including the two-stage ditch and self-forming channel design methodologies are gaining acceptance as best management practices in the Upper Midwest. The present project was conducted to provide information to Ohio NRCS to document the benefits, costs, and tradeoffs of implementing the approaches and to build capacity to implement the design approaches when and where appropriate. Channel best management practices can be used to address a number of Ohio NRCS resource concerns including Soil Erosion (e.g. bank erosion from conveyance channels), Water (e.g. excess water and water quality), and Animal (e.g. habitat). The goals of the project were to: 1) to provide information on the benefits and tradeoffs of two-stage and self-forming channel designs, 2) to provide guidance on the appropriate use of the practices to solve resource concerns, 3) to simplify the design and selection process for conservationists, and 4) to facilitate technology transfer. These goals were addressed by the following objectives: 1) development of a technical support document on alternative channel design options, 2) identification of natural resource concerns for channels, 3) the development of decision aids and guidance for local-level decision makers, 4) development of a spreadsheet design tools for alternative channels, 5) development of educational materials to facilitate technology transfer, 6) a workshop opportunity, and 7) a post-project presentation at the State Technical Committee meeting.

Project outcomes include a technical support document that outlines the history and evolution of drainage management in Ohio and the benefits, costs, and tradeoffs of alternative channel designs. A guidance document on planning and designing alternative channel projects was developed that followed the NRCS Conservation Planning Procedures. A companion spreadsheet tool that utilizes field survey data to analyze the existing channel system and evaluate proposed engineering designs was developed. Educational materials including a PowerPoint presentation on survey methods, a User Manual for the spreadsheet tool, and a design case study example were developed to facilitate technology transfer.

All of the objectives were completed except for the workshop opportunity (Deliverable #6) and post-project presentation (Deliverable #7). However, the PI is working with Mike Monnin, State Conservation Engineer, to plan and complete the workshop opportunity that will likely be held in northwest Ohio during Autumn 2013. A post-project presentation is scheduled for June 13, 2013 at the State Technical Committee meeting to satisfy Objective/Deliverable #7.

Introduction and Background Information

In many areas a combination of climatic conditions, topography, poorly drained soils, high water tables, and cropping preferences dictate the need for improved drainage to facilitate reliable and economical production of agricultural commodities. Improved drainage includes subsurface and surface drainage systems that not only affect crop production, but can have profound impacts, both positive and negative, on watershed hydrology, channel morphology, water quality, stream habitat, and aquatic biology. Subsurface drainage systems installed in agricultural fields are typically 3- to 4-ft below the ground, spaced 25- to 75-ft apart, and typically consist of 102-mm or larger perforated plastic pipes that often connect to larger unperforated subsurface mains before outletting to a surface drainage channel (Figures 1 and 2). Subsurface drains are primarily used to protect crops against extended periods of saturated conditions in the root zone and to improve trafficability increasing time available for field operations. By 1985, improved subsurface drainage had been installed on more than 100,000,000-ac of cropland in the United States (USDA, 1987).

Figure 1: Aerial photograph of an agricultural field with subsurface drainage in Ohio. Location of subsurface laterals can be seen through differences in soil moisture.

Figure 2: Subsurface drains outletting to a typical surface drainage channel in the North Central Region of the United States.

Surface drainage channels provide outlets for subsurface drainage tiles and are typically >4-ft in depth, drain >0.5-mi^2, and often designed to convey flows so that flooding into adjacent fields occurs less than once every 5- to 10-yrs or more. In Ohio, it is estimated that there are 20,000 miles of agricultural drainage channels. In some places they serve as the primary network of headwater streams in a watershed. Historically, drainage ditches have been designed with a trapezoidal geometry, uniform slope, and relatively straight planform to maximize hydraulic efficiency and conveyance capacity. This is called a trapezoidal channel and is often designed using the *threshold channel design* methodology. Unfortunately, this design is often unsustainable and the natural processes of erosion (Figure 3) and deposition (Figure 4) attempt to reshape the channel to a more natural state that balances the watershed sediment supply and hydrology. Costly and disruptive maintenance is often needed to maintain the trapezoidal channel design over the long-term (Figure 5).

Figure 3: Mass wasting of a bank from erosion of the toe making the banks steep and prone to failure.

Figure 4: Sediment deposition impacting performance of subsurface drainage system. (Photo: NRCS Gallery)

Figure 5: Channel maintenance that "dips out" bottom sediments and removes bank vegetation to reestablish the trapezoidal geometry.

Decades of research and monitoring have revealed impacts associated with traditional channel designs and drainage practices. This knowledge has led to the development of new and innovative management practices which provide the necessary drainage for agricultural production, but may have some positive benefits for water resources. Unfortunately, these practices are relatively new and often not considered in the planning and decision-making processes that guide drainage management and conservation at the local-level. Therefore, the goals of the present project are: 1) to provide information on the benefits and tradeoffs and alternative channel design options that are available, 2) to provide guidance on the appropriate use of the practices to solve resource concerns, 3) to develop a practical design tool for use by conservationists, and 4) to facilitate technology transfer. These goals are met as described in the following sections outlined by deliverable as identified in Section V of the Grant Agreement (see Appendix A). The goals of the project were specific to applications where alternative channel design options might be used as an agricultural conservation Best Management Practices and focused on providing NRCS information that would aid them in determining whether to include alternative channel design options in the Ohio Natural Conservation Service – Engineering Standard for Open Channels (Code 582). We did not address public health and safety issues or applications where the focus is on meeting EPA water quality requirements. Where EPA and/or the Army Corps of Engineers approval is necessary there might be additional requirements beyond those normally specified in a NRCS Conservation Practice Standard. Situations where state water quality standards for human health criteria apply are beyond the scope of this project. Those situations are addressed through local, state, and national regulations and requirements.

The project was completed by Jon Witter (Assistant Research Professor), Andy Ward (Professor), and Jessica D'Ambrosio (Program Manager – Ohio NEMO) of the Department of Food, Agricultural and Biological Engineering at The Ohio State University. Justin Reinhart (Conservation Engineer) and Dan Mecklenburg (Ecological Engineer) from the Division of Soil and Water Resources at the Ohio Department of Natural Resources also contributed directly to several project outcomes specifically ideas on structuring the document and programming of the spreadsheet design tool. Numerous other resources contributed through review of resources and fruitful discussions that guided the development of deliverables associated with this project. Funding for the project was provided by Ohio NRCS through Grant # NRCS 69-5E34-11-038 and cost-share and in-kind match was provided by the Department of Food, Agricultural and Biological Engineering and the Ohio Department of Natural Resources.

Review of Methods

It has been estimated that up to 80% or more of the entire stream network in some Midwest states consist of streams and drainage ditches channelized and modified to a trapezoidal geometry for agricultural purposes (Blann et al., 2009). Considerable research has documented the role of drainage ditches as conduits of field pollutants and the effects of routine ditch maintenance practices such as dredging in disrupting the natural buffering ability of ditches (Kleinman et al., 2007; Smith and Pappas, 2007; Pappas and Smith, 2007). In terms of natural resource concerns, poorly functioning drainage ditches can contribute to a number of problems. Based on recent documentation outlining primary resource concerns for Ohio NRCS (http://efotg.sc.egov.usda.gov/references/public/OH/Resource_Concerns_and_Planning_Criteria_Oct2012.pdf), alternative channel designs would address resource concerns in the SOIL EROSION, WATER, and ANIMAL concern categories. Specifically in the SOIL EROSION concern areas, alternative channel design would address the "excessive bank erosion from stream shorelines or water conveyance channels". In the WATER resource concern area, alternative channel designs would provide a potential solution to address issues related to "excess water" including flooding and ponding. These designs also address issues related to "water quality", particularly for sediments and nutrients and future research will target the benefits of alternative channel designs for mitigating impacts from pesticides, petroleum, heavy metals, and pathogens. In the ANIMAL resource concern area, alternative channel design methods address issues related to "inadequate habitat for fish and wildlife". Studies of fish and macroinvertebrates in multiple types of drainage ditches suggests that channel morphology impacts the structure of biological communities and alternative channel designs *may* be a means to improve habitat quality in row crop agriculture landscapes that are otherwise largely devoid of adequate habitat.

A growing body of research suggests the potential for using vegetated open ditches as best management practices in mitigating potential agricultural contaminants. Strock et al. (2010) identified a number of landscape and in-stream practices to reduce the off-site transport of pollutants in drainage water. There has been considerable debate on whether anthropogenic eutrophication problems could best be resolved with landscape BMPs, in-stream BMPs, or some combination in a systems approach. The debate very much reflects cultural divisions in the Midwest that may prove to be critical to the future of drainage in the Midwest as water quality problems persist and as management solutions are developed. To inform this discussion, this project involved the development and summary of information, design guidance, and tools that facilitate the implementation of alternative drainage design options, specifically two-stage and self-forming channels.

The two-stage ditch and self-forming channel designs, if implemented properly, should result in a self-flushing, self-sustaining agricultural drainage system based on the principles of fluvial geomorphology that will reduce or eliminate the need for traditional ditch clean-out activities (Figure 6; Ward et al., 2004; Jayakaran et al., 2005; 2007; Powell et al., 2007a; 2007b; Rhoads and Massey, 2012; Magner et al., 2012). The approach for designing alternative channel systems consists of: (1) providing space for an inset channel to convey the bankfull discharge, (2) space for a floodplain for the inset channel, and (3) sufficient capacity above the benches to reduce the likelihood that flow will overtop the ditch banks and flood surrounding crop land (Ward et al., 2004; Powell et al., 2007a; 2007b; Kallio, 2010). In theory, the result is a channel sized by channel-forming processes that is in a stable, quasi-equilibrium state (i.e., Schumm, 1981, Simon and Hupp, 1986; Nanson and Croke, 1992). Two-stage channels are considered stable if they are neither aggrading nor degrading based on geomorphic theory (Leopold, 1994;

Lane, 1955) and should require little or no maintenance to maintain conveyance capacity and drainage function. Major benefits of this approach include maximizing stability until vegetation can become established on the newly constructed benches and preserving local ecology that may be present.

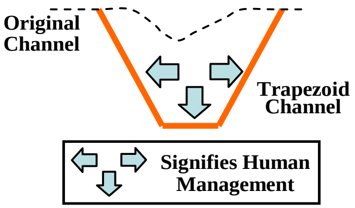
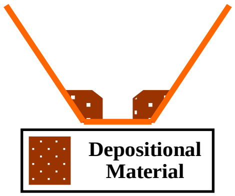
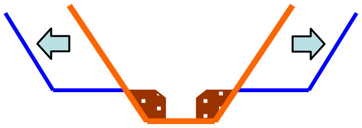
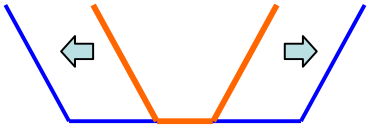
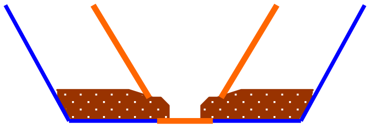
A. Trapezoidal Channel  		**An example of traditional, trapezoidal channel maintenance. It requires regular removal of sediments and vegetation to maintain drainage capacity. However, this activity may reduce or eliminate other beneficial ecosystem services.**
B. Two-Stage Channel (Naturally Formed)  		**This channel was originally constructed to a trapezoidal shape. It had sufficient space, sediment supply, and energy to build small benches within the confines of the channel. This channel has a sustainable form and should require little, if any, maintenance**
C. Two-Stage Channel (Constructed) 		**A trapezoidal channel was modified using the two-stage design approach to increase conveyance capacity. Rather than removing existing benches the channel was widened at the bench elevation. The resulting channel meets drainage needs and has stable banks.**
D. Self-Forming Channel (After Construction) 		**A self-forming design where the channel was intentionally built overwide to provide space for fluvial processes to build benches. The design allows formation of alluvial benches, whereas the two-stage design may excavate floodplain benches from subsurface soil horizons.**
E. Self-Forming Channel (1-year old) 		**A self-forming channel one year after construction (same channel as in D above). The benches will continue to build over time until a state of dynamic equilibrium between hydrology, sediment supply and transport, and channel form is reached.**

Figure 6. Conceptual diagram of traditional and alternative channel design methods.

To address the project objectives, we first conducted a literature review of the history of drainage and the management techniques used to manage drainage ditches. The report summarizes cultural views on drainage ditches, positive and negative impacts identified in the peer-reviewed literature, and the evolution of management techniques through time. Both peer-reviewed and preliminary data on the water quality benefits of alternative channel designs are presented (results largely from the laboratory of Dr. Jennifer Tank, University of Notre Dame, South Bend, IN). Next, we developed updated design guidance that is consistent with the NRCS Conservation Planning Procedures. This guidance was based on the original design procedures outlined in the USDA-National Engineering Handbook Part 654 (Chapter 10), but framed in the context of the planning procedures based on recommendations from NRCS employees in Indiana whom are actively implementing the two-stage channel design through EQIP. The guidance includes recommendations to identify resource concerns for channels and recommendations for local-level decision makers. Additionally, based on our interactions with NRCS and SWCD employees in both Indiana and Ohio a new design tool was developed to replace a series of 3 spreadsheet tools that are typically used for two-stage ditch design. The new design tool integrated the relevant functions of the 3 spreadsheets into a single, simple design tool that explicitly incorporated the self-forming channel design method as an option. To facilitate technology transfer educational aids were developed including a user manual, case study design example, and a PowerPoint presentation.

Discussion of Quality Assurance

This project did not include data collection.

Findings

Project findings are discussed by deliverable in the following sections.

Deliverable 1: Technical Support Document on Alternative Design Options

A technical support document (full document available in Appendix B) was developed that provides a review of the function and modification of natural channels and agricultural drainage as agronomic, scientific, sociopolitical and environmental cultures have evolved. Our report briefly outlines the impacts of major water works projects for irrigation and navigation in the United States and throughout the world; however, it then focuses specifically on the development and management of agricultural drainage ditches that occurred in the Midwest United States, with special attention on activities that occurred in or affected the state of Ohio. Numerous review papers have documented the impacts of agricultural drainage (Pavelis, 1987; Fausey et al., 1995; Zucker and Brown, 1998; Blann, et al., 2009, Skaggs et al., 1994; Needleman et al., 2007, among others), but few have focused primarily on the role of drainage ditches and few have included information on non-traditional drainage ditch designs as agricultural best management practices. First, we review a brief history of water management and drainage from early civilization to the 19th Century. Then, we discuss the modification of headwater and mid-order stream systems (0.5 mi^2-10 mi^2) for agricultural land drainage. We highlight the technological, sociopolitical, and scientific advances that shaped stream and ditch management in the 19th and 20th Centuries. Next, we discuss the scientific and cultural shift in how agricultural drainage ditches are viewed and managed at the local, state, and national level. Finally, we discuss alternative designs that were developed to return hydrologic function and geomorphic stability to agricultural ditches undergoing frequent maintenance activities and current research on the agricultural ditch designs to be considered an agricultural best management practice and water quality conservation practice. We primarily focus on agricultural land drainage in the Midwestern United States because of its history of extensive land drainage activities, its economically important agricultural industry, its recent history of pioneering scientific and engineering work in aquatic biological indicators and alternative drainage channel designs, and its location as the headwaters for ecologically and economically important water resources such as the Mississippi River, Gulf of Mexico and the Great Lakes.

Deliverables 2 and 3: Identification of Resource Concerns for Channels & Decision Aids and Guidance for Local-Level Decision Makers

A planning and design manual (full document available in Appendix C) was developed to aid in the identification of resource concerns and to guide implementation at the local level. Prior to this project planning and design procedures were provided in the USDA-National Engineering Handbook Part 654 (Chapter 10) and in a manuscript published in the Journal of Soil and Water Conservation (Powell et al., 2007). Those procedures were modified and integrated within the framework of the NRCS Conservation Planning Procedures. The design process relies heavily on existing engineering practices already utilized by NRCS engineers and other conservation professional that utilize NRCS conservation practice and engineering standards to design and implement conservation practices. For example, NRCS already has well-established procedures to make hydrological estimates of peak discharge rates and to conduct stability analyses. The alternative channel design procedures utilize existing guidance and references the relevant resources that are used in design, when appropriate. Additional detail was provided in the design guidance document only when existing guidance from NRCS resources was lacking. For example, regional curve concepts to size self-sustaining channels are most likely unfamiliar to most conservation professionals and, therefore, additional detail was provided on this topic and others.

Deliverable 4: Spreadsheet Design Tools

Prior to the completion of present project, the evaluation of existing channel systems, assessment of proposed alternative ditch designs, and production of construction drawings and calculations were completed using a series of 3 spreadsheet tools (i.e. Reference Reach Survey, Contrasting Channels, and Two-Stage X-Section Plots; (http://www.dnr.state.oh.us/tabid/24137/Default.aspx). These STREAM spreadsheet modules were not specific to most drainage ditch channel systems and included information and analysis that were unnecessary for most designs and that were sometimes difficult to comprehend without extensive training in stream geomorphology or assistance from the developers. To simplify the evaluation and design process these spreadsheet tools were integrated into a single design tool called "Enhanced Ditch Design Cross Section Plots version 1.0". The Enhanced Ditch Design Cross Sections Plots v. 1.0 tool has been developed specifically to aid in decision making and preliminary design purposes for alternative channels. The purpose of the spreadsheet is to evaluate the morphology, hydrology, hydraulics, and sediment transport of an existing channel, obtain a conceptual geometry for a two-stage and self-forming channel system, and analyze each design option.

The spreadsheet includes 5 visible worksheets including *Instructions, 1 Start, 2 Survey Profile, 3 Survey X Sects,* and *4 Hydraulics.* The *Instructions* worksheet provides a general overview of the module and will include updates and document major revisions to future releases of the software.

The *1 Start* worksheet allows the user to document general information (e.g. stream name, watershed, geographic coordinates, etc.) and basic properties that describe the channel and its watershed (e.g. drainage area, etc.). Here the user is also able to select an appropriate regional hydraulic geometry relationship that will be a starting point for channel sizing. There are two options to choose a regional relationship including selection from a pull down menu populated with pre-loaded values determined from other studies and a second option which allows the user to enter user defined relationships from field measurements for a specific watershed, reach, or project. Here the user is also able to define the regional hydrology by entering user input values from tools, such as StreamStats, or from user input values that are used to calculate peak discharges for multiple recurrence intervals using USGS peak discharge equations for rural and urban watershed in Ohio.

The *2 Survey Profile* worksheet allows the user to input field survey data for the existing channel. The current version of the spreadsheet only allows for data collected using a laser level, laser receiver, and surveying rod. Future versions will include the capability to input total station data with state plane coordinates (i.e. Northing, Easting, and elevation). Longitudinal survey data can be entered incrementally or as continuous measurements along the reach. Ultimately, the spreadsheet plots the longitudinal profile and calculates the reach slope of the existing channel. This worksheet also allows the user to specify elevations for the proposed design in case the longitudinal profile needs to be manipulated as part of the design.

The *3 Survey X Sects* worksheet allows the user to enter field survey data of channel cross sections. Tools are available to evaluate the bankfull and ditchfull conditions for their morphology and hydraulics. Here the user can also specify the proposed design (i.e. two-stage or self-forming channel) and the spreadsheet automatically estimates of the earthwork volume to construct the proposed project.

The *4 Hydraulics* worksheet allows the user to evaluate the hydraulics and sediment transport associated with the existing channel and the proposed alternative channel design. To make these calculations the existing channel geometry is simplified to a conceptual geometry that is an approximation of the existing channel. It is up to the user to assess whether the approximation is representative of the existing channel system. The user can modify the proposed design (e.g. slope, channel dimensions, roughness elements, etc.) as needed and ultimately the spreadsheet predicts water surface elevations, flow velocities, and shear stresses for a range of frequent and infrequent recurrence interval storm events (i.e. 0.2-yr to 100-yr events). These estimates can be used as the basis for stability analysis (e.g. permissible velocity, allowable shear, etc.). A copy of the spreadsheet design tool and a case study example are provided. In addition, a spreadsheet tool that allows for simple estimates of project cost has been included.

Deliverable 5: Education Materials to Facilitate Technology Transfer

To facilitate technology transfer the project team developed educational aids to teach conservation professionals about various aspects of the design process. In addition to the design guidance an animated PowerPoint presentation is provided that shows the process of field data collection. Additionally, a case study example of the spreadsheet design tool is provided. The example, takes measured field survey data and populates the design spreadsheet with data from Cygnet Ditch in Hancock County, Ohio. A user manual has also been developed which broadly outlines the various functions available in the spreadsheet tool.

Deliverable 6: Workshop Opportunity

A workshop was not able to be held in the project period due to a more advanced reprogramming of the spreadsheet design tools than originally envisioned which required multiple iterations based on user feedback. To rectify this shortcoming the PI has been in contact with Mike Monnin, State Conservation Engineer for Ohio NRCS. Mr. Monnin is currently contacting NRCS personnel that would benefit most from a training opportunity/workshop to determine the best time to hold a workshop. We anticipate that a workshop is most likely in late September or early October of 2013 and will be held in northwest Ohio to minimize the need for overnight travel. Additionally, we may utilize webinar technology in combination with the workshop to include others that are unable to travel. Another workshop opportunity, supported by the Great Lakes Regional Water Program, is likely to be held at the 21st Annual Non-Point Source Monitoring Conference in October 2013 in Cleveland, Ohio which would provide another outreach education opportunity for NRCS employees to attend. Copies of all files and educational materials related to the workshop will be provided to Ohio NRCS at the conclusion of that workshop.

Deliverable 7

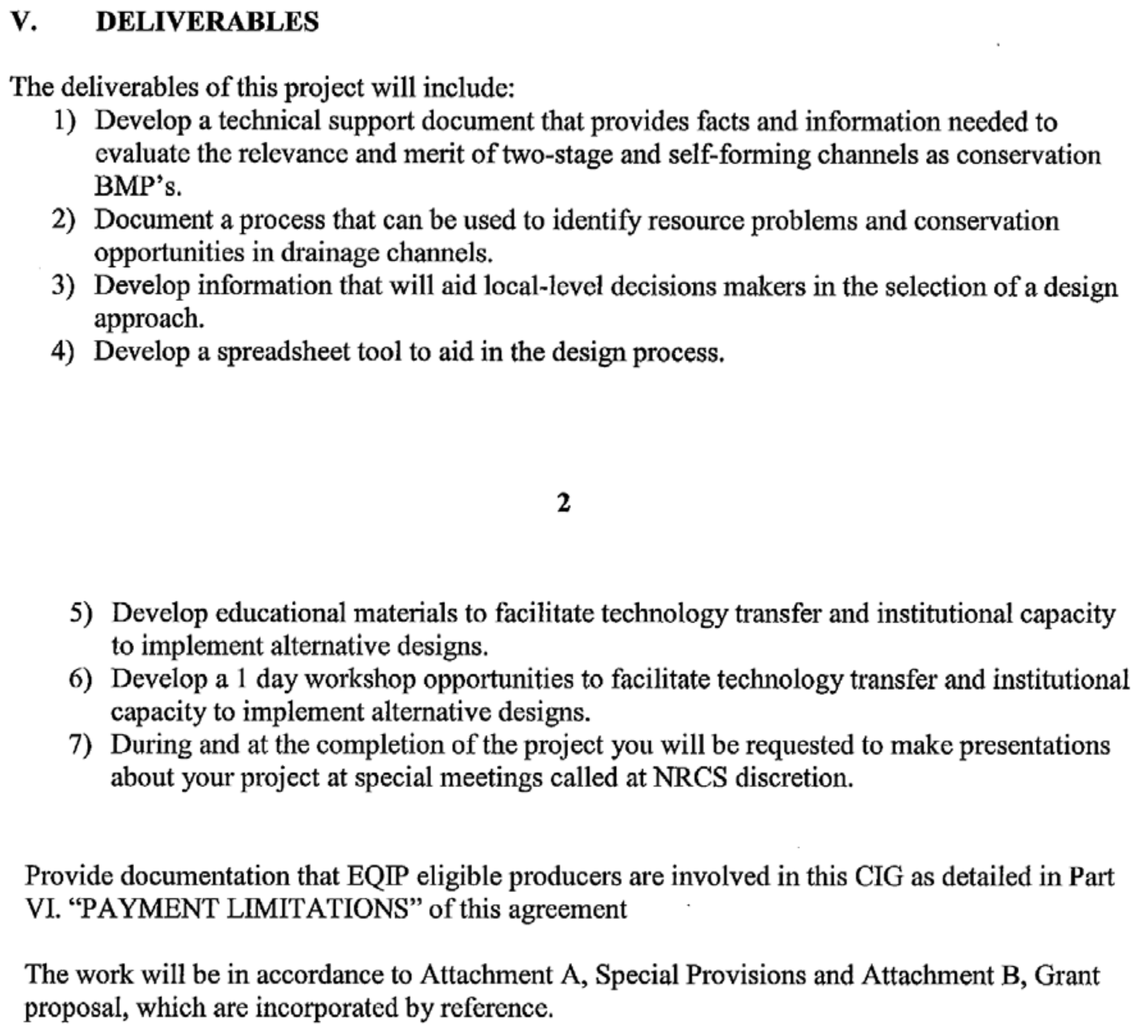
A post-project presentation is planned for June 13, 2013 at the State Technical Committee Meeting.

Conclusions and Recommendations

Alternative channel designs are being more widely used to address resource concerns from channels that function poorly. We estimate that there are >100 two-stage ditch projects and >25 self-forming channel projects that have been implemented in the Upper Midwest over the past decade and the practices are gaining acceptance in the region. The predominant barrier to more widespread implementation is education and institutional capacity to implement the designs in a responsible manner that considers the costs and benefits to landowners, government, and society. The materials developed as part of this project should help to address these needs; however, ongoing development of procedures, decision aids, tools, and educational materials is needed to continue to promote the wise and appropriate adoption of these best management practices.

Appendices

Appendix A: Deliverables from Grant Award Letter



V. DELIVERABLES

The deliverables of this project will include:

1) Develop a technical support document that provides facts and information needed to evaluate the relevance and merit of two-stage and self-forming channels as conservation BMP's.
2) Document a process that can be used to identify resource problems and conservation opportunities in drainage channels.
3) Develop information that will aid local-level decisions makers in the selection of a design approach.
4) Develop a spreadsheet tool to aid in the design process.

5) Develop educational materials to facilitate technology transfer and institutional capacity to implement alternative designs.
6) Develop a 1 day workshop opportunities to facilitate technology transfer and institutional capacity to implement alternative designs.
7) During and at the completion of the project you will be requested to make presentations about your project at special meetings called at NRCS discretion.

Provide documentation that EQIP eligible producers are involved in this CIG as detailed in Part VI. "PAYMENT LIMITATIONS" of this agreement

The work will be in accordance to Attachment A, Special Provisions and Attachment B, Grant proposal, which are incorporated by reference.

Figure A1. Screenshot of project deliverables from grant award.

Appendix B: Technical Support Document

Water Resources and Agricultural Ditch Management in the United States and Ohio

Introduction

Rivers, lakes and streams and their floodplains have supported human civilizations for millennia. Human cultures in all parts of the world throughout history established permanent settlements next to a river or stream where there would be a ready-supply of good quality water and fertile land to support food production. The primary functions of rivers and streams in early human civilization included providing a potable water supply, efficient navigation, and sustaining agricultural crop growth irrigation or draining water from the land. Water management throughout the world has rendered improvements to natural drainage conditions one of the most influential engineering technologies in human history.

The role of streams and rivers, including their floodplains, has changed concurrently with changes in the role of agriculture in society. With the societal benefits provided by natural, modified and constructed lotic systems have also come great economic and environmental costs that only in recent history have garnered sufficient attention by the scientific, engineering, and regulating communities. Agricultural ditching and drainage is very much needed today, but in some locations classic drainage system designs have resulted in over-drainage of the land, severe water quality problems, and an overall loss of watershed ecosystem function (Urban and Rhoads, 2003).

Drainage and ditching technologies developed out of necessity resulting from population growth and land development pressure. Channelization and land drainage were applied for two prevailing reasons: 1) reclamation of “swamp” land for agricultural use (referred to as horizontal expansion); and 2) improved drainage on existing agricultural land (referred to as vertical expansion). Over the past 150 years, more than 200,000 miles of waterways have been modified and 80% of some watersheds have subsurface or surface drainage in the United States (Schoof, 1980; Blann et al., 2009). The United States Department of Agriculture (USDA) Economic Research Service (Pavelis, 1987) estimated that 110 million acres of agricultural land, nearly 70% in crops, in the United States had benefited from artificial drainage. The total U.S. investment in drainage since 1855 has been estimated to be $56 billion dollars (Pavelis, 1987).

In the 21st Century, we find that along with widely recognized ecological and economic costs comes recognition that agricultural drainage system designs may need to be modified to serve wider purposes beyond agriculture (Jayakaran et al., 2010). In some cases this might simply be a non-agricultural application, but in other cases this may reflect a fully new approach to drainage design and maintenance projects that focuses on stream and watershed system function. Recognizing the need to maintain a viable agronomic economy, recent efforts have focused on returning floodplain to modified channels and maximizing ecosystem services rather than restoration to pre-settlement, pre-agricultural conditions. Innovative alternative ditch designs are emerging as in-stream agricultural best management practices that, when coupled with landscape best management practices, have potential for meeting multiple management goals in low gradient, agriculture-dominated watersheds.

We provide a review of the function and modification of natural channels and agricultural drainage as agronomic, scientific, sociopolitical and environmental cultures have evolved throughout history. We recognize the impacts of major water works projects for irrigation and navigation in the United States and throughout the world; however, this paper will focus specifically on development and management of agricultural drainage ditches that occurred in the Midwest United States, with special attention on activities that occurred in or affected the state of Ohio. Numerous review papers have documented the impacts of agricultural drainage (Pavelis, 1987; Fausey et al., 1995; Zucker and Brown, 1998; Blann, et al., 2009, Skaggs et al., 1994; Needleman et al., 2007, among others), but few have focused primarily on the role of drainage ditches, specifically two-stage ditches, as an agricultural best management practice. First, we review a brief history of water management and drainage from early civilization to the 19th Century. Then, we discuss the modification of headwater and mid-order stream systems (0.5 mi^2-10 mi^2) for agricultural land drainage. We highlight the technological, sociopolitical, and scientific advances that shaped stream and ditch management in the 19th and 20th Centuries. Next, we discuss the scientific and cultural shift in how agricultural drainage ditches are viewed and managed at the local, state, and national level. Finally, we discuss an alternative design, the two-stage ditch, developed to return hydrologic function and geomorphic stability to agricultural ditches undergoing frequent maintenance activities and current research on the two-stage ditch design to be considered an agricultural best management practice and water quality conservation practice. We primarily focus on agricultural land drainage in the Midwestern United States because of its history of extensive land drainage activities, its economically important agricultural industry, its recent history of pioneering scientific and engineering work in aquatic biological indicators and alternative drainage channel designs, and its location as the headwaters for ecologically and economically important water resources such as the Mississippi River, Gulf of Mexico and the Great Lakes.

Rivers and Early Civilization

Alluvial floodplains were very attractive to early farmers because of the nutrient rich floodplain soils. Rivers also were the principal form of transport; with river confluences often becoming foci for commercial, cultural and intellectual trade. By most accounts, water management and agriculture appeared in civilization at about 5,000 B.C. (Beauchamp, 1987; Fausey et al., 1995; Shirmohammadi et al., 1995). Mesopotamia is widely credited with the beginning of drainage and irrigation technology for agricultural use. Water management was accomplished by hand digging along the banks of rivers and streams. While early civilizations quickly mastered irrigation technology, they still faced seasonal flooding issues from the surrounding large rivers they inhabited. Historic evidence indicated serious drainage issues in heavily irrigated areas. The decline or disappearance of some early civilizations that relied on surface irrigation likely resulted from over-salinization of irrigation water, flooding, and heavy erosion problems due to poor soil conservation practices.

From about 400 B.C. the Egyptians and Greeks report using a system of surface ditches to drain surface water from individual areas. The oldest known engineering drawing, illustrated in 250 B.C., is a Greek plan of a rectangular surface ditching system (Beauchamp, 1987). The Romans were the first to use open drains to remove ponded surface water; closed drains soon followed for draining water from the soil. The Romans reportedly paid proper attention to the direction of flow, and to the cleaning and clearing of the ditches around agricultural fields. In 160 B.C. Cato, a famous Roman statesman and orator, was the first to write specific directions for draining land (Beauchamp, 1987). He outlined a trapezoidal design that was four feet deep and three times wider at the top than at the bottom, which was a design for subsurface drainage that persisted with little improvement for more than 1,000 years.

Agricultural Drainage in Europe and Early America

The Greeks and Romans used clay tiles for supplying urban areas with potable water as early as the 4th Century B.C (Beauchamp, 1987). The Hohokam Indians are credited with developing the first irrigation system in North America (Beauchamp, 1987). The French are credited with being the first to use clay roofing tile for farm drainage purposes as early as the 14th Century (Weaver, 1964). Around 1500 A.D. the first large-scale design for drainage was developed in England to prevent flooding and reclaim marshes and peat lands. A system of cylindrical clay pipe drains was discovered in France in a garden that dates back to 1620 (Beauchamp, 1987). In most countries of temperate zone, 20%-35% of agricultural land had been developed with the use of drainage by the 18th Century (Shirmohammadi et al., 1995).

European settlers brought surface drainage technology with them to America, including the use of small open ditches to drain wet spots in fields and the cleaning out of small streams. While sufficient to cultivate the land, these small-scale surface drainage systems did not lower the water table fast enough to drain the soil profile, and crop yields generally were low. Flooding after large rain events was common in areas with heavy, poorly drained soils. American farmers turned to subsurface covered drains that emptied into open ditches as a drainage solution for small, individual farm plots. Farmers quickly realized how important the outlets to the open ditches were to effectively draining the land. Many larger receiving ditches were dug at the edges of properties and existing streams were widened and deepened to accommodate subsurface tile flows. Early subsurface drains and open ditches were dug with shovels, followed by a combination of plowing and hand digging (Figure B1). Subsurface drains typically were placed 24 to 36 inches deep and two furrows wide (Skaggs et al., 1994). Open ditches were constructed and natural streams were cleared and straightened, but very little was documented on the extent of these activities throughout early America or whether a common design was developed.

Figure B1. Surface ditching and subsurface drain tile done by hand in the early 1800s.

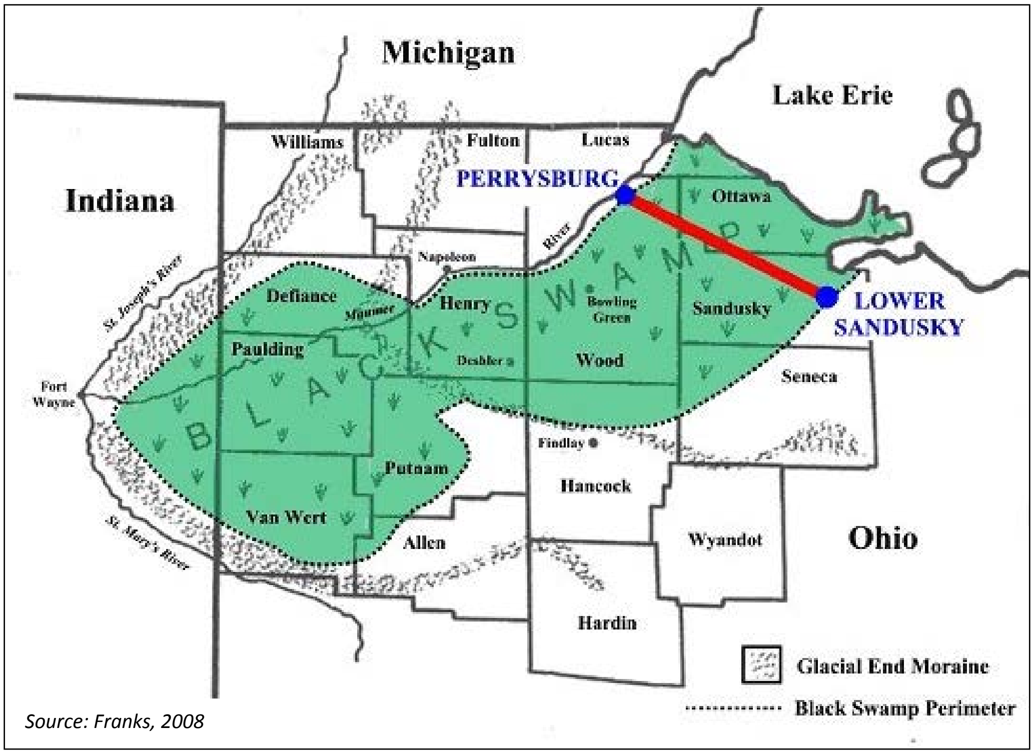
Early America's interest in drainage was not only for agricultural purposes, but also to eradicate water-borne human diseases such as malaria and spotted fever. The first large-scale American drainage effort was documented in 1754 when the colony of South Carolina passed an act to drain the Cacaw Swamp. The federal government transferred land authority to the states. Subsequent state drainage laws established drainage districts that could create large drainage outlets beyond individual farm boundaries. At this time, water policy generally fell under the Common Enemy Doctrine. Surface water was regarded as a common enemy, which each property owner could fight off or control by any means without regard to rights or well-being of their neighbor (Callahan, 1979).

Very little is documented related to natural stream and river channel modifications in Europe and early America as a result of land drainage, but forest clearing likely was extensive and had wide-ranging impacts to stream networks. It is widely accepted that most modern streams in the U.S. have little in common with those found prior to European settlement. Headwater stream channels in low gradient landscapes prior to settlement likely were either prairie wet meadows or were heavily shaded by riparian vegetation and contained large amounts of fallen wood (Petersen et al., 1992). Much of the land from western Ohio to the Mississippi River Valley was covered in dense beech, ash, and elm forests, prairie, and extensive tracts of swamp land (Petersen et al., 1992). Stream waters were characteristically described as being exceptionally clear and free of silts and pollutants, often serving as a source of potable water for the early settlers (Trautman, 1981). Additionally, beaver activity prior to the mid-1800's may have resulted in extensive impoundments throughout the stream network that would have made headwater streams wider, slower, and more mid-order in character (Minshall et al., 1985; Naiman, 1999). As populations expanded and moved west during the 1800s, vegetative cover and beaver populations across the U.S. were dramatically reduced, which likely resulted in the earliest impacts on stream systems. Drainage laws, population pressure forcing settlers to move west in search of more agricultural land, and advances in technology in the 19th Century resulted in a cascade of activities that would forever change stream networks in the North American landscape.

American Settlement of the Midwest

Technological advances in the 1800s resulted in rapid changes to farming practices of American settlers (Turner and Rabalais, 2003). John Johnston was the first person to lay drain tile in the United States on his farm in New York in 1835 (Klippart, 1861). Population pressure, a need for more suitable farmland, and completion of the Erie Canal and Ohio & Erie Canal pushed more settlements into the Ohio and Mississippi River valleys by the 1830s. The transportation industry, including the railroads and canals, facilitated westward expansion and land clearing (Turner and Rabalais, 2003). To enhance both commerce and national defense, Congress passed the first federal acts involving interstate commerce in 1824 that granted the Corps of Engineers authority to survey canal routes and “improve” the navigation of the Ohio and Mississippi rivers by removing sandbars, snags, and other obstacles (http://www.usace.army.mil/About.aspx).

Passage of the Swamp Land Acts in 1849 and 1850 further encouraged settlers to move west. The Black Swamp, a forested wetland mainly located in the northwestern corner of Ohio and estimated to have been 120 miles long and 40 miles wide, covering nearly 11 counties, was a major barrier to travel and settlement within the Midwest (Figure B2; Dahl and Allord, 1999; Gordon, 1969; Brown and Stearns, 1991; ODNR, 2009). A series of public ditch laws were passed including the Ohio Ditch Law in 1859 that facilitated land clearing and drainage of swamp land in order to develop productive agricultural lands. The new ditch laws granted local officials the authority to design and construct drainage projects, and assess local landowners for the cost of the projects. In Ohio, these laws are now known as the County Petition Ditch Law that is still in use today (Brown and Stearns, 1991; ODNR, 2009).



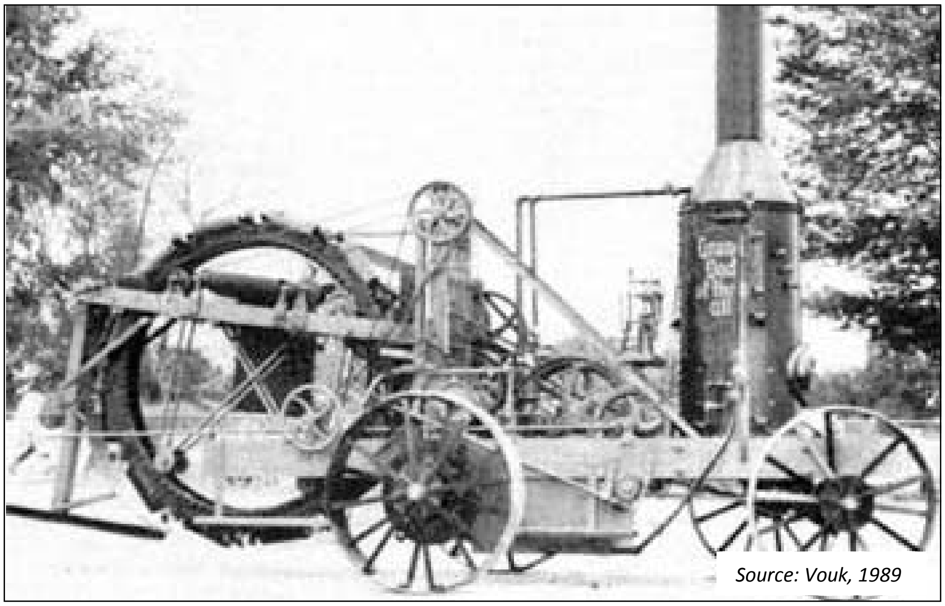
Source: Franks, 2008

Figure B2. The area of Northwest Ohio historically covered by the Black Swamp prior to it being drained in 1885. The red line represents the only known road prior to drainage.

The Black Swamp is the most extreme example of the impact of ditch laws on Ohio and the Midwest landscape. Supported by drainage and levee districts at the local and state level to help cover the immense task of land reclamation, draining of the Black Swamp had begun in 1859 and been completely drained by 1885 (Fausey et al., 1995; Turner and Rabalais, 2003; Dahl and Allord, 1999). By 1884, Ohio had 20,000 miles of public ditches designed to drain 11 million acres of land (Wooten and Jones, 1955).

As drainage laws evolved, so did national water authority throughout the 1800s. In direct opposition to the Common Enemy Doctrine, the rule of water drainage law, which later became known as Civil Law Rule, was increasingly recognized by state and federal courts. Civil Law Rule mandated that a downstream land owner must accept the surface water that naturally drained onto his land, and that the upstream land owner had no right to change the natural system of drainage to increase the burden on the landowner downstream (Callahan, 1979). The concept of riparian rights also was adopted by some states at this time. In Ohio, riparian rights mandated that a land owner had a right to use the water that passed over his land as long as it was transmitted by its natural channel to the downstream land owner (Callahan, 1979).

By the mid 19th Century, land management practices shifted from land clearing to more intensive agricultural use that spurred entirely new industries and technological advances in agricultural production. The first patent for a chemical fertilizer was issued in 1849 in Baltimore, and phosphate fertilizer production began in South Carolina in the late 1800s (Turner and Rabalais, 2003). Clay tile manufacturing for subsurface drainage boomed, and by 1867 Ohio was leading the way producing 2,000 miles of drain tile per year (Fausey et al., 1995; Skaggs et al., 1994). Also in Ohio, the steam-powered Buckeye Trencher No. 88 was built in 1892 that would become the model from which subsurface ditch trenching machines still are based on today (Figure B3; Beauchamp, 1987). The original company that patented the Buckeye Trencher was founded in Bowling Green, Ohio, in 1893, and grew to become the largest tile ditching and construction trenching company in the world (Vouk, 1989).

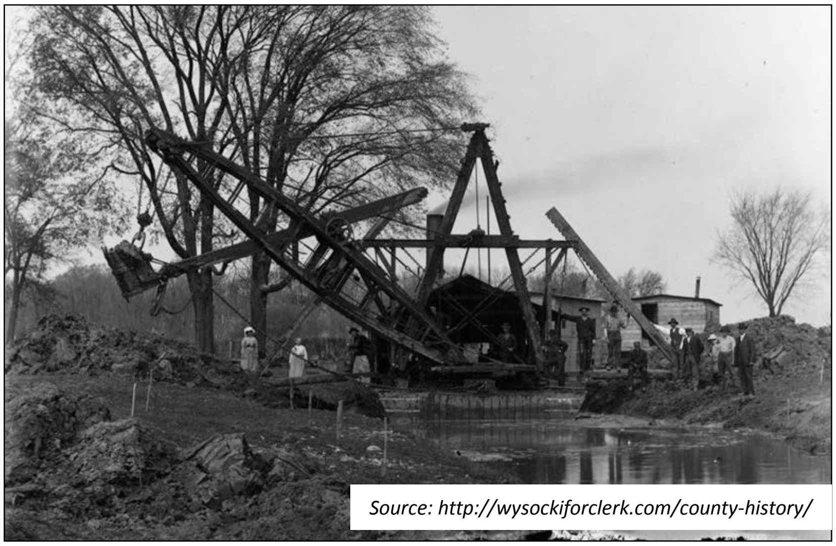


Source: Vouk, 1989

Figure B3. The steam-powered Buckeye Trencher No.88 developed in Bowling Green, Ohio, in 1892.

Subsurface drainage technology was widely credited for land reclamation of the American Midwest; however improved methods for constructing large-scale outlet ditches beyond the farm field for surface drainage probably were the most important factors in how quickly and efficiently subsurface drainage spread in the Midwest. Ditches and channels were first built and stream channels were first excavated by hand using tools such as the ditching spade, round point shovel, and a wheel barrow. Horse horse-drawn plows and slip scrapes soon followed, but these small shallow ditches did not often provide adequate drainage needed in the heavy clay soils and swamp lands of the Midwest. Engineering designs for open ditches were not well-documented at this time and it seemed that their sizing was left up to the discretion of the farmer or drainage district manager. Early on, drainage ditch sizing and design were a function of available money and equipment to build the ditch. A report from Johnstone (1834) indicated open ditch recommendations having a trapezoidal shape with a top width three times wider than the bottom width, side slopes stable enough to prevent falling in, and at a slope sufficient for the water to move obstructs but not injure the bottom. In a report to the Ohio Legislature, Klippart (1861) suggested that open ditches serving as main drains be nearly seven times wider at the top than at the bottom, 4-6 ft deep, and have a side slope ratio of 1.5:1. He also suggested that the bottom of the ditch should be 12 -18 inches below the outlet of any smaller drains. Another account from a drainage test farm in Illinois in 1908 indicated that their open ditches were 3-7 ft deep, 3 ft wide on the bottom, and had 1.5:1 ratio for side slopes.

By the late 1880s a steam powered floated dredge was invented that revolutionized open drainage ditch construction methods (Figure B4). Floating and land dredges became the most economical way to construct ditches, but the dragline excavator in the early 1900s proved to be the most universal allowing for various ditch sizes and wide berms along the ditch. By the 1930s, the crawler was commonly used because it could level ditch spoil banks and could construct v-shaped, w-shaped and wide bottom flat ditches (Fausey et al., 1995).



Source: http://wysockiforclerk.com/county-history/

Figure B4. A floating dredge used to construct drainage ditches.

The result of nearly a century of engineering and agricultural innovation was productive, well-drained, and extensively-ditched agricultural landscapes that converted the swamp lands of the American Midwest into one of the most productive agricultural regions of the world. Yet, becoming the "breadbasket" of the world was not without consequences. The impact of settlement and land reclamation to the natural wetlands of the United States and the Midwest was immense (Dahl, 1990). The impacts to natural streams and rivers, although less well-documented, likely were equally far-reaching. Land drainage and cultivation was preceded by tree cutting and burning (Figure B5). Greeley (1925) documented that the virgin forests of 1850 in the U.S. were largely remnants by 1920. Ohio's forests, for example, declined from 54% in 1853 to 18% in 1883, and were used mainly as fuel for the railroads (Gordon, 1969).

Figure B5. Land clearing preceded cultivation during early American settlement.

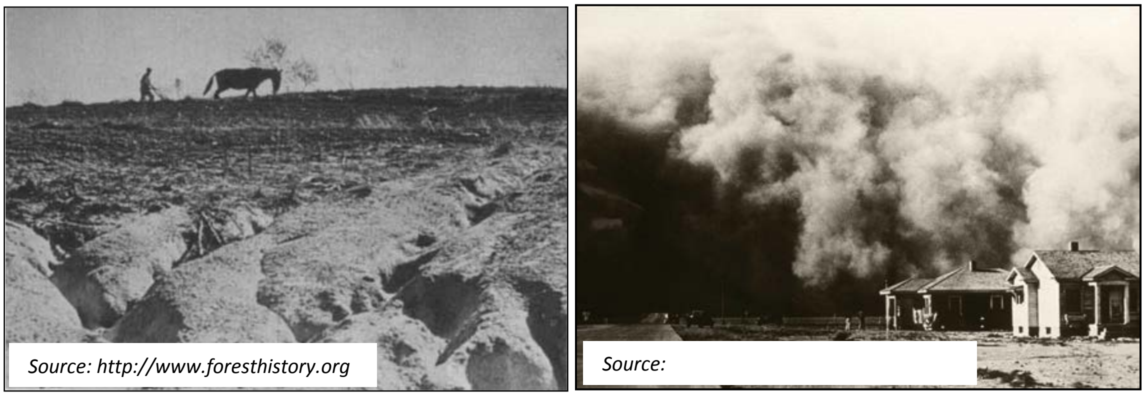
Massive forest clearing on essentially all North American rivers in the 1800's and early 1900's, together with large-scale channelization efforts to facilitate agricultural drainage, likely had severely altered the pattern and complexity of the natural stream network (Minshall et al., 1985). Mid-sized streams that were once heavily braided or meandering systems became single, relatively straight channels (Figure B6). Channelization also altered the function of the riparian zones adjacent to streams. The forested or prairie wet meadow riparian zone probably produced a very different channel than that found in the agricultural landscape today. Braided channels, backwaters, and side-channel streams probably caused many mid-sized rivers to behave more like headwaters (Minshall et al., 1985). Beaver activity may have helped ameliorate the initial impacts of channelization, but expansion of American settlement and the fur trade resulted in near extirpation of beaver from the Midwest landscape.

Figure B6. Examples of a forested Midwestern stream before (top left) and after channelization (top right); a Midwestern prairie stream before (bottom left) and after channelization (bottom right). Photos are not of the same area, but are typical examples.

While not well-documented in the literature until the 20th Century, we can surmise deleterious impacts to water quality and aquatic biota during this time. Depletion of the riparian canopy removed shading benefits to in-stream organisms and raised water temperatures. Populations of sensitive aquatic species likely were influenced by siltation and fine sediment delivery to streams. Loss of riparian vegetation along with channelization also made stream flows more variable and flashy as more water reached channels faster (Rankin and Armitage, 2006). In one account from Champaign County, Illinois, which was the headwater regions for six different rivers, an average of 95% of first order streams had been channelized since the 1850s (Mattingly et al., 1993).

Technological Advances and Legislation Affecting Agricultural Drainage Systems in the 20th Century

The earliest reported signs of trouble on the landscape as a result of extensive drainage works occurred in the early 20th Century. Naturalists and fishermen noted the decline of sport fishes and migratory hunting birds, which led to the first legislation aimed at restoring wetlands, the Migratory Hunting Bird Stamp Act of 1934. Farmers observed extensive soil loss from the landscape. Publications began to surface documenting widespread soil losses in the Midwest and the Dustbowl of 1933-34 led to the formation of the USDA Soil Erosion Service, which was renamed the Soil Conservation Service (SCS) in 1935 (Prince, 1997). Many instances of channelized streams widening and deepening that resulted in sediments burying tile drains and filling in ditches downstream were reported (Daniels, 1960). Recognition of the threat of soil erosion to farm management practices was widely acknowledged by the 1930s (Figure B7).



Source: http://www.foresthistory.org

Source:

Figure B7. Extensive soil erosion on American farms led to the Dustbowl in the 1930s.

Local water laws had evolved yet again as a result of increasing landowner conflicts stemming from flooding and erosion control measures on the landscape. The rule of 'reasonable use' was developed as an alternative between the Civil Law Rule and the Common Enemy Doctrine. The Reasonable Use Rule stipulated that a land owner can legally make reasonable use of his land, even if it alters the flow of water and causes harm to others; however, if the alteration is unreasonable, a land owner is liable for damages caused as a result (Callahan, 1979). Many states and local jurisdictions passed laws to try to prevent devastating floods. In Ohio, the Conservancy Act was passed in 1914 after the largest flood to date occurred on the Muskingum River. The Conservancy Act enable land owners or communities to establish conservancy districts to solve water management issues, including flood reduction and protection, and provide other services such as conserving and developing water supplies, treating wastewater and providing recreational opportunities. Under Ohio Drainage Law, conservancy districts had special powers to regulate use of water in streams to the extent that the flow was increased by improvements made by the district (*Sections 6101.24 and 6119.06 (N)*; Callahan, 1979). In 1933, Ohio established the Muskingum Conservancy District to assist the Army Corps of Engineers with a large-scale flood control and water conservation project that resulted in construction of 14 reservoir and dam systems along the Muskingum River.

Technological advances and new legislation in the 1940s brought a resurgence of drainage and flood control channel construction to the Midwest by local drainage districts, the SCS, and The Army Corps of Engineers. In 1941, drainage and irrigation work was approved as a conservation practice by the USDA. The Flood Control Act of 1944 together with the authorization of USDA to plan and construct drainage outlet channels in cooperation with local and state governments in 1954 led to a new way to manage drainage ditches. In Ohio, county commissioners and county engineers noticed that drainage ditches were being constructed multiple times to remove sediment or other debris that had accumulated over time resulting high costs to landowners and local governments. To address this, county commissioners were granted authority to establish a fund for the county that would be used to 'maintain' ditches and tiles installed through the petition ditch laws. At first, maintenance programs were optional. In 1957, ditch maintenance programs were mandated by the law (Brown and Stearns, 1991; ODNR, 2009).

Technological advances expanded the efficiency drainage, particularly in the Midwest, and led to the "Green Revolution" in the 1950s and 1960s (Rankin and Armitage, 2006). By 1960, corrugated plastic tubing was on the market and quickly replacing clay and cement as a cheaper and longer-lasting drain tile. The first laser grade control system that enabled the precise depth and grade of subsurface drains by regulating trenching and plow-type drainage machines was demonstrated in 1968 at the Ohio State Farm Science Review (Fouss and Fausey, 2007). Also at this time, the USDA released the first federal guidance on the design of open channels, Technical Release-25, requiring open channels to be trapezoidal and designed to convey water discharges of all magnitudes from base flow through flood flow without significant damage to the channel or to fish habitat (USDA, 1964).

Concurrent to federal legislation that promoted drainage and ditching improvements, the Surgeon General warned of widespread threats to drinking water and public health after it was reported that over 3,500 communities pumped 2.5 billion tons of raw sewage into streams, lakes, and coastal waters every day in the United States (http://www.epa.gov/lawsregs/laws/cwa.html). Historically, water regulation was left up to the states; however, Congress passed the Federal Water Pollution Control Act in 1948 in direct response to the Surgeon General's warning. The Act preserved states' control of their waterways by only regulating interstate waters, established federal technical services and grants to state and interstate government bodies and, ultimately, did very little to limit water pollution. Significant federal legislation protecting U.S. waters did not arrive for another 24 years.

Scientific and Cultural Shifts in the View of Stream Systems and Land Drainage

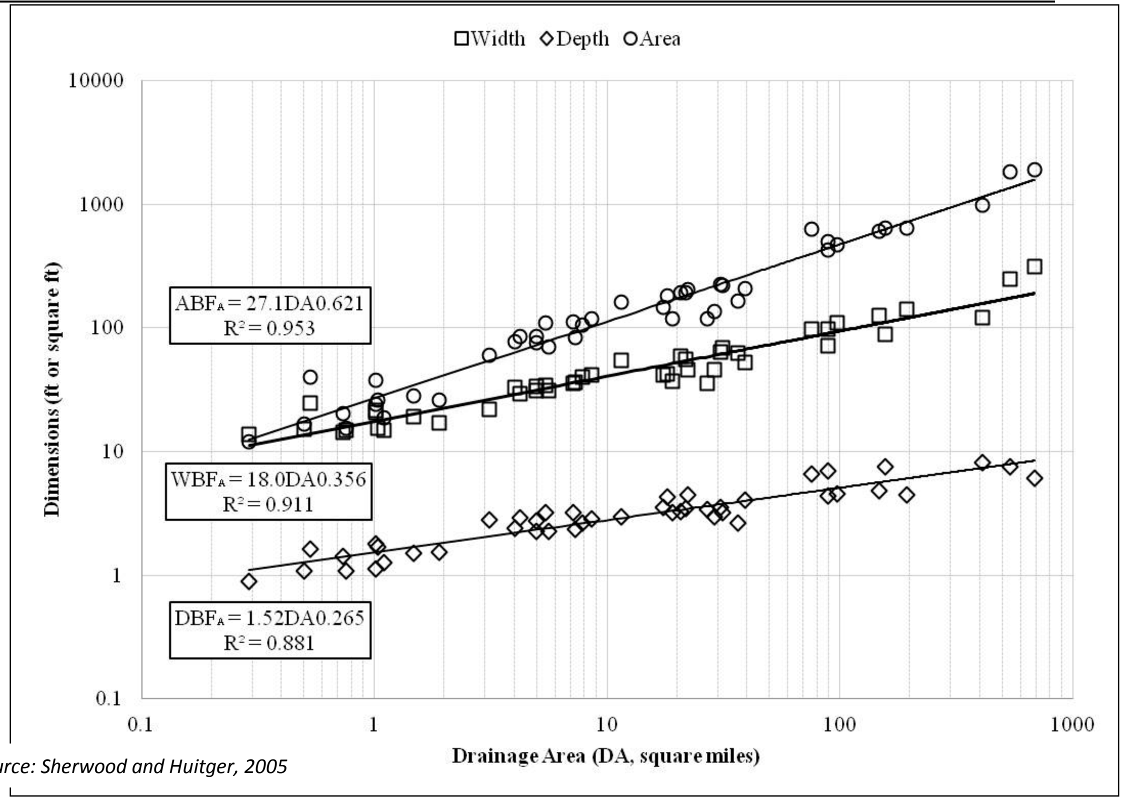
The early to mid-20th Century might be considered a period of enlightenment for stream and river research. A better understanding of stream and river systems by the scientific and regulating communities, combined with a largely grass-roots led effort against air and water pollution, resulted in significant changes in cultural views on agricultural drainage by the end of the 20th Century.

Stream and River Morphology Research

Many geologists had accepted for some time the idea that climate and geology were the ultimate determinants of river morphology through their effect on discharge and sediment load. As early as 1902, Davis defined a "graded" stream as the condition of balance between erosion and deposition attained by mature rivers. Lindley (1919) defined the regime concept as the dimensions, width, depth and gradient, of a channel to carry a given supply (of water) loaded with a given silt that were all fixed by nature. It was postulated that the floodplain of the highest quality streams experienced frequent over flow with a main goal of absorbing and dissipating energy from high flows. The main channel, in turn, adjusted its dimensions and pattern to efficiently move sediment and water during low flows. Working together, the channel and its floodplain balanced sediment and water transport, storage and supply; a process that became known as the dynamic equilibrium concept (Leopold and Maddock, 1953; Lane, 1955; Wolman and Miller, 1960; Langbein and Leopold, 1964).

In natural systems, dimensions of the main channel were associated with a range of flows referred to as the bankfull, effective, or dominant discharges. Bankfull discharge originally was described as the amount of water that filled up the main channel to a depth just before it spilled out onto the floodplain (Wolman and Leopold, 1956; and Wolman and Miller, 1960). Later, it was described as a range of flows that was most effective in forming a channel, floodplains, banks and bars (Williams, 1978). Effective discharge, in turn, was based on sediment transport concepts and was described as the flow that transports the largest cumulative sediment load over time (Wolman and Miller, 1960). Benson and Thomas (1966) were the first to define dominant discharge as the discharge that over a long time period transports the most sediment; and further describing that it was much less than bankfull-stage discharge, somewhere between the mean annual flow and the effective discharge. Collectively, bankfull and effective discharges were considered channel-forming discharges (Leopold et al., 1964).

Hydraulic geometry relationships between channel width, mean depth, mean velocity, slope and friction were developed that enabled researchers to predict characteristics of stream channels and classify them based on form (Leopold, 1953; Leopold and Wolman, 1957; Leopold and Langbein, 1962; Thakur and Scheidegger, 1968; Ferguson, 1973; Schumm, 1977; Knighton, 1977; and Hey, 1978, among others). Regional relationships for bankfull stream characteristics based on drainage area, referred to as regional curves, also were developed to verify field determinations of bankfull discharge and measured stream channel characteristics. Regional curves expressed the mathematical relationships between contributing drainage area and channel dimensions corresponding to the bankfull discharge (Witter, 2006; Sherwood and Huitger, 2005; Figure B8). Work referenced above, and by others during this time, served to make a seemingly wild, unpredictable river system predictable and, hence, manageable.



Source: Sherwood and Huitger, 2005

Figure B8. United States Geological Survey regional curves for Ohio (Sherwood and Huitger, 2005).

Effects of Channelization on Hydrology and Hydraulics

By the mid 1970s, it was widely accepted that fluvial systems were connected and that changes to one part of the system would have widespread effects throughout the entire system

(Brookes, 1985). While it had long been known that trapezoidal-shaped channels successfully drained the soil profile and efficiently moved water downstream, they were often constructed larger than what would be formed by natural fluvial processes and disconnected the channel from its floodplain. The primary reason that drainage ditches were constructed so large was to accommodate the depth of subsurface tile drains. Subsurface tile drains typically were installed 24-36 inches below the surface. To provide sufficient free-board for drainage, ditches often were dug an additional 12-24 inches below the tile outlets resulting in drainage channels that were a minimum of 5-6 ft deep (Figure B9).


Source: The k2p blog

Figure B9. An over-sized open ditch to accommodate subsurface tile outlets.

From a geomorphic perspective, trapezoidal channels were too large to transport small flows and provided no floodplain to dissipate the energy of large flows and, therefore, an imbalance was created. In response to this imbalance, natural fluvial processes worked to create a small main channel by building a floodplain or bench within the confines of the ditch; however this increased friction, sometimes buried drain tiles, and increased hydraulic residence time, which backed up water into drain pipes saturating the soil profile and limiting crop yield (Blann et al., 2009). County ditch maintenance programs would clean out vegetation and sediment deposits to restore a trapezoidal shape and maintain drainage capacity (Figure B10). Channel maintenance, which often included straightening, smoothing, and deepening stream channels, led to an immediate increase in bed slope and carrying capacity of the channels. Smoothing, or removal of woody vegetation on channel banks and sediments from channel beds, reduced friction that increased flow velocities and improved drainage capacity.

Unfortunately, in many cases, higher flow velocities caused instability on channel beds and on steep and un-vegetated banks causing channels to further deepen and widen (Daniels, 1960; Emerson, 1971; Nunnally, 1978; Ritter, 1979; Simon and Rinaldi, 2006). The newly formed and still-oversized channel failed to transport sediment, which resulted in aggradation that flattened the channel slope and increased channel hydraulic residence; the fluvial cycle of imbalance began again. Deviation from natural fluvial processes in drainage ditches drove the need for constant and frequent "improvement" to maintain drainage capacity. Routine maintenance activities typically occurred every 1-20 years. The ecological and socioeconomic impact of drainage ditch clean-out was significant. In Minnesota, $12 million dollars per year were spent on drainage ditch maintenance, and in Ohio, it was estimated that an average of $450/mile was spent annually on open-channel ditch maintenance (Hansen et al., 2006). Ohio has nearly 4,000 miles of open channels that were routinely maintained for agricultural drainage (ODNR, 2008).

Figure B10. Examples of traditional agricultural ditch maintenance activities.

Stream Ecology and Water Quality Research

A holistic view of streams as ecosystems did not begin until the late 1950s (Odum 1957; Teal 1957; Margalef, 1960). Most research at this time focused on fish and macroinvertebrates in forested streams. Ross (1963) was among the first to note similarities among stream communities over broad geographic areas and was the first to recognize the importance of the riparian-channel interaction. The importance of streams as ecosystems appeared in a seminal paper positing that stream systems should be part of the study of landscape ecology (Hynes, 1975). Work on nutrient transport in streams was occurring at this time that, collectively, became known as the nutrient spiraling concept (Webster and Patten, 1979; Newbold et al.

1981; 1982a; 1982b). Recognition that the action of flowing water, bed form and stability, and organic matter storage and transport, varied with climate began to emerge in the ecological literature that spurred a re-evaluation of the idea that streams were more than conduits that simply transported materials and, hence, to a greater appreciation of the metabolic and retention role of stream systems (Ross, 1963; Gregory and Walling, 1973; Hynes, 1975; Minshall et al., 1983). By the early 1980s, the prevalent scientific view of stream ecosystems was that of the River Continuum Concept (RCC; Vannote et al., 1980). Pioneering work in this area emphasized conditions in relatively undisturbed streams draining forests, but the broader implication of these studies, which was well supported in the literature, indicated that the floodplain was crucial to the function of stream ecosystem processes (Fisher and Likens, 1973; Minshall, 1978; Cushing et al., 1980; Fisher et al., 1982; Cummins et al., 1984; Minshall et al., 1983; and Strayer, 1983; Junk et al., 1989, among others). In Ohio, monitoring and research on fish, macroinvertebrates, in-stream habitat as indicators of stream impairments based on deviations from natural conditions led to the development of bioassessment indices (i.e., Index of Biotic Integrity, Invertebrate Community Index, and Qualitative Habitat Evaluation Index) and threshold criteria for stream health (Karr, 1981; OEPA, 1988; 1989; Rankin, 1995). Ohio became the first state to incorporate bioassessment criteria into state Water Quality Standards and served as a model for adaptation and adoption of bioassessment indices by other states. Until this time, stream health was determined from sampling water chemistry constituents.

Effects of Channelization on Stream Biota and Water Quality

Blann et al. (2009) provide a comprehensive review on the impacts of drainage on aquatic organisms. Channelization resulting in a trapezoidal-shaped channel had an immediate effect on aquatic biota by producing a channel devoid of habitat complexity. Straightening channels resulted in loss of channel length and, therefore, in-stream habitat. For example, Hansen (1971) reported a 54% total reduction in the length of a lowland reach of the Little Sioux River in Iowa. Increased flow velocities and the removal of vegetation that de-stabilized the channel bed and banks resulted in elevated concentrations of suspended sediments in the water column and increased sediment loads to rivers, which buried substrates that were key spawning area for fish (Keller, 1976; Karr and Schlosser, 1978). Increases in flow also may have had direct ecological implications since many aquatic organisms had specific water velocity requirements (Jones and King, 1950; Scott, 1958; Fraser, 1975; Gore, 1978; Milner et al., 1981). Maintenance activities to remove benches or bars that had formed also removed pool-riffle sequences that were critical feeding and breeding areas (Gibson and Power, 1975; Milner et al., 1981; Jenkins et al., 1984). Channelization also altered energy dynamics in channels and trophic interactions. Removal of shading vegetation from banks and changes in water depth affected in-stream temperatures. Since most streams receive their primary source of energy from allochthonous organic matter, loss of bank-side vegetation may have also substantially reduced energy flow in the aquatic system (Cummins, 1974; 1979).

Skaggs et al. (1994) provided a review the impact of drainage to water quality that began to appear in the literature in the 1970s and found conflicting results on the impacts of land clearing, channelization of streams and subsurface drainage improvements on peak flows, runoff, sedimentation, and nitrogen and phosphorus levels in stream systems. Impacts of agricultural drainage were as much related to design and implementation as they were to cultural practices and 'good-housekeeping'. Early studies stressed the importance of factors such as soils, climate, drainage design, and the location of drainage improvements in the effects of land drainage and effects could be minimized if appropriate measures were taken upon land development such as reseeding drainage ditches immediately after excavation.

Concurrently, by the late 1960s, the channelization work of the SCS and the Army Corps of Engineers became so controversial that Congress commissioned an independent national survey of the environmental effects of the channelization projects (Schoof, 1980). The impact of land drainage and ditching activities through sedimentation effects on aquatic biodiversity did not go unnoticed at the state and federal level, causing an added impetus for protection of agricultural soils. As a result, the implementation of various conservation tillage practices (e.g. no-till, mulch-till, and etc.) began in the 1970s and expanded so rapidly that about 40% of cropped land in the U.S. now is farmed with some type of conservation tillage (Shoof, 1980). The benefits of conservation tillage were substantial in reducing soil erosion and there were some positive biological responses to this effort.

Federal Legislation and the Culture of Agricultural Drainage

More than 34,000 miles of waterways were modified by the Army Corps of Engineers and the SCS from 1940 to 1970 for drainage and flood protection (Shoof, 1980). Most of the work occurred in five Midwestern states: Illinois, Indiana, North Dakota, Ohio, and Kansas. At the time, channelization was considered "channel improvement" or "watershed management" with clearly demonstrated societal benefits (Schoof, 1980). The primary objections to stream channelization from the environmental community were the reduction in fishery resources, the destruction of wildlife habitat due to timber removal, reduced aesthetics, and increased flooding and sedimentation downstream. Lack of federal regulation and poor state and local regulations resulted in continued water pollution throughout the U.S. Two independent events occurred that finally focused the attention of the federal government to the widespread problems of environmental degradation. The first was the publication of Rachel Carson's *Silent Spring* in 1962, which brought national awareness to the affects of pesticide use on birds and on the environment. The second was the burning of the heavily polluted Cuyahoga River in Cleveland, Ohio, in 1969. Reporters from *Time* magazine witnessed it and reported in their national publication that the river ‘oozed rather than flowed’ (Figure B11; http://www.epa.gov/greatlakes/aoc/cuyahoga.html). Growing national environmental concerns catalyzed by these events led to the federal government forming the Environmental Protection Agency in 1970 and passing the National Environmental Policy Act in 1969 and the Federal Clean Water Act in 1972.

Source: http://www.ohiohistorycentral.org

Figure B11. The Cuyahoga River fire of 1952.

At this time, the U.S. was facing a crop surplus; air quality and water quality were now as important as or more so than agricultural quality. For example, wetlands were no longer considered inaccessible, unprofitable ‘wet lands’ as much as they were unique and valuable ecosystems (Urban, 2005). The Food Security Act of 1985 exemplified a national shift toward environmentalism by eliminating indirect federal incentives to convert wetlands into cropland under the Swampbuster provision and by creating conservation programs such as Sodbuster and the Conservation Reserve Program. Shrimohammadi (1995) reported that most states in the continental U.S. prepared agricultural water quality plans in the 1970s that recommended the evaluation of certain best management practices (BMPs) in agricultural watersheds with respect to their impact on water quality. Agricultural drainage was not considered a BMP in any of these plans. Also, by this time the effects of stream channelization on water quality, benthic invertebrate communities, fisheries resources, and the recreational value of streams was well documented (Karr and Schlosser, 1978). Publications and technical guidance from SCS were updated with input from environmental interests. Channel improvements that were funded or supported by federal dollars now required environmental impacts statements. Changes in the way humans related to the local and regional ecosystem combined with the cultural legacy of agricultural drainage led to many conflicts between agriculture and environmental groups throughout the 20th Century.

The image of drainage had changed dramatically over the second half of the 20th Century, but the integration of drainage into American culture was clear. Urban (2005) provided an account of impacts of drainage on American culture, especially in the Midwest, which is summarized briefly. Natural streams that had been straightened, deepened, and widened over the last 100 years were now often identified on topographic maps as ditches. Constructed ditches were no longer considered channels that had been dredged into existence but now were included in consideration with the channelized natural streams. Most channel modifications occurred on or adjacent to farms, implicating the agricultural community in effecting changes in local stream systems (Urban and Rhoads, 2003). Increased knowledge and understanding of hydrologic and hydraulic processes in stream and river systems made it apparent that agricultural drainage not only affected regional ecosystems but also the underlying physical environment and the geomorphic processes shaping it over time. By the mid 1980s there was deep concern about the legacy effects of disruptions to the biological communities of channelized stream systems and unabated water pollution. Restoring wetlands, stream and river management, protection of coastal waters became a national cultural theme. What was a theory of stream restoration less than a decade earlier surged to become a billion dollar industry by the end of the 20st Century to deal with these impacts.

Restoration, Rehabilitation and Naturalization of Drainage Ditches

Persistent Nutrient Enrichment becomes a National Priority

Increased nitrate and phosphorus levels were detected in the Gulf of Mexico in the 1970s and in Lake Erie as early as the 1960s (Turner and Rabalais, 1991; Beeton 1961). Algal blooms as a result of eutrophication were causing major ecological problems and dead zones in these economically and ecologically valuable water bodies (Turner and Rabalais, 1991; Rabalais, 2002; Mitsch, 2001). The U.S. and Canada signed the Great Lakes Water Quality Agreement in 1972 that resulted in a 60% reduction in phosphorus loading to Lake Erie and no reports of algal blooms by the early 1980s (http://www.epa.gov/med/grosseile_site/indicators/algae-blooms.html). In contrast, algal blooms in the Gulf of Mexico had resulted in an extensive hypoxic zone related to fertilizer application on agricultural fields in the states within the Mississippi River by the mid 1980s (Turner and Rabalais, 1991).

The primary focus of drainage management that continued into the 21st Century was on nutrient and sediment export from agricultural fields (Rabalais, 2002). Nutrient enrichment and the resulting hypoxia in the Gulf of Mexico and the Great Lakes appeared to be on the decline through the latter half of the 1980s and into the early 1990s; however, harmful algal blooms increased again toward the end of the 1990s. Harmful algal blooms caused an estimated cost of $2.2 billion in losses to public health, commercial fishing, tourism, property values, and management in the United States (Dodds et al., 2009). In response, the federal government passed the Harmful Algal Bloom and Hypoxia Research and Control Act of 1998 (HABHRC), which mandated the National Oceanic and Atmospheric Association (NOAA) to advance the scientific understanding and to develop programs for research into methods of prevention, control, and mitigation of harmful algal blooms (http://www.cop.noaa.gov/). In response to the 1992 National Water Quality Inventory, which found that 56% of the stream miles surveyed was not meeting their designated use, and 44% of the remaining stream miles surveyed had sediment and nutrient impairments, fifteen federal agencies collaborated to publish the Federal Stream Corridor Restoration Handbook (NEH-653; FISRWG, 1998).

Despite extensive research efforts and the implementation of landscape best management practices (BMP's) to minimize nutrient losses from agricultural lands, water quality problems associated with anthropogenic eutrophication persisted (Carpenter et al., 1998). In 2003, toxic *Microcystis* was detected in algal blooms in western Lake Erie that forced beach closures and impacted fishing and recreation in both Ohio and Michigan. The HABHRC Act was amended in 2004 and harmful algal blooms became a high priority national issue (http://www.cop.noaa.gov/).

Managing Agricultural Drainage Ditches to Improve Water Quality

It was estimated that up to 80% or more of the entire stream network in some Midwest states consisted of streams and drainage ditches channelized and modified to a trapezoidal geometry for agricultural purposes (Blann et al., 2009). Considerable research documented the role of drainage ditches as conduits of field pollutants and the effects of routine ditch maintenance practices such as dredging in disrupting the natural buffering ability of ditches (Kleinman et al., 2007; Smith and Pappas, 2007; Pappas and Smith, 2007). A growing body of research suggests the potential for using vegetated open ditches as best management practices in mitigating potential agricultural contaminants. Strock et al. (2010) identified a number of landscape and in-stream practices to reduce the off-site transport of pollutants in drainage water. There had been considerable debate on whether anthropogenic eutrophication problems could best be resolved with landscape BMPs, in-stream BMPs, or some combination in a systems approach. Some had called for a moratorium on all drainage works. The debate very much reflected cultural divisions in the Midwest that may prove to be critical to the future of drainage in the Midwest as water quality problems persist and as management solutions are developed. Herein, we turn our attention to current research trends in agricultural drainage ditches in the Midwest that have led to the design and management of open ditches as in-stream best management practices.

Alternative Agricultural Drainage Ditch Approaches and Design

Geomorphology and Fluvial Processes in Agricultural Drainage Ditches

Significant research on geomorphology concepts was abundant, but attempts to apply these concepts to engineering design only occurred in earnest within the last three decades. Hydraulic geometry relationships relied on channel-forming discharges that were not easily measurable and, therefore, were based on calculating bankfull discharges from stream geomorphology measurements or calculating effective discharges from measured or estimated sediment and stream flow data (Ward et al., 2003). Established methods on field measurement techniques of stream geomorphology were widely available (i.e., Harrelson et al., 1994); however estimates of bankfull discharges relied on accurately identifying and measuring bankfull dimensions in the field. Most published studies on bankfull or effective discharges had been based on natural systems in the western U.S. that had steeper gradients, were not underlain by subsurface drainage, and were in less modified landscapes than systems in the Midwest (Powell, et al., 2006). Johnson and Heil (1996) questioned the use of geomorphic bankfull relationships on unstable channels like agricultural ditches; however, a few studies had shown that, if left unmaintained, disturbed headwater systems developed stable geomorphic features, such as an inset channel, bars, and vegetated benches (Figure B12; Kuhnle et al., 1999; Rhoads and Monahan, 1997; Rhoads et al. 1999; Frothingham et al., 2002; Ward et al., 2003; Landwehr and Rhoads, 2003; Jayakaran et al., 2005, 2007).

Figure B12. An agricultural drainage ditch with vegetated benches and a meandering inset channel.

Jayakaran et al. (2005), using a logistic regression model, found that stable bench formation could be predicted by the width of the ditch and drainage area in Northwest Ohio ditches. Drainage area was a key factor in determining the dimensions a stream will create for itself (Leopold et al., 1995), while ditch width was an anthropogenic constraint imposed on the channel. In a ditch that was too wide, the stream adjusted to a narrower width by building benches (Landwehr and Rhoads, 2003). Stability of a bench could be modeled as a function of drainage area and ditch width and could be sized by traditional engineering designs to accommodate extreme events (Jayakaran et al., 2005). Channel-forming discharge concepts were suitable for engineering applications in large rivers in the Midwest, but the recurrence intervals of channel-forming discharges were less in modified low gradient watersheds than the often reported 1.5-year to 2.0-year published values used for engineering design (Jayakaran, 2005; Powell et al., 2006; Leopold, 1994; Simon et al., 2004).

Ward (*personal communication*) speculated that, in ditch systems having subsurface drainage, the inset channel was formed by channel-forming discharges associated with high tile flows, which was the reason benches formed in the bottom of ditches rather than near the top. In an unpublished study, he analyzed this concept by considering typical design standards for subsurface drainage (ASABE, 2008) and fitting regional curves to inset channel data from 18 sites located in tributaries to the Portage River, Ohio, measured by Jayakaran et al. (2005). Regional curves for the Portage River watershed (Figure B13) were taken from Powell (2006), who interpreted measured data for one site differently than Jayakaran et al. (2005). The weak correlation between drainage area and measured bankfull dimensions was a result of some sites having unstable benches or no dominant fluvial features (Jayakaran et al., 2005). The analysis also included regional curves for the St Joseph River watershed, located in northwest Ohio, Indiana and Michigan (Figure B14; Powell, 2006) and the USGS Region A curves for natural streams in Ohio (Sherwood and Huitger, 2005).

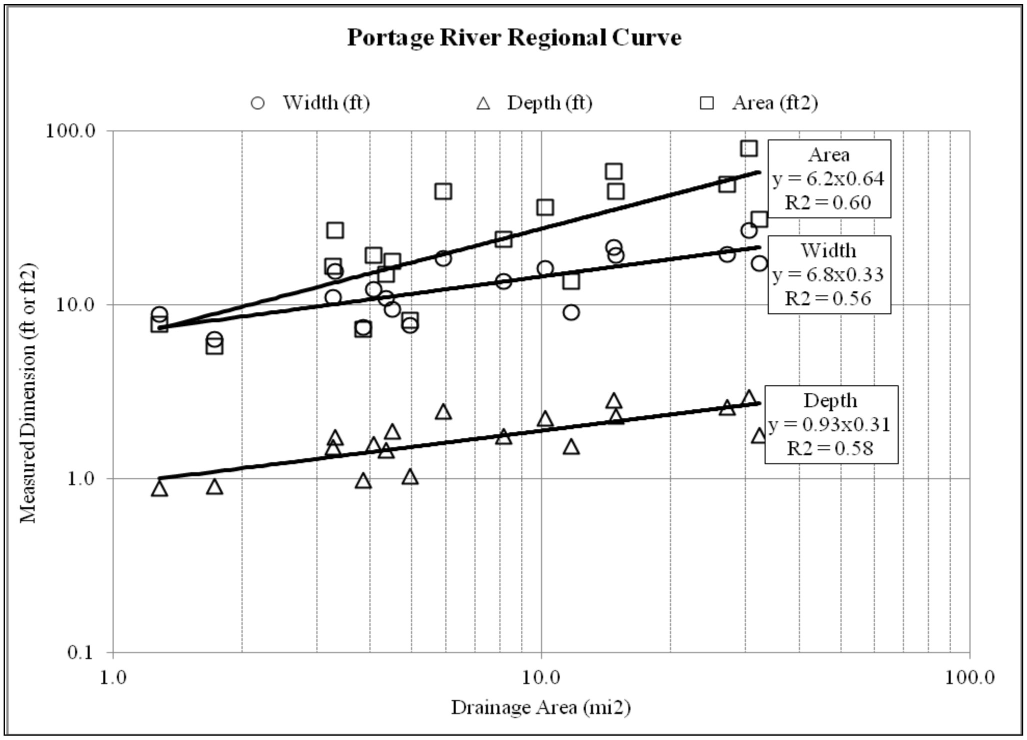


Figure B13. Portage River regional curves (as reported in Powell, 2006).

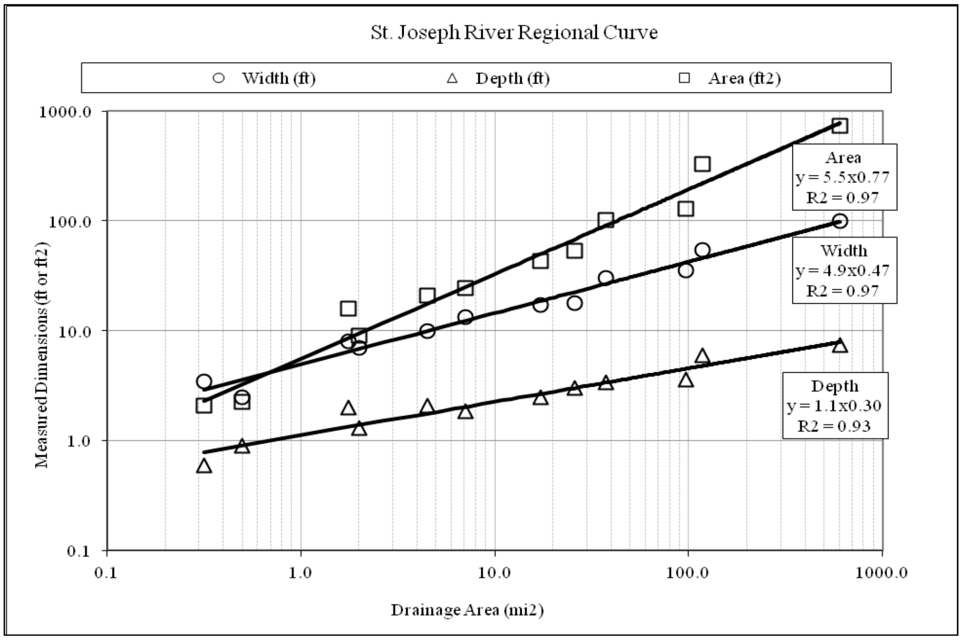


Figure B14. St. Joseph River regional curves (as reported in Powell, 2006).

The following two theoretical tile-drained scenarios were considered: Channel A that drains 320 acres of cropland in a 640 acre watershed, and has a subsurface drainage coefficient of 0.5 inches per day that produces a mean daily discharge of 6.7 cfs at the tile outlet; and Channel B that drains 480 acres of cropland in a 640 acre watershed, and has a subsurface drainage coefficient of 0.75 inches per day that produces a discharge of 15.1 cfs at the tile outlet. To represent a larger drainage system, discharges at the outlet were multiplied by 10 resulting in 67 cfs in Channel A and 151 cfs in Channel B. Using Manning's equation and the continuity equation to calculate bankfull discharge associated with channel dimensions, Ward found, at the lower threshold in the Portage River and St. Joseph River watersheds, the bankfull discharge for the inset channel in an agricultural ditch was similar to the design discharge from subsurface drainage systems (Table B1). In contrast, the bankfull discharge estimated by the USGS regional curves for natural streams (Sherwood and Huitger, 2005) was many times larger than the bankfull discharge for the inset channel (Table B1). Results of this analysis confirmed that the inset channel was formed by high tile flows that conformed to channel-forming processes and that the dimensions of the inset channel could be predicted using appropriate regional curve relationships.

Table B1. Example analysis of channel-forming discharges associated with tile flows in agricultural drainage ditches in Northwest Ohio.

			Bed slope		Subsurface Drainage	
			0.0005	**0.005**	**A**	**B**
Portage River						
DA	mi^2	1				
width	ft	6.80				
depth	ft	0.93				
Discharge	**cfs**		**5.7**	**18**	**6.7**	**15.1**
DA	mi^2	10				
width	ft	14.54				
depth	ft	1.90				
Discharge	**cfs**		**40.3**	**127.5**	**67**	**151**
St Joseph River						
DA	mi^2	1				
width	ft	4.90				
depth	ft	1.1				
Discharge	**cfs**		**5**	**15.8**	**6.7**	**15.1**
DA	mi^2	10				
width	ft	14.46				
depth	ft	2.19				
Discharge	**cfs**		**49.7**	**157.2**	**67**	**151**
Ohio Region A (Sherwood and Huitger, 2005)						
DA	mi^2	1				
width	ft	18.0				
depth	ft	1.52				
Discharge	**cfs**		**36.2**	**114.5**	**6.7**	**15.1**
DA	mi^2	10				
width	ft	40.9				
depth	ft	2.80				
Discharge	**cfs**		**231.4**	**731.9**	**67**	**151**

Jayakaran et al. (2010) provide a comprehensive review of research on fluvial processes and management of agricultural ditches, and we summarize some of the key findings pertaining to Midwest agricultural channels and the development of the two-stage ditch concept.

Jayakaran et al. (2007) reported that naturally-formed benches in agricultural ditches in Northwest Ohio evolved by vertical accretion and in similar ways to how floodplains form in natural systems. Results were consistent with research findings on ditches in Illinois (Landwehr and Rhoads, 2003). A hydrologic study of agricultural ditches containing low benches indicated that the benches were flooded between 10 and 60 days annually, and flooding events were associated with discharges equivalent to 30% of the 2-year discharge (Kallio, 2009). Additionally, simulation studies suggested that nitrate-N removal may be as great as 20% if the floodplain area is equivalent to at least 1% of the watershed area (Kallio et al., 2010). Fry et al. (2012) found that overbank flow was 1% to 4% of the total volume of flow in a small agricultural watershed with attached floodplains. Rhoads and Massey (2011) reported that lateral migration of the inset channel was minimal in an Illinois ditch that had naturally-formed with well-vegetated benches.

Aquatic Diversity and Water Quality in Agricultural Drainage Ditches

Heavily managed agricultural watersheds typically had been viewed as devoid of viable populations of aquatic life and supported little, if any, ecological function (Crail et al., 2011). Ditches largely were ignored as contributors to aquatic biodiversity (Armitage et al., 2003). Recent work has resulted in increasing awareness that highly modified agricultural watersheds could support diverse populations of aquatic biota (Herzon and Helenius, 2008). As early as the mid 1970s, Keller (1975) postulated that establishing a pilot channel in trapezoidal channels and building riffle-pool sequences in the channel could vastly improve aquatic communities. Richards et al. (1993) found that sensitive macroinvertebrate communities in Michigan ditches were most affected by substrate quality and composition. Evaluating fish communities in Illinois streams, Schlosser (1995) developed a framework for rehabilitating impaired channels to achieve best potential ecological function. Ditches were considered a high-quality habitat for certain frog species in habitat-limited agricultural watersheds in central Iowa (Rustigian et al., 2003). Work by Lyons (2000) and Rhoads et al. (2003) established a new way of thinking about riparian vegetation and the contribution of grasses to habitat heterogeneity in modified headwater streams. Studies in Ohio, Indiana and Michigan concluded that although not as complex as natural stream systems, in-stream habitat was an important determinant of fish and macroinvertebrate community structure in modified agricultural streams (Smiley et al., 2008; Janssen, 2008; D'Ambrosio et al., 2009; and Crail et al., 2011). Rhoads and Massey (2011) suggested that leaving grassed benches in ditches could provide improved habitat for aquatic organisms. Leslie et al. (2012) have suggested that recent interest in the management of drainage ditches to improve water quality may provide the potential to improve habitat for aquatic biota; and might consider tradeoffs between the benefits of ditches as a source of biodiversity and as a tool for improving water quality.

Impacts of agricultural drainage on water quality in the 21st Century currently revolve around two main activities: drainage improvements on land already used for agriculture and conversion of undrained lands to agriculture; the former being the most critical impact to hydrology and water quality (Skaggs et al., 1994; Blann et al., 2009). Subsurface drainage systems have a useful life of 20 to 40 years (Skaggs et al., 1994). In order to sustain productivity of drained lands, major renovation or replacement will be necessary that may lead to greater intensity of subsurface drainage (Skaggs et al., 1994). Studies on a wide range of soils, crops, and site conditions have shown that increasing subsurface drainage intensity on agricultural lands may have both positive and negative impacts on hydrology and water quality. For example, conversion of undrained land to subsurface drainage generally results in increased peak flows and flashy hydrographs (Skaggs, et al., 1994). Conversely, the improvement of subsurface drainage on land that was already drained could reduce runoff and peak flow rates (Skaggs, et al., 1994). Strategies such as controlled drainage and sub-irrigation are examples of water table management practices that have the potential to both substantially improve agricultural productivity and reduce environmental impacts (Gilliam and Skaggs, 1986; Evans et al., 1995; Fouss et al., 1990; and Strock et al., 2010). More extensive reviews on improved management of subsurface drainage are provided by Skaggs et al. (1994) and Blann et al. (2009).

Ecological and socioeconomic costs attributed to routine ditch maintenance in agricultural watersheds has led researchers to question the cultural practice of maintenance on ditches and contributed to a collective rethinking of ditch management strategies in the Midwest. Traditional ditch design and maintenance short-circuited hydrologic and nutrient processing functions of stream channels. Ditches, once viewed as primary nutrient and sediment conduits, now play a key role as buffers between the landscape and valuable downstream receiving systems. Agricultural streams transport most nitrates during high flow events (Royer et al., 2006). Retaining vegetated benches in ditches increases the surface area of ditches and retention time during high flows. In Ohio and Indiana, denitrification rates were greater in sediments on naturally-formed benches in ditches than in sediments from side slopes of trapezoidal ditches (Powell and Bouchard, 2010) and having benches in ditches did not reduce in-stream denitrification rates (Roley et al., 2012a; 2012b). Managing flow regimes in ditches can reduce nitrogen and moderate downstream phosphorus losses through sorption capacities (Needelman et al., 2007; Strock et al., 2007; 2010; Smith, 2009). Managing floodplains of ditch systems, either in channel (Powell et al., 2007a; 2007b) or adjacent to the channel (Evans et al., 2007) can be effective in reducing sediment export losses from agricultural watersheds.

Managing Floodplains in Agricultural Ditches: The Two-Stage Ditch Approach

The two-stage ditch is a floodplain establishment design that results in a self-flushing, self-sustaining agricultural drainage system based on the principles of fluvial geomorphology that will reduce or eliminate the need for traditional ditch clean-out activities. (Ward et al., 2004; Jayakaran et al., 2005; 2007; Powell et al., 2007a; 2007b; Rhoads and Massey, 2012; Magner et al., 2012). The approach for designing two-stage systems consisted of: (1) an inset channel to convey the bankfull discharge, (2) a floodplain for the inset channel, and (3) sufficient capacity above the benches to reduce the likelihood that flow will overtop the ditch banks and flood surrounding crop land (Figure B15; Ward et al., 2004; Powell et al., 2007a; 2007b; Kallio, 2010). In theory, the result is a channel sized by channel-forming processes that is in a stable, quasi-equilibrium state (i.e., Schumm, 1981, Simon and Hupp, 1986; Nanson and Croke, 1992). Two-stage channels are considered stable if they are neither aggrading nor degrading based on geomorphic theory (Leopold, 1994; Lane, 1955) and should require little or no maintenance to maintain conveyance capacity and drainage function. The two-stage ditch approach does not construct or alter the existing inset channel. Instead, the benches are "pulled back" to a width that is a multiple of the inset channel bankfull width (or wide enough to accommodate small machinery) and at an elevation that corresponds to the regional curve predicted inset channel bankfull depth (Figure B16). In some cases, the design predicted from regional curves is adjusted to reflect the existing geometry of the inset channel and benches that nature has already formed. The ditch banks are sloped at a 2:1 or 3:1 angle. If present, vegetation growing along the edge of the channel is left intact during construction. Major benefits of this approach include maximizing stability until vegetation can become established on the newly constructed benches and preserving local ecology that may be present.

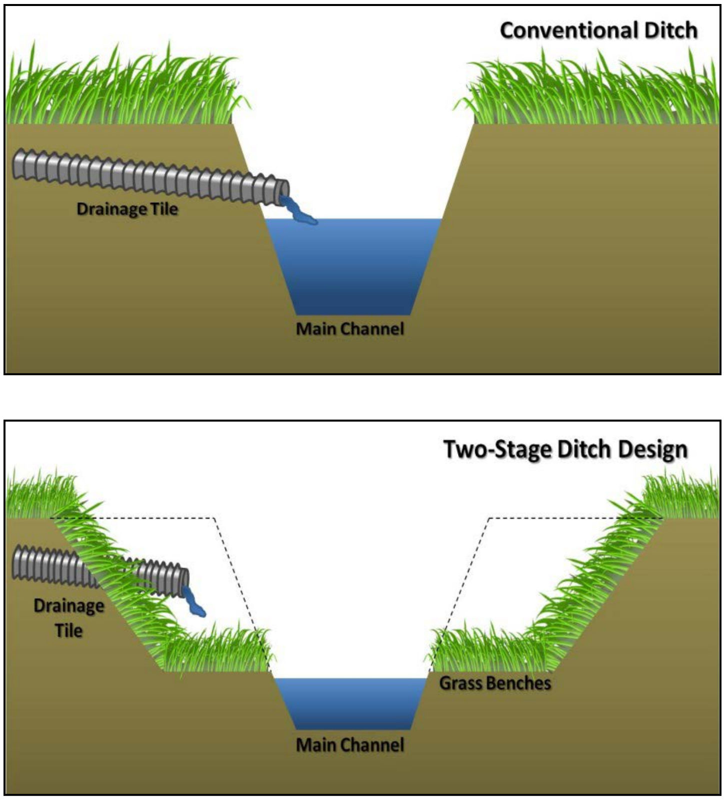


Figure B15. Schematic comparing conventional trapezoidal ditch design and two-stage ditch design.

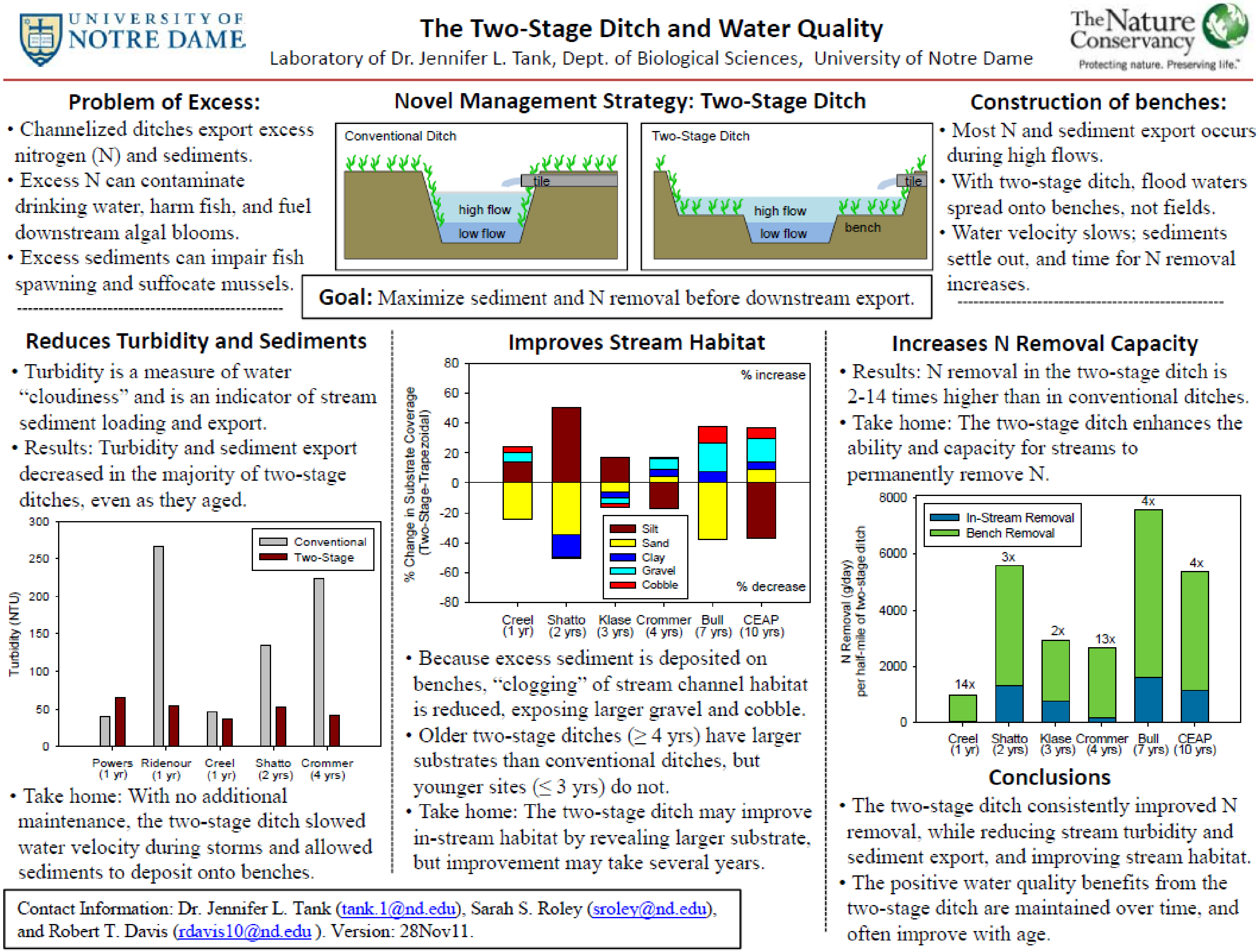
Figure B16. Construction of a two-stage ditch leaves the inset channel intact and "pulls back" the benches to a width that is a multiple of the bankfull channel width or wide enough to accommodate small machinery.

The first two-stage ditch designed using engineering principles and channel-forming concepts was constructed in Wood County, Ohio, in 2002 (Powell, 2006; Powell et al., 2007a; 2007b). The primary goal of the project was to increase the capacity of the under-sized ditch and reduce flooding of adjacent fields after rain events. The project was considered a prototype for future two-stage channels. It led to development of a 9-step procedure outlining the design of two-stage ditches (Powell et al., 2007a). Powell et al. (2007b) provide a case study review of the first 8 two-stage ditch projects in Ohio, Indiana, and Michigan designed or constructed using the 9-step procedure. Ward et al. (2008a) investigated floodplain ratios in constructed two-stage channels that would maximize bench stability, provide floodplain benefits, and not promote lateral migration of the inset channel within the ditch. Results from that study suggested design guidance that benches be constructed at a width of 3 to 5 times the bankfull inset channel width.

The two-stage ditch approach originally developed in Ohio as an alternative to traditional ditch maintenance for the purpose of increasing ditch stability, reducing bank erosion, and reducing flooding into adjacent fields. Work by Kallio (2010) and D'Ambrosio (unpublished) evaluated the evolution of two-stage channels in Ohio, Indiana and Michigan designed and constructed using the 9-step procedure outlined in Powell et al. (2007a) to determine where geomorphic changes were occurring over time (i.e., scour on ditch side slopes, scour or deposition on constructed benches, or aggradation or degradation of the inset channel), if they were maintaining drainage capacity, and what maintenance had been needed since construction. Preliminary findings of a weight-of-evidence approach presented by D'Ambrosio (2012) suggest that two-stage ditches 3 to 11 years after construction have experienced small adjustments to their dimensions over time, but have remained stable and maintained both overall ditch capacity and an inset channel (i.e., have not aggraded or degraded; Figure B17). None of the ditches have required traditional maintenance since construction. Additionally, all of the ditches constructed with a goal to improve bank stability and/or reduce flooding into adjacent fields have successfully achieved these goals.

Figure B17. A stable two-stage channel in Hillsdale County, Michigan, six years after construction.

Ongoing research on constructed two-stage ditches in the tri-state region indicates that improved soil-water-vegetation interactions on the benches may have implications for water quality and ecological benefits (Roley et al., 2012a; 2012b; Davis et al., *in prep*). To our knowledge, the vast majority of water quality research in constructed two-stage ditches has been led by Dr. Jennifer Tank and her laboratory at the University of Notre Dame. The findings of their work are summarized as following factsheets (Figures B19 and B20). Additional findings are currently being prepared for publication in peer-reviewed manuscripts.



The Two-Stage Ditch and Water Quality

Laboratory of Dr. Jennifer L. Tank, Dept. of Biological Sciences, University of Notre Dame

Problem of Excess:

- Channelized ditches export excess nitrogen (N) and sediments.
- Excess N can contaminate drinking water, harm fish, and fuel downstream algal blooms.
- Excess sediments can impair fish spawning and suffocate mussels.

Novel Management Strategy: Two-Stage Ditch

Goal: Maximize sediment and N removal before downstream export.

Construction of benches:

- Most N and sediment export occurs during high flows.
- With two-stage ditch, flood waters spread onto benches, not fields.
- Water velocity slows; sediments settle out, and time for N removal increases.

Reduces Turbidity and Sediments

- Turbidity is a measure of water "cloudiness" and is an indicator of stream sediment loading and export.
- Results: Turbidity and sediment export decreased in the majority of two-stage ditches, even as they aged.

- Take home: With no additional maintenance, the two-stage ditch slowed water velocity during storms and allowed sediments to deposit onto benches.

Improves Stream Habitat

- Because excess sediment is deposited on benches, "clogging" of stream channel habitat is reduced, exposing larger gravel and cobble.
- Older two-stage ditches (≥ 4 yrs) have larger substrates than conventional ditches, but younger sites (≤ 3 yrs) do not.
- Take home: The two-stage ditch may improve in-stream habitat by revealing larger substrate, but improvement may take several years.

Increases N Removal Capacity

- Results: N removal in the two-stage ditch is 2-14 times higher than in conventional ditches.
- Take home: The two-stage ditch enhances the ability and capacity for streams to permanently remove N.

Conclusions

- The two-stage ditch consistently improved N removal, while reducing stream turbidity and sediment export, and improving stream habitat.
- The positive water quality benefits from the two-stage ditch are maintained over time, and often improve with age.

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Figure B18. Factsheet on water quality benefits of two-stage ditches.

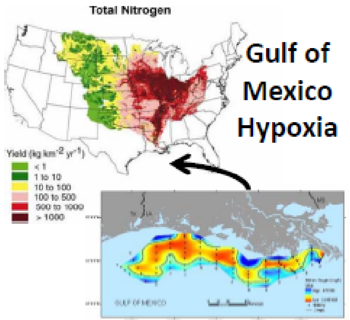
Two-Stage Management: Nitrogen & Sediment Dynamics in Agricultural Streams

Laboratory of Dr. Jennifer Tank, Department of Biological Sciences

Problem of Excess

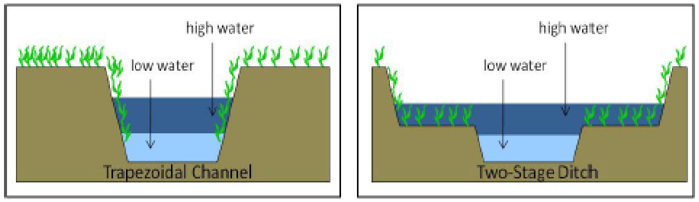
Streams in the agricultural Midwest can be a source of excess nutrients and sediments that pollute downstream ecosystems. Example: fertilizer runoff is responsible for the periodic "dead zone" in the Gulf of Mexico. Our goal is to maximize in-stream N and sediment removal before downstream export.

Can 2-stage ditch management reduce nitrogen and sediment export?



Gulf of Mexico Hypoxia

Two-Stage Restoration Strategy



During high flows, water spreads onto the floodplains, increasing the area over which N removal can occur.

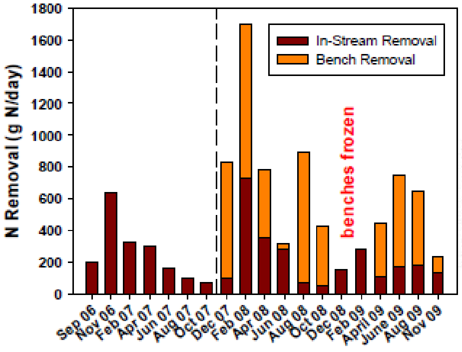
N Removal via Denitrification

- Denitrification is the microbial conversion of nitrate (NO_3^-) to dinitrogen gas (N_2), and is a **permanent removal of nitrogen**
- Denitrification occurs naturally in stream sediments
- The two-stage ditch increases stream surface area, resulting in increased permanent N removal

Shatto Ditch Demonstration Project

Bench Flooding

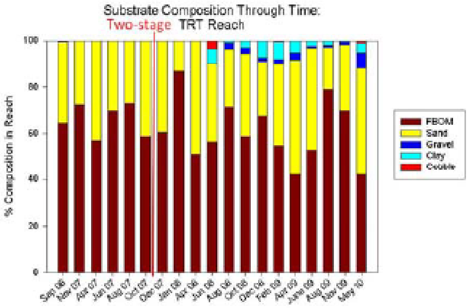
- Most N & sediment export occurs during high flows
- Flooded benches increase water residence time, which results in increased N processing and sediment removal
- Conditions are ideal for denitrification in flooded benches (high NO_3^- and C, anoxia)



Data from Roley et al. in press, 29 July 2011

Sediment Effects

- Water column turbidity decreased by 43%
- New streambed substrates are exposed



Implications for Downstream Water Quality

- Because of very high N loads, the increase in N removal translates only to 2-16% of the NO_3^- load
- In-stream management practices are most effective if coupled with watershed and landscape-level management programs
- **Both enhancing in-stream removal and reducing inputs are necessary to reduce downstream export**

Future Directions

- Study the effect of the two-stage across a range of streams and determine the change in two-stage function over time and with varying nitrate loads.
- Develop a management tool to evaluate the influence of the two-stage in different conservation scenarios.

Figure B19. Factsheet on the water quality benefits of two-stage ditches.

Finally, the two-stage ditch practice appears to be an economical practice to reduce nitrate-nitrogen pollution (Roley et al., in review). In an analysis of two-stage ditch effectiveness relative to wetlands and cover crops across a range of time horizons and interests rates the two-stage ditch (over a time horizon of 50 years) reduced nitrate-nitrogen at a cost of \$1.07-\$1.44 per kg N. Compared to the estimated cost of excess N to society, \$63-\$66 (Dodds et al., 2009; Birch et al., 2011; Compton et al., 2011), the practice appears to be a viable pollution abatement technology.

Conclusions

Successful implementation of the two-stage ditch concept in Ohio, Michigan, and Indiana led to its incorporation in Part 654 of the Stream Restoration Design National Engineering Handbook (USDA-NRCS, 2007). Additionally, the two-stage ditch is an approved best management practice for Indiana's Environmental Quality Incentive Program and has seen application in other upper Midwest states with great success (Magner et al., 2012; Bruce Wilson, *personal communication*). Like any practice designed for highly managed landscape, implementation of the two-stage ditch has trade-offs that have resulted in barriers to adoption at the local, state and regional level. Discussed further in Witter et al. (2011), trade-offs include: land must be taken out of production to accommodate the wider benches of the two-stage design; existing federal cost-share practices on the landscape (i.e., grass buffers) might be impacted, which may have implications to the cost-share agreement; and the cost of two-stage ditch construction might be higher than traditional ditch maintenance practices. Other barriers to adoption that warrant further education and investigation include visual perception of a ditch that does not have the traditional trapezoidal shape, the ditch filling in, concerns about ditch bank stability during high flow events, increased capacity causing downstream flooding, and actual water quality benefit gained from constructing benches, and compatibility with existing drainage ditch laws, among others.

Appendix C: Planning and Design Manual

Planning and Design Guidance for Two-Stage and Self-Forming Channels

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INTRODUCTION

In many areas a combination of climatic conditions, topography, poorly drained soils, high water tables, and cropping preferences dictate the need for improved drainage to facilitate reliable and economical production of agricultural commodities. Improved drainage includes subsurface and surface drainage systems that not only affect crop production, but can have profound impacts, both positive and negative, on watershed hydrology, channel morphology, water quality, stream habitat, and aquatic biology. Subsurface drainage systems installed in agricultural fields are typically 3- to 4-ft below the ground, spaced 25- to 75-ft apart, and typically consist of 102-mm or larger perforated plastic pipes that often connect to larger unperforated subsurface mains before outletting to a surface drainage channel (Figures C1 and C2). Subsurface drains are primarily used to protect crops against extended periods of saturated conditions in the root zone and to improve trafficability increasing time available for field operations. By 1985, improved subsurface drainage had been installed on more than 100,000,000-ac of cropland in the United States (USDA, 1987).

Figure C1. Aerial photograph of an agricultural field with subsurface drainage in Ohio. Location of subsurface laterals can be seen through differences in soil moisture.

Figure C2: Subsurface drains outletting to a typical surface drainage channel in the North Central Region of the United States.

Surface drainage channels that are the focus of this guidance document provide outlets for subsurface drainage tiles and are typically >4-ft in depth, drain >0.5-mi^2, and often designed to convey flows so that flooding into adjacent fields occurs less than once every 5- to 10-yrs or more. In some places they serve as the primary network of headwater streams in a watershed.

Historically, drainage ditches have been designed with a trapezoidal geometry, uniform slope, and relatively straight planform to maximize hydraulic efficiency and conveyance capacity. This is called a trapezoidal channel and is often designed using the *threshold channel design* methodology *(USDA, 1977; USDA, 2007)*. Unfortunately, this design is often unsustainable and the natural processes of erosion (Figure C3) and deposition (Figure C4) attempt to reshape the channel to a more natural state that balances the watershed sediment supply and hydrology. Costly and disruptive maintenance is often needed to maintain the trapezoidal channel design over the long-term (Figure C5).

Figure C3: Mass wasting of a bank from erosion of the toe making the banks steep and prone to failure.

Figure C4: Sediment deposition impacting performance of subsurface drainage system. (Photo: NRCS Gallery)

Figure C5: Channel maintenance that "dips out" bottom sediments and removes bank vegetation to reestablish the trapezoidal geometry.

Decades of research and monitoring have revealed impacts associated with traditional channel designs and drainage practices. This knowledge has led to the development of new and innovative management practices which provide the necessary drainage, but may have some positive benefits for water resources. Unfortunately, these practices are relatively new and often not considered in the planning and decision-making processes that guide drainage management and conservation at the local level. The remainder of this section describes these alternative management practices and the tradeoffs amongst them. The sections that follow describe the these practices within the context of the NRCS Conservation Planning Process (CPP) and lay out considerations for the selection of a resource management system (RMS) that includes drainage channel management and the design of two-stage and self-forming channels.

MANAGEMENT OPTIONS FOR DRAINAGE CHANNELS

At any potential project site at least 6 management options for drainage channels should be considered when developing a RMS: 1) do nothing, 2) passive enhancement, 3) threshold channel design, 4) two-stage channel design, 5) self-forming channel design, and 6) natural channel design. In many cases more than one approach may lead to an acceptable outcome and these practices may need to be implemented in conjunction with other conservation best management practices that enhance or maintain conveyance capacity (e.g. NRCS Conservation Practice Standards 326 (Clearing and Snagging)) and channel stability (e.g. NRCS Conservation Practice Standards 322 (Channel Bank Vegetation), 342 (Critical Area Planting), 382 (Fence), 395 (Stream Habitat Improvement and Management), 472 (Use Exclusion), 484 (Mulching), 578 (Stream Crossing), 580 (Streambank and Shoreline Protection), 584 (Channel Stabilization), and 647 (Early Successional Habitat Development/Management)).

The “Do Nothing” and “Passive Enhancement” do not actively alter channel form. The remaining approaches physically alter the existing channel and the primary differences between the approaches are associated with: A) the space required for implementation; B) how the form of the channel is established; C) the dimension, pattern, and profile of the channel; 4) what measures are taken to stabilize the system; and D) cost. The approach selected will depend on a variety of factors based on site specific information and project goals including but not limited to: a real or perceived problem being caused by the system; a desire or need to enhance the system to provide water quality and/or ecosystem services; available funding; meeting any applicable state or federal regulations; site-specific conditions; willing landowners; needs to reduce flooding or erosion; promoting agriculture, development or industry; protecting native species and habitats; and legal requirements. The management approaches are described briefly in the sections that follow.

Do Nothing **-** this approach involves simply leaving the channel in its current state. It is common for channels to go through a period of stabilization after construction or a maintenance activity. Allowing these adjustments to occur can help channels achieve a stable form and recover some level of ecological services while in many cases providing adequate drainage. Generally, if the system is not causing a problem, the *Do Nothing* approach should be considered. This may be a particularly useful strategy in channels that have predetermined maintenance regimes that landowners pay for through regular tax assessments. In many cases, the channels may perform well in terms of drainage and ecological function, but maintenance is undertaken simply because landowners have paid for it and it is on a prescribed maintenance schedule. Indiscriminant maintenance may lead to loss of some ecological services while only providing a marginal and temporary improvement in drainage and thus may be a poor investment of landowner or taxpayer resources. An example of a system that was functioning well for drainage, but was "cleaned out" due to a scheduled maintenance activity is provided in Figures C6 and C7. The Do Nothing approach would have cost nothing to implement and resulted in substantial savings to landowners while the drainage benefit was likely small and temporary.

Figure C6: A section of ditch in Minnesota prior to a maintenance activity.

Figure C7: The same ditch seen in Figure 6 after the maintenance activity.

Passive Enhancement **-** this approach involves stopping activities that cause degradation or prevent recovery and allowing natural processes to aid the channel system in recovery. In highly modified channel systems, passive enhancement might include livestock fencing, purchasing conservation easements, invasive species removal, native vegetation planting, and establishing no-mow zones. Although passive approaches may have positive effects, the approach may not be viable for low-energy channels that have been so degraded that recovery can take decades or longer or where accelerated erosion of high banks is severe and may impact sensitive downstream resources. This approach requires little to no engineering input, can be relatively inexpensive, and can greatly enhance some impaired ecosystem functions.

Threshold Channel Design and Maintenance - this approach is the traditional, trapezoidal design (see Figure C7 above) suitable for use in rigid boundary systems where erosion of the channel should be minimal for flows below the design discharge. A threshold channel should also transport the sediment load supplied without significant aggradation of the channel bed. In some systems, regular maintenance to remove bank vegetation, clean out bed sediments, or reconstruct the channel boundary is often needed to maintain a stable channel with adequate conveyance capacity. In most cases this approach provides few if any water quality or ecological services. However, in some cases the approach could provide a water quality benefit where there is correct disposal of sediments with high agrichemical or nutrient loads.

Two-Stage Channel Design **-** this approach is essentially a floodplain construction practice. First, it leaves in place any silt bars or benches that have formed within the confines of the channel and expands the floodplain at the bench elevation (Figures C8 and C9), if additional conveyance capacity is needed. The benches form through natural processes and confine low-flows within the larger drainage channel transporting fine sediments and providing stability to the channel sideslopes. The resulting channel form is more likely to maintain balance between sediment supply and transport and reduce the need for maintenance over time. In a two-stage channel system (Figure C10), the first stage includes the channel bed up to the floodplain bench elevation. This first stage is also referred to as the inset channel or a channel within the channel. The second stage extends up from the floodplain bench to the field. The second stage is typically designed to contain a certain size (i.e. recurrence interval) storm event without flooding into the adjacent fields. Typically, benches on each side of the inset channel will constructed to be 1 to 2 times the top width of the inset channel; where the inset channel top width is determined from an appropriate regional curve of bankfull dimensions.

Figure C8: A tributary channel to Bull Creek in Wood County, OH during two-stage channel construction.

Figure C9: Crommer Ditch two-stage reach approximately 6-years after construction.

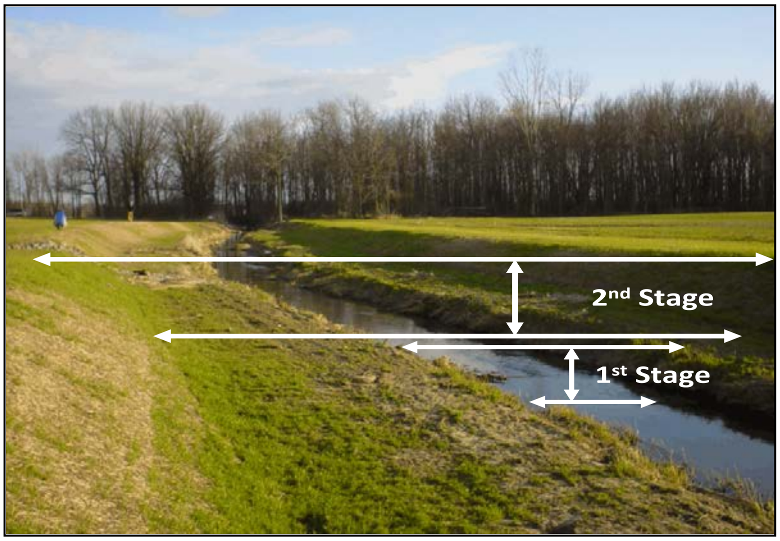

Figure C10: An annotated photograph of a two-stage channel depicting the first and second stages.

Self-forming Channel Design - this approach establishes the initial conditions upon which a channel and floodplain system will develop over time. It involves excavating the channel bed to an over-wide width and allowing natural processes to develop bars, benches, and an inset channel that is stable and sustainable by natural processes (Figures C11, C12, and C13). The self-forming channel design, in effect, is creating a valley without a floodplain, which results in the spreading of channel flows at low flow rates. Herbaceous vegetation quickly establishes in the bed of the channel, which promotes sediment deposition that forms the floodplains. One of the main benefits of this approach is that it allows space for the system to self-organize to a form that fits to the existing watershed and valley conditions. Depending on these conditions, the approach may result in a well-defined channel or may represent more of a wetland stream system. Another benefit is that the benches form from sediment and associated pollutants (e.g. nutrients, pesticides, etc.) that would otherwise be transported downstream and therefore is acting as both a sediment and pollution sink. This sink occurs at an accelerated rate in the early stages of succession and diminishes to natural rates as the benches develop and establish a two-stage system over time. Locations where the self-forming approach is suitable include low gradient channels that are not prone to incision; channels transporting low quantities of coarse bed material, where vegetation will be vigorous and unlimited; where in-stream habitat and biota already might not be achieving their attainment status; or where early successional habitat is encouraged.

Figure C11: Self-formed stream at the tributary to Muddy Creek near Kansas, OH. Photograph is shortly after construction.

Figure C12: Self-formed stream at the tributary to Muddy Creek near Kansas, OH. Photograph is 1-year after construction.

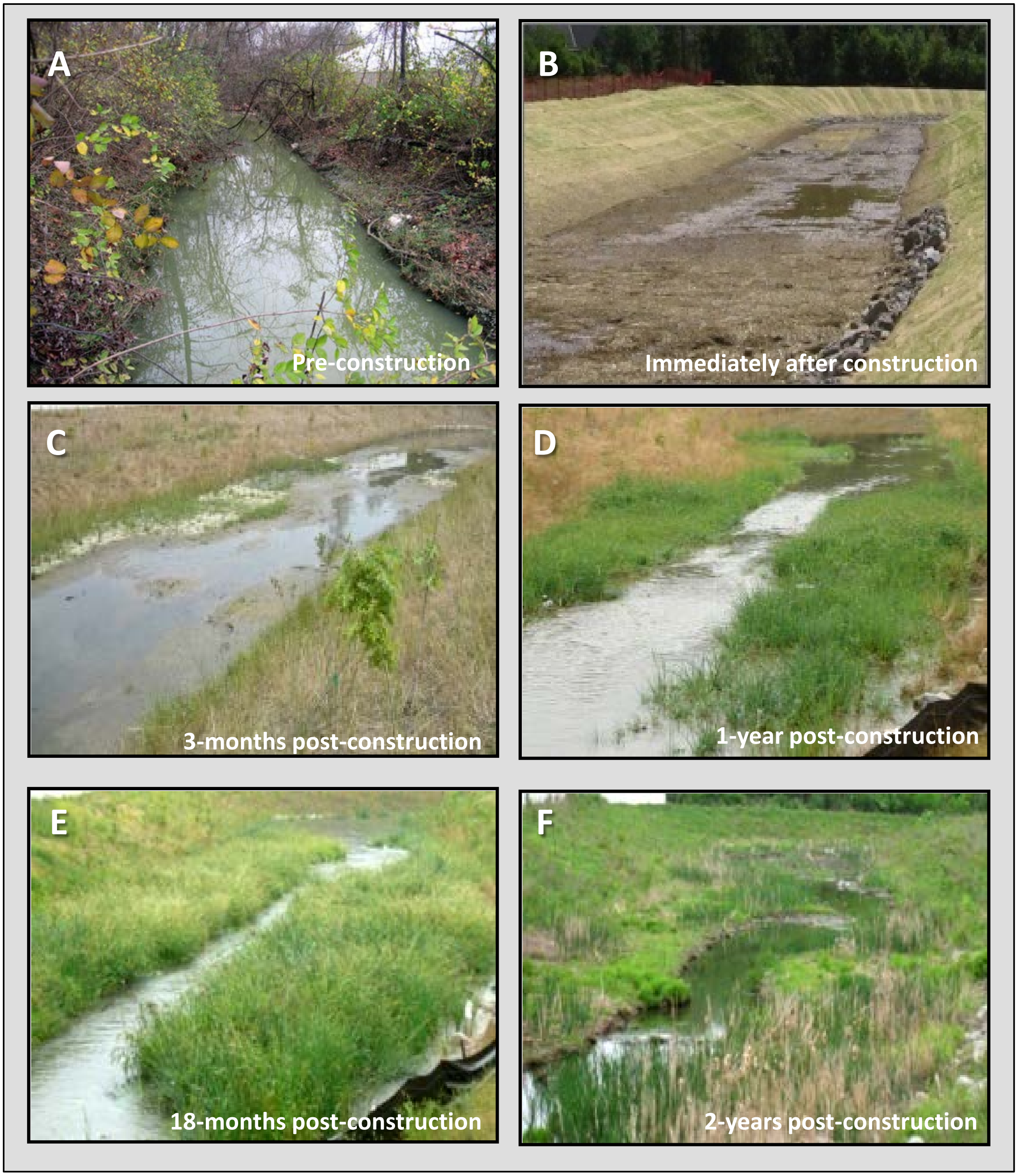

Figure C13: Time series photographs of Beem Ditch in Columbus, Ohio. A) Pre-construction, B) immediately after construction, C) 1-year post-construction, D) 1-year post-construction, E) 18-months post-construction, and F) 2-years post-construction.

Natural Channel Design **-** this approach involves construction of the channel itself and typically the floodplain. Designs may reconnect channel-forming flows to the floodplain either by raising the bed of the channel to the existing floodplain or by excavating the floodplain down to the channel bed (Figure C14). This approach may include channel shaping such as meanders, riffles, and pools. Structures sometimes are used to improve aquatic habitat, as grade control, and to provide bed and bank stability. These structures include a combination of large rocks and the root masses and trunks from trees. There are numerous methods for determining the criteria for constructed stream design that require a sound understanding of theory and careful consideration of the applicability of the chosen approach to a particular project (Skidmore et al., 2007). The natural channel design approach may be better suited to sites that have stabilized from past disturbances, where past and future land use change is well-known, or where adequate knowledge of sediment transport and fluvial processes are well understood (Nagle, 2007; Niezgoda and Johnson, 2005; Montgomery and MacDonald, 2002).

Figure C14: A natural channel design during construction.

THE NRCS CONSERVATION PLANNING PROCESS

USDA-NRCS has a well-established 3-phase, 9-step conservation planning process (CPP) that guides the conservationist through the development and implementation of a RMS. It is not the purpose of this document to present extensive detail on the CPP as that information is provided in Part 600 of the National Planning Procedures Handbook, but the remaining document is structured according to the USDA-NRCS CPP. More specific guidance on the application of the CPP to channel projects is provided in Chapters 2 and 4 of the USDA-NRCS National Engineering Handbook Part 654. The 3 phases of the CPP include: 1) data collection and analysis, 2) decision support, and 3) application and evaluation. These phases essentially allow the conservationist to understand resource problems and opportunities, understand potential solutions, and understand the results. The phases and steps (Table C1) of the CPP and their interrelationships are depicted in a conceptual diagram (Figure C15) that illustrates the dynamic nature of the CPP. Steps early in the process inform latter stages and may need to be revisited as the process progresses and knowledge gaps are identified, new knowledge is developed, and/or project objectives shift. While the CPP is presented sequentially here, linkages to previous and subsequent steps in the process are highlighted and discussed.

Table C1: Phases and steps in the USDA-NRCS Conservation Planning Process (CPP).

Step no.	Step Description
Phase I – Collection and analysis (understanding problems/opportunities)	
1	Identify problems and opportunities
2	Determine objectives
3	Inventory resources
4	Analyze resource data
Phase II – Decision Support (understanding solutions)	
5	Formulate alternatives
6	Evaluate alternatives
7	Make decisions
Phase III – Application and evaluation (understanding the results)	
8	Implement the plan
9	Evaluate the plan

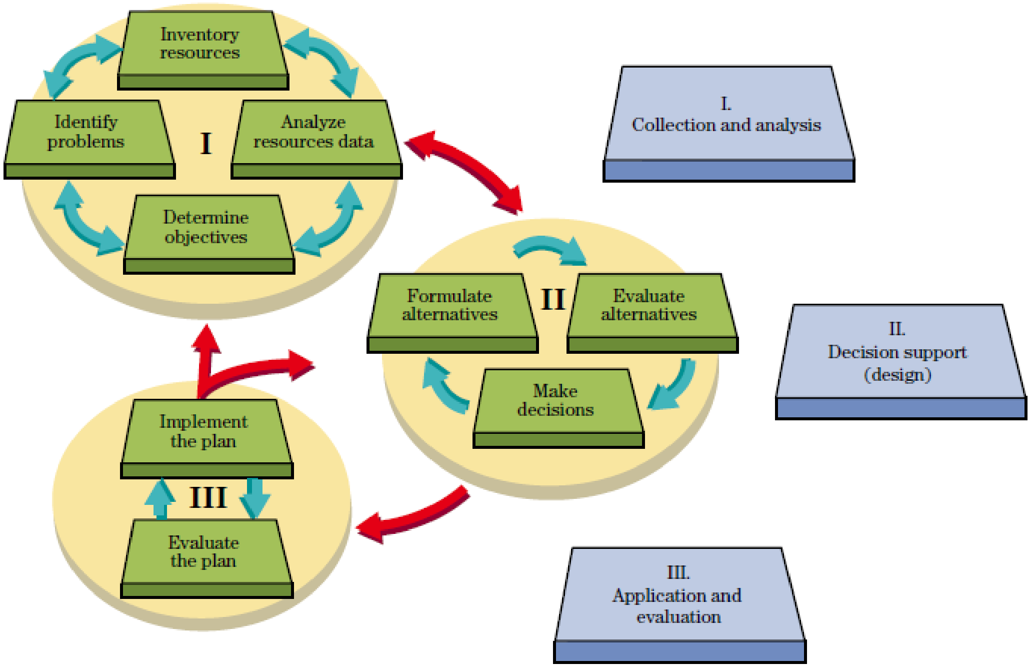

Figure C15: Conceptual diagram of the USDA-NRCS Conservation Planning Process (CPP). (Source: USDA-NRCS National Engineering Handbook Part 654 (Chapter 2; Page 5)).

Step 1: Identify Problems and Opportunities

Problem identification is a crucial step of the planning process, yet it often receives inadequate attention and unsatisfactory project outcomes typically can be attributed to poor understanding of the factors and processes impacting the resource. Good planning normally begins by clearly identifying any real or perceived problems of stakeholders, understanding potential constraints, and recognizing opportunities. Common problems that initiate channel construction or maintenance projects include a need to relocate an existing channel, bank instabilities (Figure C16), excessive sediment deposition reducing channel conveyance capacity and/or restricting subsurface drainage outlets, or inadequate surface drainage capacity (Figure C17). While these projects address drainage needs of landowners for crop production and land development projects, channel projects are more frequently being completed to enhance water resources and protect downstream resources and these goals should also be considered in the planning, decision-making, and management processes.

Figure C16: Bank failure threatening an agricultural field in Indiana.

Figure C17: Inadequate drainage capacity. (Source: NRCS Photo Gallery)

Thorough problem identification will involve: 1) identification of all relevant stakeholders, 2) stakeholder interaction and engagement, and 3) assessment of stakeholder tolerance to risk. Early in the process, meetings with the landowner(s) should be conducted to identify and document any real or perceived issues with drainage function, channel stability, water quality, or other resource concerns. Other stakeholders including local agencies, upstream or downstream communities, watershed groups, and others should be engaged throughout the process as needed and appropriate. These entities can aid in the identification of problems beyond individual sites or channel reaches. At this time, it is also important to gauge landowner willingness to adopt alternatives to the traditional management practices (i.e. trapezoidal channel design and maintenance). Some education may be required as alternative management designs (e.g. two-stage and self-forming channels) are relatively new and many stakeholders are unfamiliar with the concepts, their costs, potential positive and negative impacts, and tradeoffs amongst management strategies. Finally, any potential constraints such as federal, state, and local regulations (e.g. protecting endangered species, flood protection, etc.) that may impact the selection of a RMS should be identified and documented at this time, if possible and practical.

Outcome of Problem Identification

The primary result of this step should be a comprehensive understanding of local and watershed resource concerns of stakeholders and any constraints that may be limiting or opportunities that may be beneficial. Findings should be documented in sufficient detail to be revisited and revised, as needed, throughout the project period.

Step 2: Determine Objectives

During this step, the conservationist should work with stakeholders to clearly define and document resource goals and objectives on, and off-site of, the project reach. Often stakeholders have competing goals and comprises may be needed to balance various stakeholder objectives. As new information becomes available in subsequent steps of the planning process, it may be necessary to revise project objectives iteratively. A preliminary set of project goals and objectives may not be set until the completion of Step 4 (Analyze Resource Data) and may be further revised as alternatives are evaluated (CPP Step 6). Good objective statements will be: 1) specific, 2) realistic, 3) achievable, and 4) measurable. Common objectives of channel projects are to address bank instability and excessive erosion, prevent flooding, protect infrastructure and land, protect water supplies, enhance aquatic and riparian habitat, and improve or protect water quality.

Outcome of Determine Objectives

The outcome of this step is a documented list of stakeholder objectives.

Step 3: Inventory Resources

The primary purpose of this step is to document baseline conditions and develop datasets to assess the existing channel system. The data will also be used as a basis for design (CPP Phase II). The inventory and analysis step that follows may be completed concurrently and the outcomes will allow for a more complete and refined definition of resource problems and identification of opportunities described in previous steps (CPP Steps 1 and 2).

PRELIMINARY DATA COLLECTION AND INVENTORY

An initial site visit and watershed evaluation should be conducted to identify and confirm any resource concerns and to qualitatively evaluate conditions of the channel and surrounding landscape. Site evaluations typically include walking all reaches in an area of concern and documenting problems, making rough measurements of channel dimensions (e.g. widths and depth), identification and measurement of any fluvial features (e.g. existing floodplain benches and a stable bankfull channel (i.e. inset channel) that might be present, identifying and documenting tile outlets and areas in need of erosion control, and overall vegetative condition. Photographic documentation (Figure C18) and mapping of resource problems on maps or aerial images (Figure C19) may also be useful during the inventory process.

Figure C18: Photographic documentation collected during preliminary data collection phase.

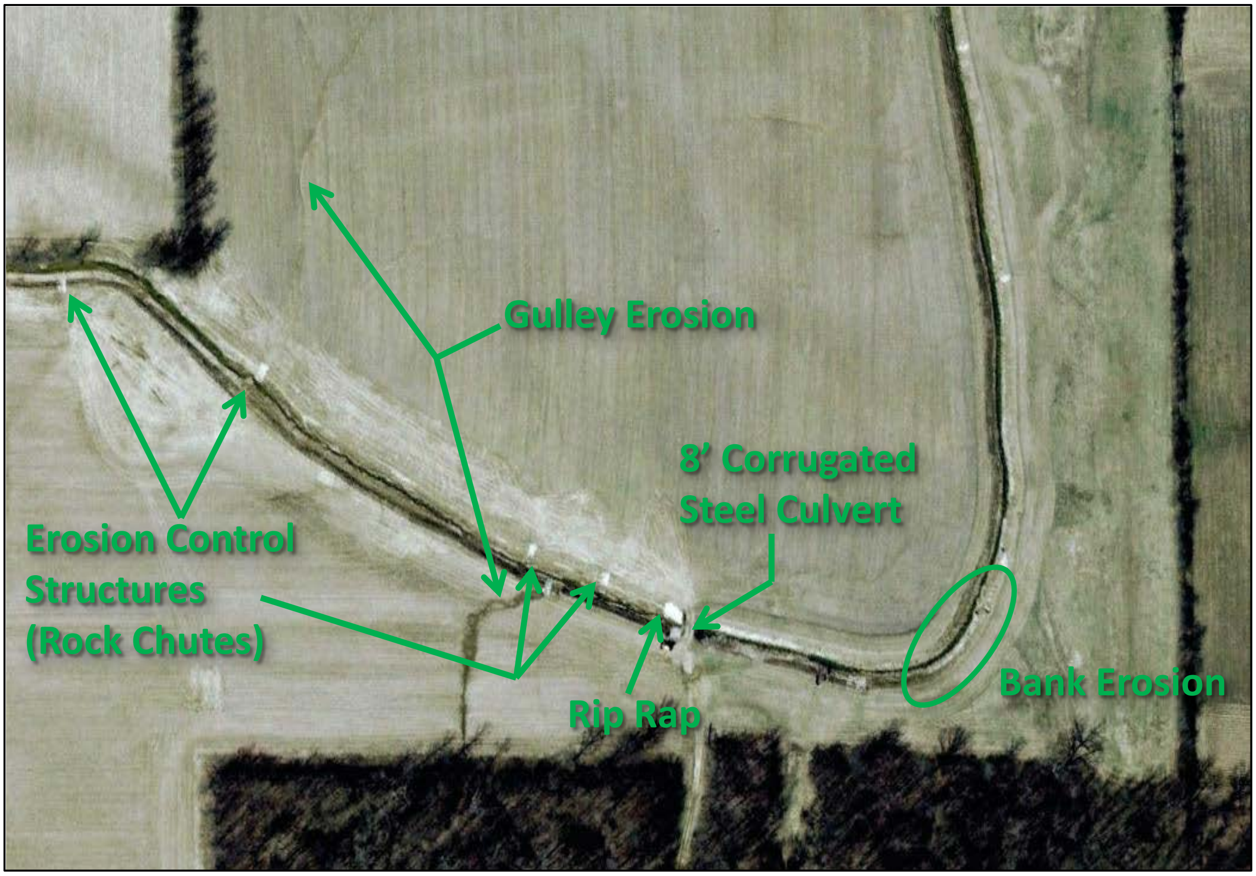

Figure C19: Planform map documenting location of resource concerns and existing structural features.

In addition to reach-level data, preliminary data on the watershed should be obtained. Watershed data should be collected as the channel and its watershed are inextricably linked and management activities and instabilities outside the project reach may impact the site in the future. Reconnaissance or “wind shield” surveys typically involve a driving tour of the contributing watershed area and inspection of channel reaches downstream from the project reach. It is recommended that a GIS map which includes roadways and watershed boundaries draped over recent aerial imagery is developed and used in the field to spatially document any relevant information. Areas of significant land cover or land use change should be noted on the map to identify potential alterations to watershed hydrology (e.g. urbanization, deforestation, etc.) that might impact the project design. Whenever possible, photographic documentation with geospatial location information is recommended to document conditions.

In addition to an inventory of current conditions, the conservationist may want to contact other local agencies that may be able to provide additional insights on watershed history and future development plans for an area which could impact selection and design of a RMS. Preparation for the windshield tour may include review of historical imagery (e.g. Google Earth) to assess land cover and land use changes over time. During the windshield survey it is also recommended to stop at points along roads where channels intersect and qualitatively assess their condition and the presence or absence of any geomorphological features (e.g. inset bankfull channel) that might have formed within the larger channel. This assessment will provide locations of sites that may be used in the development of hydraulic geometry relationships for the watershed which are needed to assess baseline conditions and during the design process. The watershed reconnaissance also provides an opportunity to identify unstable channels upstream from a project site that may supply excessive sediment loading to a channel reach or unstable downstream channels may result in instability (e.g. a headcut) that migrates upstream with potentially destabilizing effects on the project reach.

DETAILED DATA COLLECTION AND INVENTORY

DETAILED REACH GEOMORPHOLOGY SURVEYS

A detailed survey of a project reach under consideration should be conducted to characterize important physical channel features, such as channel cross sectional geometry, bankfull channel dimensions, channel planform, longitudinal profile and slope, channel bed materials, and locations of tile outlets and erosion control structures. Surveys can be conducted with common survey equipment including laser levels, total stations, or GPS. Detailed procedures from the United States Forest Service protocols (Harrelson et al., 1994) are often used to collect channel geomorphology data. However, in drainage ditches which typically exhibit a simplified, uniform geometry it is often sufficient to survey channel cross sections every 100- to 200-ft, making sure to capture any locations with significant changes is physical character (e.g. rapid change in slope or cross sectional area) that do not occur on the set distance interval. It is also important to survey any features associated with the bankfull channel dimensions, if any are present. In surveys that will be used for design and construction, control points should be established on nearby structures which are unlikely to be disturbed, such as bridge abutments or culvert inverts. Survey methods may employ an arbitrary datum or geographic coordinate system. Spreadsheet tools that facilitate design have been developed to utilize data with an arbitrary datum or state plane coordinates (i.e. Northings (y-coordinates), Eastings (x-coordinates), and elevations (z-coordinates)). If appropriate, channel bed materials should be measured using the Wolman Pebble Count method (Wolman, 1954). Educational modules with details on stream geomorphology concepts, surveying techniques, and use of the design tools are available at http://streams.osu.edu. Survey methods are also demonstrated in a PowerPoint presentation that accompanies this design manual.

RAPID REACH GEOMORPHOLOGY SURVEYS

Detailed channel geomorphology surveys may be time and resource intensive to collect and may not be practical or necessary beyond the project reach. However, it is often appropriate to collect channel geomorphology data at other stable sites with similar site and watershed characteristics to the project reach in the region. These data are used to develop hydraulic geometry relationships called regional curves that are used in the design process to predict the dimensions of a bankfull channel that is likely to be stable and sustainable at a site. Development of a regional curve involves the measurement of bankfull channel dimensions at multiple locations across a range of drainage areas. Bankfull dimensions are then plotted as a function of drainage area on a log-log scale and fit with a power function regression line (e.g. Figure C20). A rapid method to collect data for the development of regional curves would typically involve the selection of representative cross sections at many stable sites and either surveying the cross sections or simply measuring the bankfull channel width and estimating the mean depth from multiple measurements of depth across the inset channel (Figure C21). Bankfull dimensions are then plotted against the drainage area of the site. In many cases a few measurements might be made and compared to an existing regional curve to determine consistency. Additional in depth information on regional curves is provided in Section 654.0905 of Chapter 9 in the National Engineering Handbook Part 654.

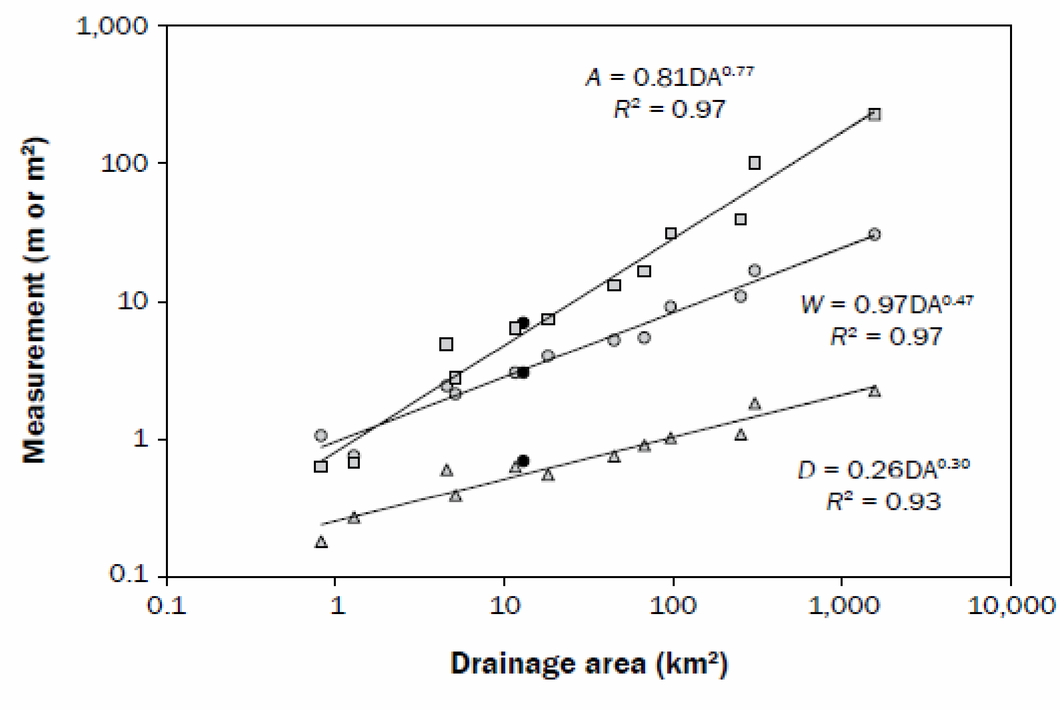

Figure C20: Regional curves for the Portage River watershed.

Figure C21: Rapid measurement of bankfull channel width.

BED, BENCH AND BANK GEOTECHNICAL PROPERTIES

In some cases, additional measurements may be needed to assess the stability of the existing channel. These measurements are made to determine the resistance of the bed and bank soils to hydraulic erosion and geotechnical failures, to estimate sediment transport, and to approximate water movement through banks. Assessment techniques that could be used include: 1) inspection of exposed soils along channel banks and bottom, 2) digging soil pits, 3) extraction of soil cores (Figure C22) to test (e.g. unconfined compression tests) in the laboratory, 4) in situ shear tests (e.g. Iowa Borehole Shear Method; Figure C23), and 5) bed, bench and bank erodibility tests (e.g. non-vertical submerged jet tests). Other methods of investigation are acceptable, but all methods should be conducted by qualified personnel.

Inspection of exposed soils should be undertaken by a soil scientist and soils borings should be analyzed by qualified laboratories. Soils properties that may be useful for judging stability include textural class, particle size distribution, soil consistency (e.g. liquid and plastic limits), void ratio, unit weight, and shear strength (e.g. unconfined compression tests). Details on the methods and sampling designs to assess channel stability are provided in Chapter 3 of USDA-SCS Technical Release 25 (1977) and Chapter 8 of the National Engineering Handbook Part 654.

Figure C22: Soil core extracted for inspection and lab analysis to determine unconfined compression strength.

Figure C23: Iowa borehole shear test to make in situ measurements of bank geotechnical properties.

Existing benches provide useful information on fluvial processes and/or bank stability; however, they require careful evaluation. Of particular importance is to determine if the benches are due to deposition of sediment transported by discharge in the system or due to slumping/sluffing of the banks. If they are due to bank failures there is sometime a separation between the benches and the sides of the banks. Also benches associate with bank failures often have a very uneven surface that might be located higher in the ditch than the bottom third of the ditch depth. If the benches are associated with mass failure of the banks it is particularly important to identify the causes of the failures. In some cases benches formed by fluvial processes are unstable and scour or wash out during large events. Instability in these benches might be associated with high tractive forces, or high base flows, and an inability to naturally build to a stable geometry.

HYDROLOGY DATA COLLECTION

Measurements or estimates of discharge rates and frequency, typically for flows that occur many times annually up to extreme events such as the 100 year discharge, are needed to assess channel geomorphology, hydraulics, sediment transport, and risk. Predictions of discharge are typically made with empirical equations or computer models, but for some projects it may be desirable to collect field data or utilize USGS gage data to evaluate and calibrate discharge estimates at ungaged sites. Field measurements of discharge typically involve measurement of channel form to describe cross sectional flow area and flow velocity measurements which can be used in conjunction with survey data to calculate discharge. Measurements at multiple stages can be used to construct stage-discharge-velocity relationships to check or calibrate open channel hydraulics estimates used in evaluation and design. These methods are described in detail in Chapter 14 of the USDA-NRCS National Engineering Handbook Part 630.

OUTCOME OF INVENTORY RESOURCES

The primary outcome of the Inventory Resources step is to document benchmark conditions including information on human considerations, ecological concerns, cultural resources, physical infrastructure, types of management activities and their timing, and detailed site data describing the conservation management unit (CMU).

Step 4: Analyze Resource Data

Analysis of resource data should focus on determining the current status of the channel and riparian zone and clearly defining resource conditions, including limitations to their use and potential uses. This step also serves as the basis needed to formulate and evaluate RMS alternatives (CPP Steps 5 and 6).

ASSESSMENT OF EXISTING CHANNEL CONDITION

Channel condition is influenced by geology, topography, hydrology, land use, soils, climate, management activities, and other abiotic and biotic factors. The interactions amongst these factors generate runoff and channel flow which exerts forces (i.e. the driving forces) on channel boundaries which have some ability to resist those forces. Channel form develops and adjusts to changes in these driving and resisting forces seeking a balance between sediment supply and transport. Channels that balance supply and transport are said to be in a state of *dynamic or quasi-equilibrium* and are stable or exhibit normative or acceptable rates of change. Channels that transport more sediment than supplied are *failing* through the process of erosion either vertically (i.e. channel incision) or laterally (i.e. bank failures and mass wasting) and the primary mode of failure depends on the resistance of the bed and bank materials to erosion. Channels can also fail through excessive deposition that negatively impacts a resource and does not result in a more sustainable and stable form in a reasonable timeframe; however, aggrading streams are typically viewed as being in a state of *recovery* characterized by the development of point bars and floodplain benches. In many systems recovery may take a few years, many decades, or even centuries depending on site and watershed characteristics, climatic conditions, and human management practices.

A useful starting point in the development of a RMS for a drainage channel is to understand its current condition. Knowledge of the current state will aid in the determination of potential management options that are likely to succeed and meet project goals. For example, a channel that is actively failing is likely to further incise or widen before recovery takes place. If this does not impact adjacent and upstream land uses and the downstream effects of sediment and associated nutrients are acceptable then a passive enhancement approach may be an acceptable management choice. If these impacts are unacceptable, a more active management approach which mitigates or eliminates stressors (e.g. reduces runoff rates and volumes from the landscape), stabilizes the channel, and/or promotes recovery should be implemented.

In natural systems subject to a great deal of variability, such as channels, there is often considerable uncertainty in making predictions of channel conditions and process rates difficult. Therefore, several researchers (Powell et al., 2007a,b; Montgomery and MacDonald, 2002) have recommended the use of multi-factor “weight-of-evidence” approaches to assess channel condition. Any suitable method can be used to make an appropriate assessment methods will vary be region. The following factors have been shown to be useful for assessment in low-gradient channels of the Midwestern US (Powell et al., 2007a,b): 1) a comparison of bankfull channel dimensions to expected values from regional curve relationships, 2) a comparison of channel bed materials to the estimated particle size at incipient motion using tractive force theory (Ward and Trimble, 2004), 3) the recurrence interval of the bankfull discharge, 4) an estimate of bank stability, and 5) a comparison of the existing bankfull channel depth to the theoretical bankfull elevation based on effective discharge theory. Additional details on the weight-of-evidence assessment procedure are provided in Powell et al., 2007a,b).

OUTCOME OF ANALYZE RESOURCE DATA

The primary outcomes of the Analyze Resource Data step will be: 1) an analysis of all inventoried resources, 2) determination of channel equilibrium state, 3) environmental and cultural evaluation data, 4) identification of causes of resource concerns, and 5) a complete statement of project objectives (i.e. step 2 is essentially finalized).

Step 5: Formulate Alternatives

This step focuses on the development of alternatives that will meet client/stakeholder objectives, solve relevant problems, take advantage of any opportunities, and avoid negative consequences from occurring. At this point, a broad spectrum of practical alternatives should be developed with input from the client/stakeholders. Engaging the end user in the process typically leads to better solutions and greater acceptance.

When developing a RMS for a channel and riparian corridor the conservationist has a suite of best management practices to address resource concerns. USDA-NRCS (2007) has developed a conceptual framework (Figure C24) which defines a continuum of zones from channel to uplands. Chapter 4 (specifically Tables 4-4, 4-5, and 4-6) of the National Engineering Handbook Part 654 contains extensive guidance on the selection of best management practices, with references to NRCS Conservation Practice Standards, for a range of resource concerns in each of the zones. It is not the purpose of this document to supplant that guidance, but to incorporate additional practices into existing guidance where appropriate. The following proposed modifications focus solely on the addition of two-stage and self-forming channel designs. The proposed modifications are highlighted in Table C2. However, additional modifications to this guidance and the Open Channel Conservation Practice Standard (582) could include other practices, such as natural channel design. Attachment of an active floodplain to a bankfull channel is a common component of the natural channel design approach and forms two-stage systems. Allowing the construction of an appropriate meandering bankfull channel would be a simple and appropriate addition to the Open Channel Conservation Practice Standard (582). However, the inclusion of woody vegetation on the floodplain, adding hydraulic control structures, and bioengineering of the banks (beyond using grass) did not fall within the scope of the current project. This guidance is desirable and might best be developed by scientists, engineers, and practitioners with experience with natural channel design applications in agricultural ditches.

OUTCOME OF FORMULATE ALTERNATIVES

The primary outcome of this stage is a description of the RMS alternatives available to the client/stakeholders.

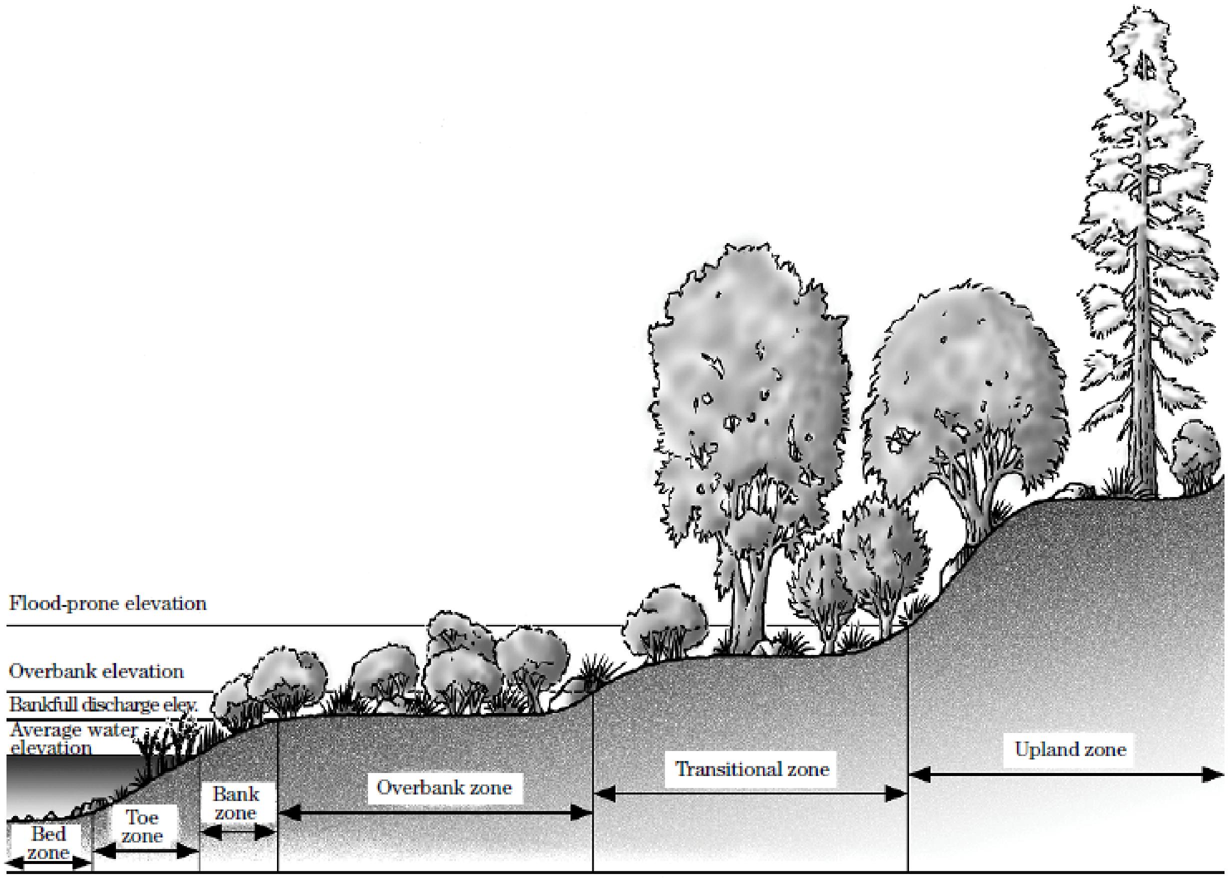

Figure C24: Conceptual cross section of management zones. The zones are described in detail in Chapter 4 of the USDA-NRCS National Engineering Handbook Part 654. (Source of Figure: USDA-NRCS National Engineering Handbook Part 654; Figure 4-6)

Table C2: Modifications to Tables 4-4, 4-5, and 4-6 from the National Engineering Handbook Part 654. Revisions highlighted in bold and italics.

Page (Ch. 4 NEH 654)	Impairment	Zones	Primary NRCS Practice Standards	Considerations and effects
4-10	Unbalanced channel sediment transport and deposition; unstable channel bed and/or gradient	Bed, toe	Open Channel (582)	Various techniques including ***two-stage channels, self-forming channels, and/or*** channel meander reconstruction at a site will reconfigure the ~~bed and bank topography~~ ***channel and/or floodplain form*** and influence the extent of overbank and transitional zones and related soil moisture and the selection of vegetation species
4-10	Accelerated bank erosion and instability	Bank, toe	***Open Channel (582)***	***Modify channel and/or floodplain form using various techniques including two-stage, self-forming, and natural channel design to reduce shear stress at the bank toe interface. May be combined with Channel Bank Vegetation (322), Streambank and Shoreline Protection (580), Clearing and Snagging (326), Critical Area Planting (342), or Mulching (484).***
4-14	Obstructions or channel configurations affecting flow capacity or fish passage	Bed, toe, and bank	Open Channel (582)	Various techniques including ***two-stage channels, self-forming channels, and/or*** channel meander reconstruction at a site will reconfigure ~~the bed and bank topography~~ ***channel and/or floodplain form*** and influence the overbank extent, soil moisture and vegetation species. **Modifying an existing channel to a** ***self-forming geometry addresses flow capacity, but might negatively impact aquatic biology during early stages of development.***
4-15	Lack of early successional habitat for target wildlife	***Bed***, bank, toe, overbank, and transitional	***Open Channel (582)***	***Implementation of the self-forming channel design initiates the development of early successional habitat***

Step 6: Evaluate Alternatives

To provide stakeholders with sufficient information to select a channel management practice as part of a RMS, each of the potential solutions must be evaluated thoroughly to assess channel stability, costs, and potential benefits and impacts. All projects are unique to some degree and it is up to the conservationist to select and/or modify an appropriate approach when evaluating alternatives. The approach selected should be based on knowledge of the existing system, underlying processes, and sound engineering principles. A general recommended starting point for designing two-stage and self-forming channels is as follows:

Step 6.1: Develop an initial design.
Step 6.2: Assess stability of proposed channel.
Step 6.3: If design meets stability checks go to step 5. Otherwise, redesign channel dimensions.
Step 6.4: If redesign does not satisfy stability checks or meet project requirements/constraints integrate temporary and/or permanent erosion control and reassess stability.
Step 6.5: Estimate costs, benefits, impacts, and long-term maintenance needs.

Each of the steps is described in greater detail in the sections that follow and the **Channel Design** spreadsheet tool can be used as an aid in the evaluation process.

Step 1 – Initial Design

For a self-formed channel the primary design variables are slope and width. Most channel projects in agricultural drainage ditches will maintain the current bed slope leaving width as the only design variable. The width of the inset channel that is expected to develop as the self-forming channel evolves over time will be estimated using a hydraulic geometry relationship. The hydraulic geometry relationship that is selected for design should be representative of the site and watershed conditions. Sites used in its development should not differ significantly from the project site in terms of hydrology, hydraulics, and sediment transport. Once an appropriate relationship is developed and an expected bankfull channel width is estimated and the minimum width of the self-forming channel bottom should be at least 3 times that value. A minimum of 3 times the bankfull width is recommended as floodplain benches are less likely to establish and remain stable below this threshold.

In a two-stage channel the primary design variables are slope, width, and bankfull channel depth. Once again slope will most likely be maintained to the existing channel bed. The depth of the inset channel will be determined from field measurements of the bankfull channel depth and estimates from the regional hydraulic geometry relationships. It is also unlikely the overall ditch depth (from channel bottom to the field elevation) will change and thus overall ditch depth typically will not be a design variable that is manipulated significantly. Therefore the width of the channel at the bankfull elevation is the primary design variable. Similar to the self-forming channel the minimum width of the floodplain benches should be a minimum of 3 times the bankfull channel width. The width of the benches on each side of the inset channel does not need to be identical but one-sided construction is not recommended. The second stage channel can also be sized to convey a specific design event that conveys discharge without flooding into adjacent fields

Step 2 – Assess Stability

There are multiple methods to assess channel stability, but the predominant method used in channels that have been determined to be stable (see step 4) is to estimate whether the proposed design will result in flow velocities and shear stresses that are lower than the current configuration. The basic assumption is that if the existing channel is stable then reducing velocity and shear stresses should only enhance stability.

Additional methods of stability analysis are provided by USDA (2007; Chapter 8). The selection of a method to assess stability depends upon the composition of the boundary materials within the threshold channel. Standard methods for threshold channels include the permissible velocity, allowable shear stress, and allowable tractive power approaches. The allowable velocity approach is appropriate for use in systems with boundary material smaller than sand and the allowable shear stress is appropriate for systems with boundary material larger than sand. If boundary materials do not act as discrete particles the allowable tractive power method is recommended. When the system is alluvial with a mobile boundary under normal flow conditions the conservationist is directed to Chapter 9 of the National Engineering Handbook Part 654 (USDA-NRCS, 2007).

Channel stability will typically be evaluated for a range of conditions. Immediately after construction a bare earth or “unaged” channel will likely be more vulnerable to failure than a vegetated or “aged” channel that develops in the months and years following construction or a channel protected by erosion control. Often the unaged condition will be evaluated for a more frequent design discharge, such as the 10-yr recurrence interval event. The aged channel condition would often be evaluated for the 100-yr or ditchfull design discharge. Design specifications should be outlined in the Open Channel (582) Conservation Practice Standard for the project state or region.

If warranted, the conservationist may determine the need to perform additional stability checks using a range of methods and tools (Table C4). Numerous spreadsheet tools (e.g. Bank Stability and Toe Erosion Model) and numerical models (e.g. HEC-RAS, SAM) are reasonable design aids, well documented, and freely available. Often experience and judgment may be used to estimate some elements of design, such as stable channel sideslopes, when risk of failure is low or the result of a failure is unlikely to cause harm.

Table C4: Links to tools that can be used to aid in the design process.

Issue	Tool	Link
Bank Stability	Bank Stability and Toe Erosion Model	http://www.ars.usda.gov/Research/docs.htm?docid=5044
Sediment Transport	Sediment Analysis Methods (SAM)	http://chl.erdc.usace.army.mil/chl.aspx?p=s&a=ARTICLES;67
	Sediment Impact Analysis Methods (SIAM)	Integrated into HEC-RAS (see link below)
Flood Routing	HEC-RAS	http://www.hec.usace.army.mil/software/hec-ras/

Step 3 – Redesign (as needed)

Depending on the outcome of the initial stability analysis it may be necessary to redesign the proposed channel. In both self-forming and two-stage channels the width may be manipulated to meet stability requirements. Widening of the proposed channel will reduce the hydraulic radius, flow velocity, and shear stress at a particular design discharge. However, it will be necessary to develop a design which fits within project constraints. For example, a wider channel may not be acceptable to a landowner trying to minimize land loss to achieve channel stability. In some cases, integration of temporary or permanent erosion control may provide a useful alternative (see Step 4 below).

Step 4 – Erosion control (as needed)

In channels that do not meet stability requirements during the unaged condition, temporary erosion control (e.g. straw mats, geotextiles, etc.) may be installed during construction. For channels that do not meet stability requirements after the channel has aged, grade control structures and bank rip-rap provide a more permanent solution. In some cases, permanent erosion control may be needed intermittently throughout a reach, such as around curves where flow velocities on the outer bends are higher. Both designs will also necessitate the reconstruction of tile outlets and any existing erosion control structures that deliver surface runoff to the channel.

Step 5 – Estimate costs/benefits

After one or more stable design solutions are developed, each should be evaluated to determine costs and estimate potential benefits. In addition to identifying an optimal RMS which best addresses resources concerns, the planner must also consider a broad range of factors which affect the practicality of the design solution. Several factors which must be considered include: 1) construction access and scheduling, 2) safety concerns, 3) availability of construction equipment and materials, 4) pollution control requirements, and 5) legal regulations.

OUTCOME OF EVALUATE ALTERNATIVES

The end outcome of this step is a set of practical and implementable RMS alternatives that are compatible with client/stakeholder objectives. A thorough evaluation of each RMS and the effects and impacts is the basis for decision-making (step 7).

Step 7: Make Decisions

In this step the conservationist presents the design alternatives and assists the client/stakeholders in the selection of a RMS. In the case of an area-wide conservation plan, a public review and comment period may be needed before a final decision is reached.

OUTCOME OF DECISION-MAKING

The outcome of decision-making is the final selection of a RMS.

Step 8: Implement Plan

Plan implementation involves providing technical assistance to landowners and contractors. Some relevant issues for channel work may include obtaining permits, funding, assessing land rights, and inspections of as-built practices. Permitting issues for channel work vary by county and state and it is up to the conservationist to determine which requirements need to be satisfied. Often agricultural drainage channels with small drainage areas are exempt from state and federal regulations; however, this should be investigated closely to avoid project delays and potential fines or penalties.

Most drainage contractors will not be familiar with the two-stage and self-forming channel designs and may need some technical assistance and oversight during initial stages of construction; however, the concepts are simple to construct and can be undertaken by drainage contractors experienced in traditional channel construction and maintenance. Key issues involve: 1) excavation of the channel features at the design elevations, 2) proper reconstruction of the tile outlets and placement of any structural erosion control practices, 3) proper removal, placement, seeding, and/or disposal of excavated materials, 4) proper implementation of seeding/planting plans, if specified, and 5) proper operation and maintenance over time to sustain function. Construction of channel features is most important in the two-stage design where it is important to excavate the floodplain bench at or slightly below the design elevation. Floodplains that are too high are more prone to incision and failure than floodplains that flood frequently dissipating the energy of higher flows out onto the floodplain benches. In two-stage ditch construction it is also recommended that vegetation on floodplains along the channel margin (Figure C8) are not disturbed as they provide stability to the benches left in place. In some cases, it may be desirable to construct the floodplain width so it is at least wide enough to allow vehicle access. For example, the two-stage channel constructed at Crommer Ditch in Hillsdale County, Michigan, provided a floodplain width slightly larger than originally planned to allow a bulldozer sufficient room to conduct earth work and to provide future access for maintenance, if needed (Figure C25).

Figure C25: Construction of a bench wide enough to accommodate a bulldozer for any maintenance needs, if necessary.

As the floodplain is widened it will be necessary to reconstruct tile outlets which likely will discharge directly onto the floodplain benches. To minimize erosion on the bench it may be necessary to construct an apron to dissipate the energy of tile water discharge and eliminate gullying across the bench surface. Erosion control practices (e.g. rock chutes, berming, drop structures, etc.) should be constructed to safely convey water from the field surface to the channel and protect against hydraulic erosion (e.g. mulching, etc.), if prescribed in the design. Where a purpose in constructing a two-stage system is to improve water quality the orientation of the tile outlets might be modified to allow tile discharges to flow along the benches to increase interaction between bench soils and vegetation.

As in any practice requiring seeding or planting plans, it is necessary to prepare a proper seedbed and provide growing conditions to promote vegetation establishment in a reasonable timeframe. Construction scheduling should be planned in conjunction with field operations of the landowner, but should consider the need to establish vegetation in the channel during appropriate time periods. In the north-central region of the United States, late spring to early fall provides a window of opportunity when flood flows are less likely and conditions support establishment of vegetation before winter conditions set in. For construction that is completed late in the season the conservationist may elect to plant a cover crop such as annual rye or oats that established quickly to protect against high flows in winter or spring. Replanting of the benches and sideslopes may occur the following year or simply allowed to vegetate by volunteering species of plants.

OUTCOME OF IMPLEMENT PLAN

The outcome of plan implementation will be a properly installed conservation practice. Proper operation and maintenance plans, if necessary, should be clearly communicated to the landowner or stakeholder group(s).

Step 9: Evaluate Plan

Plan evaluation lets the conservationist determine whether the RMS is functioning as planned and achieving project objectives. Furthermore, it allows the conservationist and opportunity to identify short and long-term operation and maintenance needs to ensure proper function. When results deviate from those anticipated, it allows the conservationist to learn from success and failures and apply adaptive management techniques. This may lead to revisions of future project goals and target values, conservation plans, and conservation practice standards.

OUTCOME OF EVALUATE PLAN

The outcome of plan evaluation is to ensure that the RMS is functioning properly and being maintained. It also provides an opportunity to learn from implementation and guide future conservation planning and implementation activities.

Technology Review Criteria

Alternative channel design options have been incorporated into Ohio Natural Conservation Service – Engineering Standard for Open Channels (Code 582). The standard has been drafted by Mike Monnin, State Conservation Engineer for Ohio NRCS with input and suggested revisions from multiple members of the CIG project team.