This article was listed in Forest Nursery Notes, Winter 2008

180. Improved management of agricultural drainage ditches for water quality protection: an overview. Needelman, B. A., Kleinman, P. J. A., Strock, J. S., and Allen, A. L. Journal of Soil and Water Conservation 62(4):171-178. 2007.

Improved management of agricultural drainage ditches for water quality protection: An overview

B.A. Needelman, P.J.A. Kleinman, J.S. Strock, and A.L. Allen

Abstract: Agricultural drainage ditches are essential for the removal of surface and ground water to allow for crop production in poorly drained agricultural landscapes. Ditches also mediate the flow of pollutants from agroecosystems to downstream water bodies. This paper provides an overview of the science, management, and policy of ditches. Ditches provide a unique opportunity to address nonpoint source pollution problems from agriculture due to the concentration of the contaminants and the engineered nature of ditch systems. A better understanding of the nature of these complex system and the technologies available and under development to improve their management will assist in the design and implementation of water quality protection programs.

Key words: canals—channelized streams--drainage ditches—water quality

Artificial drainage and ditching are essential for crop production in many areas of the 'United States, either for direct land drainage or as conduits for tile drain and irrigation effluent. Ditches are unique ecosystems in that they integrate characteristics of streams and wetlands. Some ditches are straightened streams with stream-bottom sediments while others are intermittent wetlands with perennial vegetation throughout the ditch bottom (figure 1) and thick accumulations of soil organic matter. Ditches range in size from small depressed channels designed primarily to carry surface runoff to major channelized streams draining large watersheds and regional groundwater. Because of their engineered nature, ditches do not follow natural fluvial networks, though mechanisms of fluvial geomorphology do function to shape ditches.

Ditches serve as primary conduits for drainage and therefore carry pollutants from agroecosystems to downstream water bodies. Ditches also function to control water tables in the landscape, influencing landscape hydrologic, chemical, and biological processes, and serve as active zones of chemical and biological activity to transform, emit, and retain various pollutants. The management of agricultural ditches has historically focused on water conveyance and management; there is increased interest to improve management for environmental quality benefits related to water quality, habitat, diversity, and emissions.

Humans have long used open-air ditches for land drainage, including ditching in Mesopotamia around 9000 BP (van Schilfgaarde 1971) and the Egyptians and Greeks around 2400 BP (Shirmohammadi et al. 1995).The Long Marsh ditch in 1789 was the first recorded ditch project in Maryland. By the early 20th century, land drainage was a large-scale endeavor involving state and federal partnerships focused primarily on the removal of surface water and groundwater. Ditches are extensive in the Midwest, irrigated lands in California, and the Atlantic Coastal Plain. Over two million acres in North Carolina are affected by canal and ditch drainage. In Indiana, there are over 36,000 miles of public ditches (McCall and Knox 1979). In Maryland, there are over 821 miles of publicly administered drainage ditches and hundreds of miles more of privately managed ditches (Mister 2006).

In this paper, we provide an overview of the science, management, and policy of agricultural drainage ditches as related to water quality protection and introduce the papers in this special section of the *Journal of* Soil and Water Conservation. Papers include reviews on phosphorus (P), nitrogen (N), soil formation, and biogeochemistry in ditches; original research on fundamental processes operating in ditches; and methodologies and case studies of innovative ditch management practices. It is our hope that this special section will provide a fundamental resource to scientists, practitioners, and policy makers working to improve ditch management for increased agricultural efficiency and environmental quality.

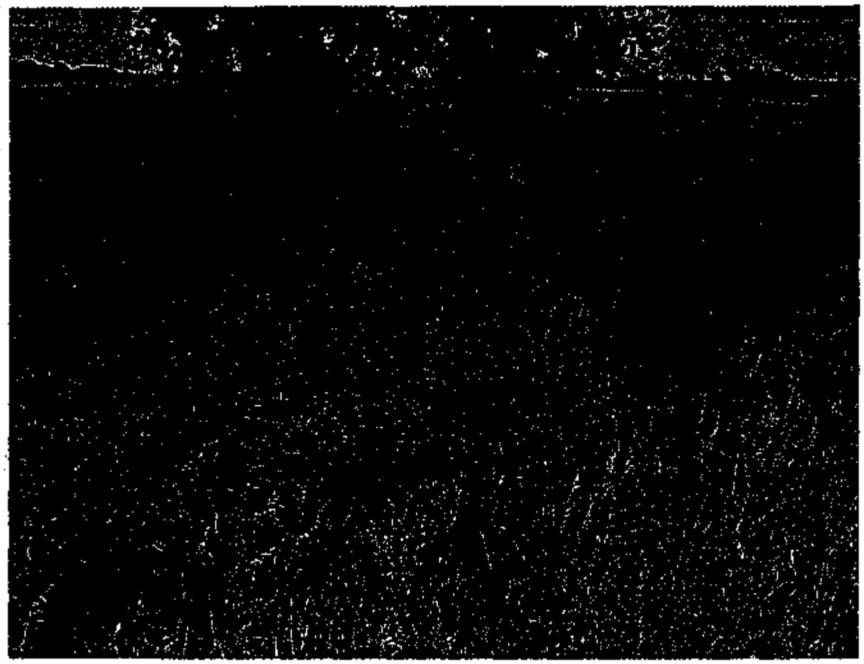
The Science of Drainage Ditches

Hydrology. *The* essential function of ditches is to prevent flooding through the rapid removal of surface water during storm and snowmelt events and to lower the water table during and between events to prevent crop stress and to allow field soils to dry such that they may be driven upon and worked with agronomic equipment. Drainage ditches function within general systems of land drainage that have been reviewed extensively elsewhere (see Skaggs and Schilfgaarde 1999; Skaggs et al. 2005a). In this issue,Vadas et al. (2007) discuss the importance of lateral subsurface flow in supplying stormflow to shallow ditches. In the general drainage community, researchers and practitioners are working to develop and implement systems of drainage water management to improve water quality protection with methods such as water-control structures within tile drains to promote denitrification within field soils (Skaggs et al. 1994, 2005b) and in-ground bioreactors for N reduction.

Chemistry. The chemistry of ditch systems is complex with dissolved, colloidal, and particulate materials interacting within soils, sediments, and organisms through chemical and biogeochemical pathways. In this issue,

Brian A. Needelman is an assistant professor at the University of Maryland, College Park, Maryland. **Peter J.A. Kleinman** is a soil scientist at the Pasture Systems and Watershed Management Research Unit, USDA Agricultural Research Service, University Park, Pennsylvania. **Jeffrey S. Strock** is an associate professor at the Southwest Research and Outreach Center, University of Minnesota, Lamberton, Minnesota. **Arthur L. Allen** is an associate professor at the University of Maryland Eastern Shore, Princess Anne, Maryland.

Figure 1
Vegetated ditch in Minnesota.

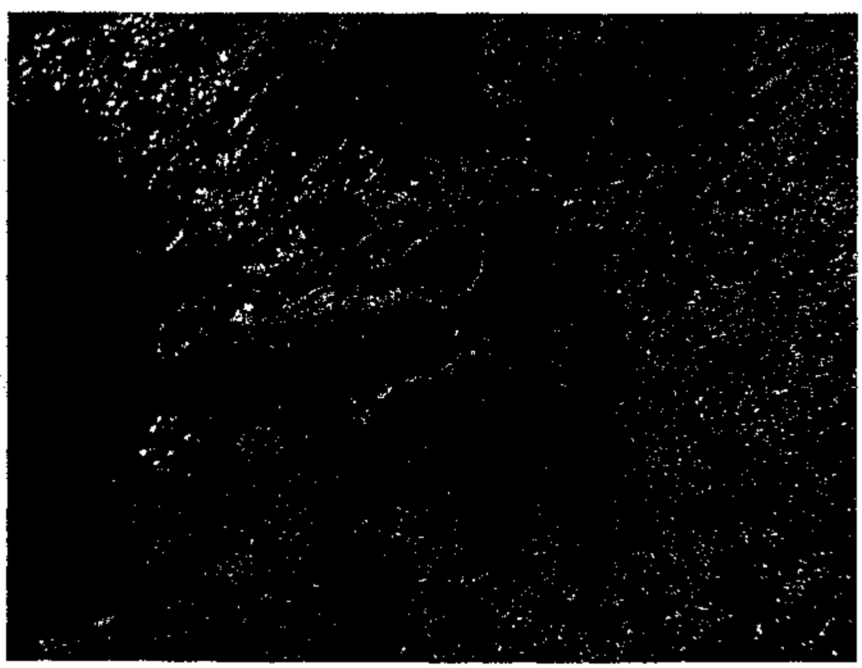


a variety of reviews on the cycling of particular elements are provided, including N (Strock et al 2007), P (Sharpley et al 2007), and iron and sulfur (Needelman et al. 2007). These reviews underscore opportunities for improved management of ditches to protect water quality.

Biology and Ecology. Ditches provide aquatic and wetland habitat across landscapes, including many that wouldn't otherwise have these habitats. Ditch vegetation species composition within ditch bottoms and along banks is affected by soil and water table characteristics (van Strien et al. 1989; Pierce et al. 2007), ditch structure (Bouldin et al. 2004), grazing (van Strien et al.1989), nutrient inputs (van Strien et al. 1989; Portielje and Roijackers 1995), ditch management (van Strien et al. 1991) and eutrophication status (Janse 1998; Janse and Van Puijenbroek 1998). Pierce et al. (2007) present results from a greenhouse study on the response to flooding of *Leersia oryzoides* (rice cutgrass), a common plant in agricultural ditches. They found that flooding did not negatively affect plant productivity unless it led to extended soil oxygen depletion.

Macroinvertebrates are diverse and active in many ditch systems and may be useful as indicators of ditch environmental quality (Karr and Chu 1999; Davis et al. 2003; Langheinrich et al. 2004). Macroinvertebrates function to mediate carbon and nutrient cycles through organic matter decomposition and shredding. Bioturbation by macroinvertebrates such as crayfish may serve to cycle nutrients between surficial and subsurface layers and provide rapid flow pathways within ditch sediments and soils (figure 2) (Needelman et al. 2007).

Figure 2
Crayfish exposed by a ditch-dredging operation on the Coastal Plain of Maryland.



Algae are abundant in many drainage ditches, particularly those rich in nutrients (figure 3). Algae may be important for ditch nutrient cycles, removing nutrients from ditch waters and returning carbon and nutrients to ditch sediments and soils upon loss of inundation in a ditch. Kleinman et al. (2007) provide evidence that algae in ditches may contribute to the loss of particulate P from ditches during storm events.

Geomorphology and Pedology. Ditches are present within a specific geomorphological setting that will affect their physical, chemical, and biological functions. The composition of the ditch bottom and bank materials following excavation is dependent on the nature of these materials; they will be altered with time under the contrasting hydrologic and biogeochemical processes operating in the. ditch system. The fluvial geomorphology of ditches differs from that of natural flow channels because ditches are dredged and straightened, thereby increasing channel capacity and gradient (Simon 2006). This may result in increases in bed mate-

Figure 3
Abundant algal growth in standing water of a ditch.

rial discharge, causing upstream degradation, downstream aggradation, and bank instabilities along ditches and connected tributaries. Degradation will occur under increased peak discharge or channel gradient. Channel incision *and* widening are dominant forms of ditch degradation that may result in substantial sediment yield increases compared to stable systems. Some ditches, particularly in low-relief landscapes, undergo an aggradational response, eventually reaching stability due to insufficient transport capacity relative to loadings.

Needelman et al. (2007) discuss the role that processes of soil formation have in water quality in some ditches. When the sediments and underlying soil materials in ditches are stable, they may become young soils and thereby are able to support vegetation and may form soil horizons through processes such as organic matter accumulation, structure formation, faunal activity, and biogeochemical transformations of iron and sulfur.

Drainage Ditches and Water Quality

Nitrogen. Considerable research exists on the fate of agricultural N in relationship to artificial drainage (e.g., Skaggs et al. 2005b). Ditches often have high concentrations of N and, compared with other water courses, tend to be N-saturated. Numerous processes and mechanisms are involved in N cycling dynamics and transport pathways in ditches including N mineralization, nitrification, and denitrification (Struck et al. 2007). Not surprisingly, ditches draining agricultural fields can transport large amounts of N. Schmidt et al. (2007) monitored seven ditches draining soils with a long history of receiving poultry litter. They found that shallow ditches (<0.6 m [<2 ft]) served primarily as conduits for surface water, with most ditches exporting N at rates of 5.1 to 15.5 kg N ha^{-1} yr^{-1} (4.6 to 13.8 lb N ac^{-1} yr^{-1}). One shallow ditch had an annual loss of 43.5 kg N ha^{-1} (38.8 lb N ac^{-1}), corresponding with likely contributions from point sources that included poultry barns and a litter storage facility. Ditch management, in conjunction with other agronomic, ecological, and engineering approaches to mitigating nonpoint source pollution, offers land managers opportunities for reducing N export from artificially drained agroecosystems.

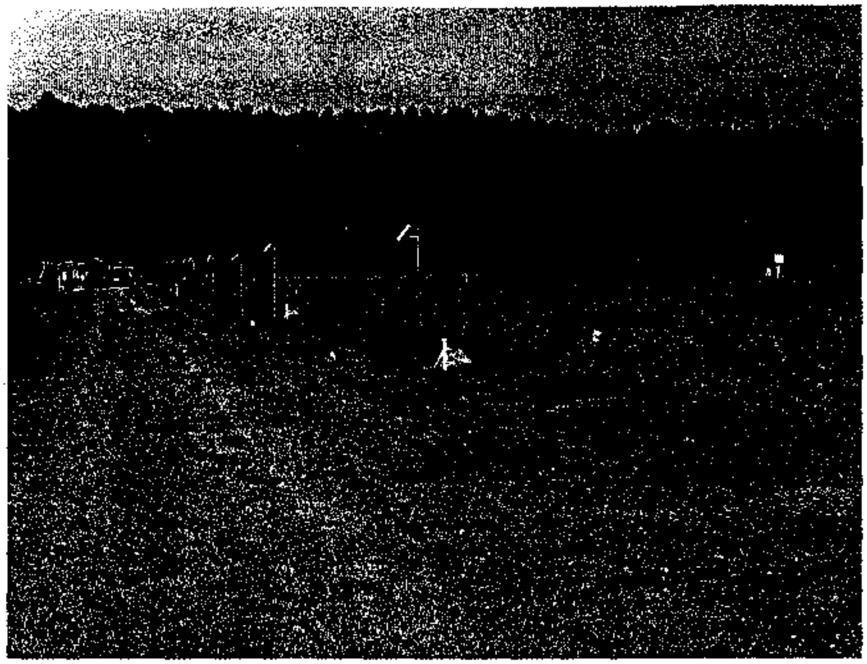
Phosphorus. A growing body of research now exists on the function of ditches to mediate the transport of agricultural P. As conduits for point and nonpoint sources of P, ditches can yield loads that are of environmental concern. Kleinman et al. (2007) monitored ditches draining Coastal Plain soils that had received more than 20 years of poultry litter application. Over five years, mean losses of total P from two ditches draining nonpoint sources averaged 13.9 kg ha^{-1} yr^{-1}, with single year losses as high as 26.2 kg ha^{-1}. Very little of this P derived from overland flow from adjacent fields (<4% of total P) (figure 4), pointing to subsurface flows, ditch soils, and potentially mats of algae as important sources of P.

Ditches likely play a role in moderating downstream P losses via processes of hyporheic exchange (Nguyen and Sukias 2002). Research by Dunne et al. (2007) and Vaughan et al. (2007) confirms that ditch soils can serve as large stores of P, particularly in intensively managed systems where significant amounts of P have been land applied. Dunne et al. (2007) examined ditch soil P characteristics under several land uses in Florida. In that study, unimproved pasture ditch soils had lower contents of total P, water-extractable P, and Mehlich-1 P than did ditch soils from dairies and improved pastures. Vaughan et al. (2007) observed large variability in P concentrations within Maryland ditches, highlighting the role of spatial variability in ditch soil P. Their research revealed that materials accumulating within ditch channels can have substantial sorption capacities and therefore should not be discounted as buffers for dissolved P.

The studies of Sharpley et al. (2007) and Smith and Pappas (2007) provide insight into the role of bed materials (soils and sediments) in controlling P losses. Sharpley et al. (2007) found that soils in Maryland ditches draining agricultural areas maintained higher dissolved reactive P (DRP) concentration in flowing water than did soils from a ditch in a forested area. Differences were consistent with relative concentrations of Mehlich-3 P and equilibrium P concentration at zero sorption (EPC_o) of the ditch soils. When ditch soils were exposed to simulated runoff water rich in DRP, ditch soils served to remove P from the flowing water, with P uptake by the soils related to a soil's P sorption maximum and clay content. Microbial immobilization appeared to account for up to 40% of P uptake.

Sediment. Ditches serve as a conduit for sediment, even in low-relief landscapes. Sediment is a significant water pollutant and it also carries particulate-bound nutrients and other contaminants. Sediment transported through ditches is derived from particulates in surface water and groundwater inputs and from the erosion and failure of

Figure 4
Ditch and field runoff monitoring at the University of Maryland Eastern Shore research farm on the Coastal Plain of Maryland.



ditch banks. Sediment may undergo repeated cycles of deposition and resuspension within ditch networks. Vegetation and organic matter accumulation provide a means to entrain and stabilize sediment (Needelman et al. 2007); disruption of these materials through ditch maintenance, such as a clean-out, may make the ditch system susceptible to greater sediment losses. An effective means to control downstream sediment losses is to provide floodplain areas for ditches, either within the channel itself (Powell et al. 2007a, 2007b) or within an adjacent floodplain (Evans et al. 2007).

Carbon. Many ditches have a higher net primary productivity than streams due to the presence of vegetation and high algal growth due to eutrophication and periods of stagnation. This organic matter may become a source of biological oxygen demand if transported downstream. Soil organic matter accumulation in some ditches represents a significant contrast from most fluvial systems. This organic matter accumulation occurs under low flow conditions, which prevents scouring and depresses decomposition rates under anaerobic conditions (Needelman et al. 2007).

Acidity. The formation of monosulfides has been documented in ditches draining acid sulfate soil landscapes in Australia and the United States (Bush et al. 2004; Vaughan et al. forthcoming). When sulfides oxidize, they produce acidity, which has been associated with fish kills and other environmental problems. However, monosulfides have also been documented in ditches in landscapes without acid sulfate soils (Needelman et al. 2007), indicating sufficiently anaerobic conditions to reduce sulfur. The sulfur source in agricultural systems may be animal manures or agrochemical inputs (Vaughan et al. forthcoming).

Other Contaminants and Emissions. Ditches also serve as conduits for other contaminants such as heavy metals, pesticides, pathogens, and pharmaceuticals (Cooper et al. 2004; Bennet et al. 2005). The unique characteristics of ditches may lead to high retention and transformation rates of many contaminants. Pappas and Smith (2007) found that sediments exposed by dredging had a reduced capacity to remove the herbicides atrazine, metolachlor, and glyphosate than did the sediments present prior to. dredging. The biofilms developed on ditch soil and sediment surfaces and vegetation may play an important role in pathogen interception and removal (Stott and Tanner 2005). Crum et al. (1998) found that the disappearance of the herbicide Linuron was slowed at cooler temperatures in ditches with an alternating stagnant/flowing water regime. Ditches may emit and influence the landscape-scale emission of greenhouse gases such as nitrous oxide and methane. The emission of nitrous oxide is discussed by Strock et al. (2007). Minkkinen and Laine (2006) observed that methane emissions from ditches were influence by vegetative community and water level in a drained forested peatland; however, in a follow-up study it was found that the emissions from ditches were not sufficient to change landscape-scale estimates (Minkkinen et al. 1997).

Management of Drainage Ditches

In-Ditch Practices. Ditches require management to maintain hydraulic function including vegetation maintenance and clean-outs or dredging if sediment accumulation restricts flow. There are a variety of additional ditch management practices that can improve water quality, provide habitat, and improve water management for agricultural production. The Maryland Department of Agriculture has developed and field-tested a "weed wiper," a tool to selectively apply herbicides to woody vegetation in ditches instead of the common practices of mowing and broad herbicide applications (R hoderick et al. 2006). With this technology, nonwoody vegetation is maintained to retain sediment, stabilize soils and banks, and provide ecosystem habitat. Woody vegetation is removed to maintain flow capacity and prevent serious blockages after dislodgement.

Smith and Pappas (2007; also see Smith et al. 2006) quantified differences in the cycling of nutrients and herbicides from Illinois ditch sediments representing dredged and pre-dredged conditions (figure 5). Sediments were packed in flumes and exposed to a regime of recirculating flows that exposed them to varying concentrations of N (NH_4N, NO_3-N), dissolved P, and herbicides (atrazine, glyphosate). Due to stratification of ditch sediment properties, sediments exposed to ditch flow prior to dredging were able to remove more N, P, and glyphosate from the water column than did sediments representing the bed material after dredging. Under these circumstances, Smith and Pappas (2007) suggest that dredging be conducted during periods of the year when contaminant loads are expected to be low and that producers should minimize P applications during and immediately after dredging.

Figure 5
Ditch dredging or "clean out" operation.

The installation of water-control structures is a common means to retain plant-available water within the agricultural landscape while decreasing pollutant losses and promoting denitrification (figure 6) (Gilliam et al. 1979; Evans et al. 2007). Strock et al. (2007) describe preliminary findings from two Minnesota ditches used in a paired watershed experiment to test the role of water-control structures. Over the first year after a water-control structure was installed in one of the two ditches, the total-N load was similar for the two ditches. However, analysis of nonstorm event samples indicated a greater decline in N concentration in flow from the ditch with the water-control structure, with total-N concentrations up to 71% lower than observed in the ditch that was not equipped with a water-control structure. Opportunities also exist to deploy water-control structures in conjunction with "bioreactors" or "biological "curtains" that provide sources of organic matter under reducing conditions to convert nitrate-N to gaseous forms of N (Schmidt et al. 2007).

Given the growing concern of P losses from ditches, novel management practices are being developed to curtail the transfers of dissolved forms of P. which are not targeted by traditional management practices such as dredging and drainage management (flow control). Penn et al. (2007) review the potential to use P-sorbing materials in drainage ditches to sequester dissolved P from ditch water. They describe an array of traditional agronomic amendments, water treatment materials, and industrial byproducts that can serve to convert dissolved P in ditch water to insoluble forms. A variety of approaches exist to using P-sorbing materials in ditches such as broadcasting to ditch soils, dosing ditch effluent with dissolved compounds, and routing ditch water through structures that contain solid materials. Preliminary evidence from an experimental structure designed to treat effluent from a small ditch indicates a high potential for P removal and similar potential to remove other pollutants of concern such as arsenic, copper, nickel, and zinc.

Powell et al. (2007a, 2007b) provide and test an approach to size agricultural ditches with a two-stage channel: a sediment underlain channel designed for flow conveyance surrounded by a vegetated bench that evolves as a floodplain due to overbank accretion (figure 7) (Jayakaran and Ward 2007). While more expensive to construct than traditional ditch channels, two-stage channels require less long-term maintenance and provide the ecosystem services of sediment entrainment and habitat improvement (Powell et al. 2007b).

Evans et al. (2007) describe two alternate in-ditch management practices: the establishment of in-stream wetlands and the redesign

Figure 6
Water-control structure raising the water table to near the soil surface.

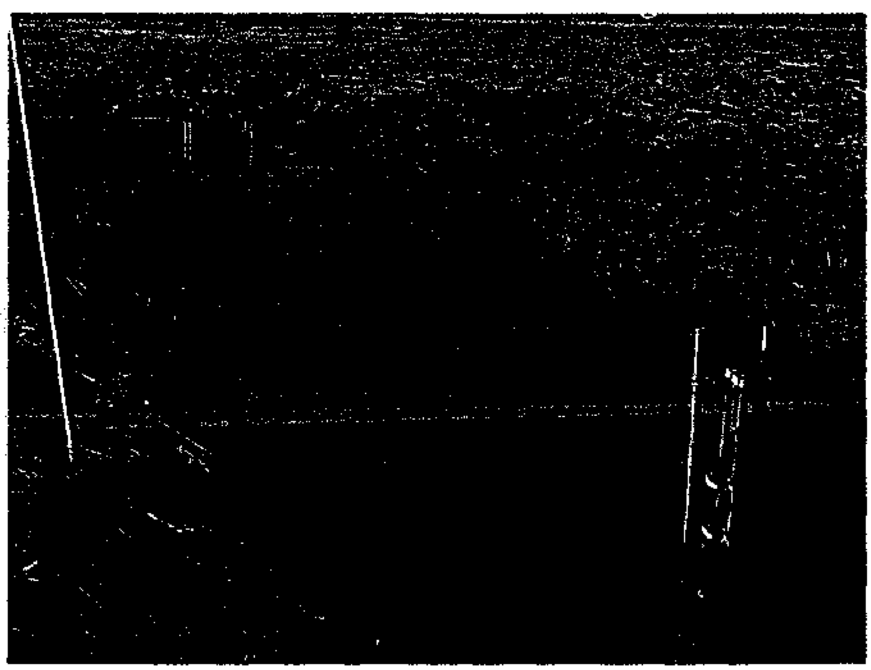


Figure 7
Natural benches formed in a drainage ditch.

of channels using natural design principles. In-stream wetlands have been found as an effective means to mitigate nonpoint source N pollution (Hunt et al. 1999).

External Ditch Practices. Several management practices are available for installation adjacent to ditches to provide a variety of ecosystem services. Most ditches are disconnected from their natural floodplains, and therefore during large flows transported sediment is not deposited. Evans et al. (2007) describe a practice applied in North Carolina where the floodplain surrounding a ditch is lowered, thereby reconnecting it to the ditch network. The establishment of riparian buffer zones and wetlands around ditches is an option to reduce pollutant inputs by providing a zone of remediation for overland and subsurface flow (Evans et al. 2007).

Ditch Conversion Projects. Ditch segments may be restored to wetland or floodplain systems in order to improve water quality and provide wildlife habitat. The Delaware Department of Natural Resources and Environmental Control is monitoring a conversion of a ditch to a riparian wetland to determine the effectiveness of the system at treating agricultural runoff (Barthelmeh and Biddle 2006). In Maryland, a series of ditches were converted to wetlands to offset wetlands disturbed during state highway construction (Jellick 2006; Mister 2006).

The Policy of Drainage Ditches

National. At a national level, drainage ditch policy generally falls within the broader category of drainage management (Carman 2006). Federally, many ditch-related programs are administered by the USDA. Cost-share assistance program are generally administered through the USDA Natural Resources Conservation Service (NRCS) such as the Environmental Quality Incentives Program, the Conservation Security Program, the Flood Plain Easement Program, the Farmland Protection Program, and the Wetlands Reserve Program. The USDA Farm Service Agency administers the Conservation Reserve Program and the Conservation Buffer Initiative. The **USDA NRCS *National Engineering Field Handbook*** (available online at wwwinfo.usda.gov/CED/) includes chapters on water table control, wetland restoration, and drainage management.

The Agricultural Drainage Management SystemsTask Force is a USDA technical work group addressing water management issues on agriculturally drained lands (Agricultural Drainage Management Systems Task Force 2007). Collaborators include federal, academic, and private members. TheAg icultural Drainage Management Coalition is an organization of private companies working to promote drainage water management in order to reduce the nutrient enrichment of water bodies, protect against droughts, and enhance wildlife habitat (Agricultural Drainage Management Coalition 2007).

State. The ownership and management of ditches varies by state in the United States. In Maryland, most larger ditches are owned and maintained by Public Drainage Associations and Public Watershed Associations (Mister 2006). The associations are governed by elected managers and include annual member meetings. Landowners benefiting from drainage are taxed; funds are used for ditch operation and maintenance. The Maryland Department of Agriculture has the responsibility to regulate and oversee the drainage and watershed associations and conduct annual walking inventories in conjunction with ditch managers, leading to formal operation and maintenance plans. Cost-sharing assistance for ditch best management practice (BMP) implementation is made available in part *through* United States Environmental Protection Agency Section 319 grants.

The first comprehensive drainage law in Minnesota was passed in 1887. Under Minnesota drainage law (Helland 1998), general authority for public drainage is vested in individual counties, although some drainage systems are located in and under the supervision of a watershed district. Minnesota law requires a permanent grass buffer on each side of a new ditch or when improvements are made to an existing ditch. The law also stipulates that environmental criteria must be considered when considering a proposed drainage project. Recently, some groups have expressed interest in modernizing the drainage law.

Evans et al. (2007) discuss the role of drainage districts and water management service districts in North Carolina. Both of these programs provide for the establishment, taxation, and governance of drainage system. Water management service districts provide greater flexibility than drainage districts in that they allow for multiple objectives, such as water quality improvement, while a drainage district is restricted to the objective of drainage and flood protection.

Summary and Conclusions

Ditches are unique engineered ecosystems with characteristics of streams and wetlands. There is growing interest in the improvement of ditch management to mitigate the loss of pollutants from agroecosystems to downstream water bodies while increasing agricultural efficiency. Optimal design of ditch management practices will require continued advances in the understanding of the ecological, chemical, and hydrological processes operating within ditches and their surrounding landscapes. Application of innovative methods to treat and remove pollutants from ditches may prove instrumental for the achievement of watershed management objectives.

Acknowledgements

Support for the 2006 Ditch Project Field Tour and Symposium was provided, in part, by funding through the USDA Cooperative State Research, Education, and Extension Service National Integrated Water Quality Program award number 2003-51130-02109 and a grant from the Keith Campbell Foundation for the Environment. We are particularly grateful to the following individuals who oversaw the editing of individual manuscripts from the symposium: Ray Bryant (Pasture Systems and Watershed Management Research Unit, USDA Agricultural Research Service), Curt Dell (Pasture Systems and Watershed Management Research Unit, USDA Agricultural Research Service), Ed Dunne (Institute of Food and Agricultural Sciences, University of Florida), Brian Needelman (University of Maryland), Doug Smith (National Erosion Research Laboratory, USDA Agricultural Research Service), Jeff Struck (University of Minnesota), and Andy Ward (Ohio State University). We also thank the participants at the event for their many insights and contributions. Additional information about this event, including symposium presentations and the field tour guide, is available at http://www.sawgal.umd.edu/DrainageDitches 2006DitchTour.html.

References

Agricultural Drainage Management Coalition. 2007. Owatonna, MN: Agricultural Drainage Management Coalition. www.admcoalition.com

Agricultural Drainage Management Systems Task Force. 2007. Columbus, OH: Ohio State University Extension. http://extension.osu.edu/~usdasdru/ADMS ADMSindex.htm.

Barthelmeh, T., and M. Biddle. 2006. The Hairier stream and wetland restoration project at prong 6 of the Petersburg tax ditch, Felton, DE: Effectiveness of restored wetlands for the treatment of agricultural runoff. In Improved Management of Agricultural Drainage Ditches for Water Quality Protection: Field Tour Guide, ed. B.A. Needelman and S.A. Wills. College Park, MD: University of Maryland. www.sawgal.umd. edu/DrainageDitches/2006_tourandsymposium/.

Bennett, E.R., M.T. Moore, C.M. Cooper, S. Smith Jr., ED. Shields Jr., K.G. Drouillard, and R. Schulz. 2005. Vegetated agricultural drainage ditches for the mitigation of pyrethroid-associated runoff. Environmental Toxicology and Chemistry 24:2121-2127.

Bouldin, J.L., J.L. Farris, M.T. Moore, and C.M. Cooper. 2004. Vegetative and structural characteristics of agricultural drainages in the Mississippi Delta landscapes. Environmental Pollution 132:403-411.

Bush, R.T., D. Fyfe, and L.A. Sullivan. 2004. Occurrence and abundance of monosulfidic black ooze in a coastal acid sulfate soil landscape. Australian Journal of Soil Research 42:609-616.

Carman, D. 2006. Federal programs and ditch management. Its Improved Management of Agricultural Drainage Ditches for Water Quality Protection: Field Tour Guide, ed. B.A. Needelman and S.A. Wills. College Park, MD: University of Maryland. wwwsawgal.umd. edu/DrainageDitches/2006_tourandsymposium/.

Cooper, C.M., M.T. Moore, E.R. Bennett, S. Smith Jr., J.L. Farris, C.D. Milam, and ED. Shields Jr. 2004. Innovative uses of vegetated drainage ditches for reducing agricultural runoff. Water Science and Technology 49:117:123.

Crum, SJ.H., G.H. Aalderink, and T.C.M. Brock, 1998. Fate of the herbicide linuron in outdoor experimental ditches. Chemosphere 36.2175-2190.

Davis, S., S.W. Golladay, G. Vellidis, and C.M. Pringle. 2003. Macroinvertebrate biomonitoring in intermittent coastal plain streams impacted by animal agriculture. Journal of Environmental Quality 32:1036-1043.

Dunne, E J., K.A. McKee, M.W. Clark, S. Grunwald, and K.R. Reddy. 2007. Phosphorus in agricultural ditch soil and potential implications for water quality. Journal of Soil and Water Conservation 62(4):244-252.

Evans, R.O., K.L. Bass, M.R. Burchell, R.D. Hinson, R. Johnson, and M. Doxey. 2007. Management alternatives to enhance water quality and ecological function of channelized streams and drainage canals. Journal of Soil and Water Conservation. 62(4):308-320.

Gilliam, J.W, R.W. Skaggs, and S.B. Weed. 1979. Drainage control to diminish nitrate loss from agricultural fields. Journal of Environmental Quality 8:137-142.

Helland, J. 1999. The drainage issue. St. Paul, MN: Minnesota House of Representatives. www.house.leg. state.mn.us/hrd/pubs/drainage.pdf.

Hunt, PG., K.C. Stone, F.J. Humenik, T.A. Matheny, and M.H. Johnson. 1999. In-stream wetland mitigation of nitrogen contamination in a USA coastal plain stream. Journal of Environmental Quality 28:249-256.

Janse, J.H. 1998. A model of ditch vegetation in relation to eutrophication. Water Science and Technology 37:139-149.

Janse, J.H., and P. Van Puijenbtoek. 1998. Effects of eutrophication in drainage ditches. Environmental Pollution 102:547-552..

Jayakaran,A.D., and A.D. Ward. 2007. Geometry of inset channels and the sediment composition of fluvial benches in agricultural drainage systems in Ohio. Journal of Soil and Water Conservation 62(4):296-307.

Jellick,G.2006.The Cropper site, Snow Hill,MD : Integrating Maryland highway construction with the Coastal Bays Program. In Improved Management of Agricultural Drainage Ditches for Water Quality Protection: Field Tour Guide, ed. B.A. Needelman and S.A.Wills. College Park, MD: University of Maryland. www.sawgal.umd. edu/DrainageDitches/2006_tourandsymposium/.

Karr, J.R., and E. W. Chu. 1999. Restoring Life in Running Waters: Better Biological Monitoring. Washington, DC: Island Press.

Kleinman, P.J.A., A.L. Allen, B.A. Needelman , A.N. Sharpley P.A. Vadas, L.S. Saporito, G.J. Folmar, and RB. Bryant. 2007. Dynamics of phosphorus transfers from heavily manured Coastal Plain soils to drainage ditches. Journal of Soil and Water Conservation 62(4):225-235.

Langheinrich, U.S. Tischew, R.M. Gersberg, and V. Luderitz. 2004. Ditches and canals in management of fens: Opportunity or risk? A case study in the Dromling National Park, Germany. Wetlands Ecology and Management 12.429-445.

McCall, J.D., and R.F. Knox. 1979. Riparian habitat in channelization projects. United States Department of Agriculture Forest Service General Technical Report WO-USDA 12:125-128.

Minkkinen, K., and J. Laine. 2006. Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant and Soil 285:289-302.

Minkkinen, K, J. Laine, H. Nykanen, and P.J. Martikainen. 1997. Importance of drainage ditches in emissions of methane from mires drained in forestry. Canadian Journal of Forest Research 27:949-952.

Mister, D. 2006. Public drainage in Maryland. In Improved Management of Agricultural Drainage Ditches for Water Quality Protection: Field Tour Guide, ed. B.A. Needelman and S.A. Wills. www.sawgal.umd.edu/ DrainageDitches/2006_tourandsymposium/. College Park, MD: University of Maryland.

Needelman, B.A., D.E. Ruppert, and R.E. Vaughan. 2007. The role of ditch soil formation and redox biogeochemistry in mitigating nutrient and pollutant losses from agriculture. Journal of Soil and Water Conservation 62(4):207-215.

Nguyen, L., and J. Sukias. 2002. Phosphorus fractions and retention in drainage ditch sediments receiving surface runoff and subsurface drainage from agricultural catchments in the North Island, New Zealand. Agriculture Ecosystems and Environment 92:49-69.

Pappas, E.A., and D.R. Smith. 2007. Effects of dredging an agricultural drainage ditch on water column herbicide concentration, as predicted by fluvarium techniques. Journal of Soil and Water Conservation 62(4):262-268.

Penn, C.J., R.B. Bryant, P.J.A. Kleinman , and A.L. Allen. 2007. Removing dissolved phosphorus from drainage ditch water with phosphorus sorbing materials. Journal of Soil and Water Conservation 62(4):269-276.

Pierce, S.C., S.R. Pezeshki, and M.T. Moore. 2007. Ditch plant response to variable flooding. A case study of Leersia *oryzoides* (rice cutgrass). Journal of Soil and Water Conservation 62(4):216-225.

Portielje, R., and R.M.M. Roijackers.1995. Primary succession of aquatic macrophytes in experimental ditches in relation to nutrient input.Aquatic Botany 50:127-140.

Powell, G.E., A.D. Ward, D.E. Mecklenburg, J. Draper, and W. Word. 2007a. Two-stage channel systems: Part 2, case studies. Journal of Soil and Water Conservation 62(4):286-296.

Powell, G.E., A.D. Ward, D.E. Mecklenburg, and A.D. Jayakaran. 2007b. Two-stage channel systems: Part 1, Aapractical approach for sizing agricultural ditches. Journal of Soil and Water Conservation 62(4):277-286.

Rhoderick, J., J. Keppler, W.D. Hively, G. McCarty, T. Fisher, and T. Jordon. 2006. The Collier farm, Goldsboro, MD: Choptank River watershed study. *In I*mproved Management of Agricultural Drainage Ditches for Water Quality Protection: Field Tour Guide, ed. B.A. Needelman and S.A. Wills. College Park, MD: University of Maryland. www.sawgal.umd. edu/DrainageDitches /2006_tourandsymposium/.

Schmidt, J.P., C.J. Dell, P.A. Vadas, and A.L. Allen. 2007. Nitrogen export from Coastal Plain field ditches.Journal of Soil and Water Conservation 62(4):235-243.

Sharpley, A.N.. T. Krogstad, P.J.A. Kleinman, B. Haggard, F. Shigaki, and L.S. Saporito. 2007. Managing natural processes in drainage ditches for nonpoint source phosphorus control. Journal of Soil and Water Conservation 62(4):197-206.

Shirmohammadi, A., R.D. Wenberg, W.F. Ritter, and ES. Wright. 1995. Effect of agricultural drainage on water quality in Mid-Atlantic states. Journal of Irrigation and Drainage Engineering 121:302-306.

Simon, A. 2006. Understanding ditch management from a geomorphological perspective. In Improved Management of Agricultural Drainage Ditches for

Water Quality Protection: Symposium. College Park, MD: University of Maryland. www.sawgal.umd.edu/DrainageDitches/2006_tourandsymposium/.

Skaggs, R.W., M.A. Breve, and J.W. Gilliam. 1994. Hydrologic and water-quality impacts of agricultural drainage. Critical Reviews in Environmental Science and Technology 24:1-32.

Skaggs, R.W., and J.V. Schilfgaarde, eds. 1999. Agricultural drainage. Agronomy Monograph 38. Madison, WI: American Society of Agronomy-Crop Science Society of America-Soil Science Society ofAmerica.

Skaggs, R.W., G.M. Chesheir, and B.D. Phillips. 2005a. Methods to determine lateral effect of a drainage ditch on wetland hydrology Transactions of the ASAE 48:577-584.

Skaggs, R.W, A.A. Youssef, G.M. Chescheir, and J.W. Gilliam. 2005b. Effect of drainage intensity on nitrogen losses from drained lands. Transactions of the ASAE 48:2169-2177.

Smith, D.R., and E.A. Pappas. 2007 Effect of ditch dredging on the fate of nutrients in deep drainage ditches of the Midwestern United States. Journal of Soil and Water Conservation 62(4):252-261.

Smith, DR., E.A. Warnemuende, B.E. Haggard, and C. Huang. 2006. Dredging of drainage ditches increases short-term transport of soluble phosphorus. Journal of Environmental Quality 35:611-616.

Scott, R., and C.C. Tanner. 2005. Influence of biofilm on removal of surrogate faecal microbes in a constructed wetland and maturation pond. Water Science and Technology 51:315-322.

Strock, J.S., C.J. Dell, and J.P. Schmidt. 2007. Managing natural processes in drainage ditches for nonpoint source nitrogen control. Journal of Soil and Water Conservation 62(4):188-196.

Vadas, P.A., M.S. Srinivasan, P.J.A. Kleinman,J.P. Schmidt, and A.L. Allen. 2007. Hydrology and groundwater nutrient concentrations in a ditch-drained agroecosystem. Journal of Soil and Water Conservation 62(4):178-188.

van Schilfgaarde, J. 1971. Drainage yesterday, today, and tomorrow. In Proceedings of the ASAE National Drainage Symposium. St. Joseph, MI: American Society of Agricultural Engineers.

van Strien,A J.,J.Van Der Linden,T.C.P.Melman, and M.A.W. Noordervliet. 1989. Factors affecting the vegetation of ditch banks in peat areas in the western Netherlands. Journal of Applied Ecology 26:989-1004.

van Strien, Aj., T. Van Der Burg, WJ. Rip, and R.C.W. Strucker. 1991. Effects of mechanical ditch management on the vegetation of ditch banks in Dutch peat areas. Journal of Applied Ecology 28:501-513.

Vaughan, R.E., B.A. Needelman, P.J.A. Kleinman, and A.L. Allen. 2007. Spatial variation of soil phosphorus within a drainage ditch network. Journal of Environmental Quality 36:1096-1104.

Vaughan, R.E., B.A. Needelman, P.J.A. Kleinman, and M.C. Rabenhorst. Forthcoming. Morphology and characterization of ditch soils at an Atlantic Coastal Plain farm. Soil Science Society of America Journal.