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MINNESOTA AGRICULTURAL DITCH REACH ASSESSMENT FOR STABILITY (MADRAS): A DECISION SUPPORT TOOL

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ABSTRACT Selected ditches in Minnesota and throughout the upper Midwestern USA have become morphologically unstable via geotechnical failure, channel enlargement and/or aggradation. Most ditches adjust channel form over time; some remain stable whereas other ditches unravel and require thousands of dollars worth of maintenance. Unstable ditch channels in Minnesota have also resulted in loss of biotic habitat and excessive sediment transport to downstream water bodies resulting in an impaired waters designation under the Clean Water Act, Section 303(d). There are climatic, geologic and land use reasons why ditch channels become unstable over time. We provide an assessment tool for evaluating channel and bank processes occurring within a given ditch reach. The tool systematically considers factors driving ditch channel instability and offers potential remediation actions related to nutrient attenuation. MADRAS is a relatively rapid assessment tool that considers both channel hydraulics and geotechnical factors associated with channel instability. A ditch reach must be walked by an evaluator to gather field evidence and determine processes such as toe slope erosion, bank seepage, bank angle, vegetation, slumping and the relative in-channel sediment storage and transport. Observations of physical processes and hydrologic pathways are documented and then interpreted to diagnosis the ditch condition. Localized ground water seepage induced slumps require a different solution compared to bank slumping induced by systematic hydrologic changes within a watershed. Ditch reach assessment offers the local drainage authority a means to define and prioritize the nature of ditch channel instability and a framework for guiding the maintenance response to unstable ditches.

Keywords: Ditch, Channel stability, Assessment, Erosion, Aggradation.

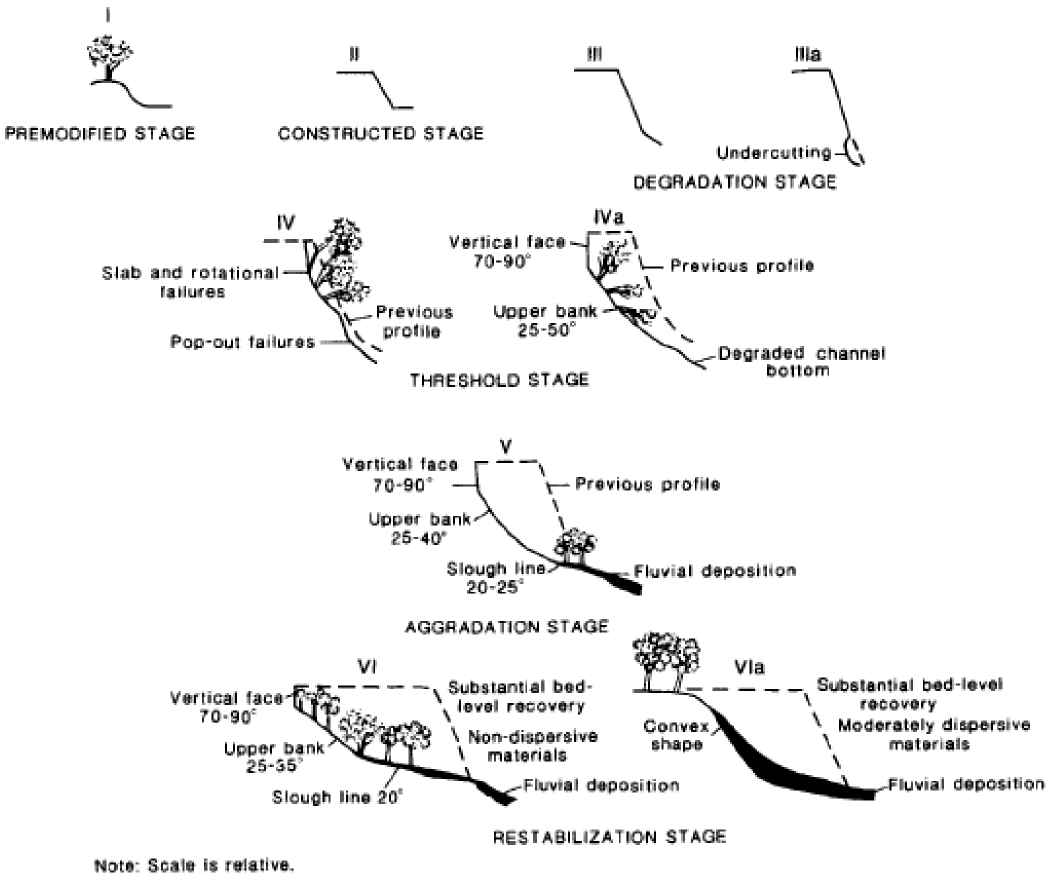
INTRODUCTION Drainage ditches are essential for agricultural production for many farmers in Minnesota and the upper Midwestern USA. There is an estimated 27,000 miles of drainage ditches in Minnesota. Most of these ditches were designed using concepts developed in the 1920s and 1930s. These designs are often inadequate in regard to ditch stability from both production agriculture and environmental perspectives. From a production agriculture perspective, the maintenance of drainage channels is expensive, requiring a substantial financial commitment from counties and watershed districts that assess landowners the costs of maintaining their drainage systems. One estimate suggests that up to 12 million dollars per year in Minnesota is spent on drainage ditch maintenance and cleanout. Some of our constructed ditches have been converted from natural streams, with substantial alterations. The human-altered hydrology and channel features in certain regions result in inherently unstable systems that require nearly constant attention. Blue Earth County, located in south-central Minnesota, alone spent $650,000 in 2005; Ohio estimates an average of $450/mile will be spent annually on open-ditch maintenance (Wilson, 2004).

A pressing environmental concern related to drainage ditches is the hypoxic zone in the Gulf of Mexico and the current Total Maximum Daily Load (TMDL) process. This hypoxia zone has been tied to nutrient loading caused by increased use of nitrogen fertilizer (Vitousek et al., 1997) and subsurface tile drainage (Stensland, 1999, Magner et al., 2004). It has been shown that higher order streams (larger) have limited ability to attenuate nutrients (Alexander et al., 2000). Smaller, low order streams are more capable of processing excess nutrients, with up to a 50 percent reduction during periods of high biological activity. The main buffer system between the high nitrogen concentrations from tile drainage and downstream water quality are small ditches and streams (Peterson et al., 2001). Channel geometry and the presence of vegetation in the bed and/or adjacent floodplain will influence channel stability and water quality (Ward et al., 2004, Christner et al., 2004, Smiley and Dibble, 2005). Unfortunately, many kilometres of smaller low order streams have been converted to drainage ditches. Because drainage ditches are relatively straight channels that are periodically dug out via a trackhoe for maintenance, they have limited ability to develop a sufficient biological community to effectively mediate high nutrient loads. The process of construction and maintenance of drainage ditches is also one of the leading causes of aquatic life use impairment in extensively drained landscapes. The average index of biotic integrity (IBI) score for 5 ditches in the south-western Minnesota was 32.9 (poor), compared to the average of 20 natural streams of 42.5 (fair) (Anderson, 2008). TMDL allocations for sediment and nutrients will need to focus on reducing the loads discharged from drainage ditches into streams and rivers.

Once a ditch is constructed or a stream channelized it will attempt to return to a natural state by meandering; this process results in greater potential for erosion and aggradation (Hansen et al., 2006). Because ditches make up a significant percentage of the river miles in southern and north-western Minnesota it is important that specific tools be developed that lead to robust ditch design and functionality. Tools have been developed to understand natural fluvial processes; however, only a few metrics of riverine tools apply well to ditch systems. Recent biological monitoring by the Minnesota Pollution control Agency (MPCA) has identified many ditch reaches as impaired water bodies: requiring detailed assessment and prescriptive stabilizing action. In summary the problems are costly maintenance for local government, nutrient & sediment contributions to larger downstream rivers and low IBI scores suggesting limited ecological services for the local biotic community (e.g., poor nutrient assimilation and sediment transport).

This paper provides a framework of data collection that provides decision support to drainage inspectors for a small defined ditch reach or entire ditch-shed. Given the load reduction demands of future TMDLs, local drainage authorities will need to prioritize ditch reaches not only for maintenance, but also for re-design/retrofit to maximize channel stability and pollutant reduction.

ASSESSMENT HISTORY AND THEORETICAL RATIONALE Over the past half century, engineers and earth scientists (Leopold et al., 1964, Schumm, 2005, Rosgen, 1996) have sought to explain river variability and provide a method for describing or classifying riverine systems. The methods developed were mostly oriented toward natural wild-land streams and not agricultural ditches. However, Simon and Hupp (1986) created a conceptual model of channel evolution for a natural stream that was converted to a trapezoidal channel illustrating six stages of bank-slope development (Figure 1).



Note: Scale is relative.

Figure 5. The six stages of bank-slope development

Figure 1. Simon & Hupp six stages of bank-slope development; source (NRCS, 2007)

The first stage, (I) *Premodified Stage*, has stable banks, with minimal aggradation, basal erosion on outside bends and deposition on inside bends, and a meandering channel. Bank conditions are the result of natural fluvial processes associated with the channel forming flow (Wolman & Miller, 1960). Stage two, (II) *Constructed Stage*, typically involves the removal of vegetation, excavation and reshaping the existing channel banks to a trapezoidal shape, and even a repositioning of the channel to enhance water drainage to maximize crop production. Banks are generally steepened and heightened, with respect to the channel forming flow to contain frequent peak flows and prevent cropland flooding. Simon and Hupp (1986) developed the second stage based on observations of channelization in low gradient regions of the Midwestern USA; they further noted that the construction phase was a transition from the stable state to a more unstable incised state. The third stage, (III) *Degradation Stage*, is marked by rapid erosion (downcutting) on the channel bed, and basal erosion on the banks, resulting in higher and steeper banks. Stage four, (IV) *Threshold Stage*, results from continued degradation as the channel enlarges. In cohesive soils, mass wasting processes occur and the stream bed over-widens at a new base elevation. Stage five, (V) *Aggradation Stage*, is marked by aggradation on the over-wide channel bed, beginning downstream and progressing upstream in time. Bank stability begins to improve because bank angles have flattened and a meandering low-flow thalweg with channel bars develop within the new channel geometry. The final stage, (VI) *Restabilization Stage*, is marked by further development of the meandering thalweg, continued deposition and stabilization of alternate channel bars, and the reestablishment of vegetation within the constructed channel geometry.

The Simon and Hupp channel evolution model (CEM) is a useful model with respect to channelization and the prediction of how channelized streams will respond over time to changes in channel geometry. The application of this observational field tool can be implemented relatively easily and inexpensively if the evaluator is trained in fluvial geomorphology. Yet, as with any observational tool it is subjective, with the exception of measuring the bank angles and quantifiable measurements do not necessarily distinguish one evolutionary stage from the next. Further the CEM works under an assumption that successive stages of evolution are driven by an initial land use change and not interrupted by other successive disturbances. In the Midwestern USA, the agricultural landscape is disturbed every year by field operations or where new subsurface tile drainage is installed prior to field disturbance. Field management can alter hydrologic pathways, setting into motion new channel adjustments; therefore, ditches can be at varying stages of channel evolution based on land use change. Based on field sheets developed for rapid geomorphic assessment (RGA) (Simon & Downs, 1995), we have adapted some of RGA metrics to tailor a field assessment sheet for ditches with flat gradients, cohesive soils and potential groundwater discharge.

WORKSHEET METRIC RATIONALE The worksheet (Tables 1 and 2) is designed to provide the evaluator with a range of scores that separate the good and fair conditions from those that truly require attention. Ditch reaches that have > than 50 % disruption indicate that some land use change has occurred that exceeds the former ditch sediment continuity. Ditch sediment continuity is defined by sediment supply, sediment transport, geotechnical adjustment or a catastrophic storm event that has displaced upland or channel material. Sediment supply could increase as a result of agricultural field management; removal of terraces or deep mowboard plowing before a large storm event, or a decrease in sediment supply in the channel from the addition of subsurface tile drainage. Relatively clean shallow groundwater will be sediment poor and can add large amounts of water to a ditch if a shift in hydrologic pathways occurs from surface to subsurface. If clean groundwater becomes the dominant ditch source water, then boundary shear forces will seek to erode the bed and lower banks of the ditch leading to a stage III condition described above.

Table 1. Suggested Worksheet Metrics and Scores.

			Percent of area		
		0%	1-10%	10-50%	>50%
Left Bank Condition	Slumpage*	1	2	4	8
Right Bank Condition	Slumpage*	1	2	4	8
Bed Deposition*		1	2	6	12
			Supportive Evidence		
Channel Slope*	Riffle*	Run*	Pooled*	Slow-moving*	Backed-up*
	1	1	2	4	8
Bank Angle*		45° Stable	2-angles*	90° Unstable	Seepage*
		1	2	6	8
Scour*		None	Present	Toe Undercut*	Extreme
		1	2	6	8
			Type, Age & Condition		
Crossing*	Old Culvert	Old Bridge	Perched	Sediment*	Sediment*
	Small Size*	Constriction*	Culvert*	Culvert	Bridge
	Rusted	Wooden	Any Age	New	New
	1	1	4	8	8

Because ditches are often established in low-gradient terrain, stream power will be weak; at times, too weak to transport excessive channel sediment. The build-up of excessive bed sediment will flatten the channel slope during low-flow conditions; if water backs-up in the channel it could decrease the efficiency of subsurface tile drainage. If subsurface drainage decreases, then the phreatic surface of saturated soils could adversely affect crop growth. Observant landowners have empirically derived this connection; thus the

Table 2. Worksheet Metric Definitions.

Slumpage* = mass failure of bank material that has fallen into the channel bed.

Bed Deposition* = too much sediment accumulating on channel bed

Channel Slope* = measured fall of water over a defined distance

Riffle = steep slope over a short distance with stream power to move water and sediment

Run = moderate slope with weak to adequate water and sediment transport

Pooled = little or no slope, deep water > 2 feet, leading to saturated bank soil

Slow-moving = little or no slope, shallow water (< 1 foot) that appears stagnant

Backed-up = suggests aggradation and loss of low-flow sediment transport

(Beaver activity or a debris jam will cause the water level to rise)

Bank Angle* = direction of change (stable-to-unstable)

2-angles* = a continuous angle does not exist, compound channel

Is any portion of the bank angle = to or > 90°? If so rank it unstable.

Seepage* = evidence of ground water seeping out of a channel bank

Scour* = opposite of deposition, eating the channel that leads to enlargement

Is there any evidence that scouring is present? If so rank at 2

Toe Undercut* = is the toe-slope of the bank exposed (bare soil)?

Extreme = abundant evidence of scour at several locations.

Crossing* = the type, relative age & observable features

Old Culvert/Bridge = may suggest flow stability, thus channel stability

Perched Culvert = suggests channel downcutting loss of vertical stability

Sediment = over-wide culvert or bridge allows for slow velocity & deposition

(a scour-hole below crossing suggests a change hydrology)

problem of sediment transport fuels an industry of trackhoe contractors ready to clean out aggraded ditches. Depending on how and where the ditch was constructed, channel maintenance can vary from rarely (once every 20 years) to more than once a year.

Glacially derived soils with sand and gravel heterogeneities will provide zones of strong groundwater seepage that will weaken a ditch bank during times of high water and subsequent pore pressure. These zones differ from bank failure that occurs due to hydraulic toe-slope erosion. Nevertheless, where flat row-crop fields limit surface erosion, groundwater seepage or clean groundwater from subsurface tile drainage will destabilize ditch channel banks over time and lead to planar or rotational bank failure into the channel bed. Bank failure delivers a sediment supply requiring complete transport to prevent a change in the channel slope.

The most direct and simple observation a ditch evaluator will make is that of slumpage. If the slumpage is large and bank sediment spreads across the bed, then the water surface of the channel will flatten (decreased sediment transport capacity); this condition may require immediate attention. Nevertheless, slumpage may not be evident, yet the bed shows evidence of small sand bars – why? The evaluator will need to look up-ditch to determine if a new sediment supply has been introduced or if debris (in a culvert) or beaver activity has decreased the channel gradient. These are the chief observations an evaluator must look for when filling out the MADRAS worksheet.

If the evaluator is familiar with the ditch system and surrounding landscape, then location of specific channel facets can provide a reference point for change. For example, a riffle observable from the road during base-flow conditions should remain constant over time; if the riffle goes below water then something down-ditch has backed-up water and requires more investigation. Another question to consider: has the riffle changed location over time – has is moved up-ditch? If the answer is yes, then systemic change maybe occurring throughout the watershed; as an evaluator you will need to closely examine toe-slopes below the riffle. Ditch reaches that are at risk will show signs of scour below undersized culverts or old narrow bridges. Scour will inevitably lead to steeper bank angles and the concordant risk of mass failure in the future. However, if scour is not evident and an older road crossing structure is still functional, the channel will likely be stable. New road crossing structures can present sediment transport issues because of an over-widened channel condition; e.g., three-box culverts all set at same elevation. A single box culvert set at the bed grade with one or two box culverts set at the bankfull elevation would provide sediment transport during low-flow conditions and high-flow capacity during flood events. To better address both production and ecological issues the MADRAS procedure should lead to decision support about drainage management.

DITCH MANAGEMENT OPTIONS Today drainage management must not only consider the movement of water, management must also consider the environment (Smiley & Dibble, 2005). Because ditches where primarily designed to drain water from the surrounding landscape, ecological function was typically not a design consideration. However, the design of a ditch may hold the key for future attainment of water quality standards. Options for mitigating issues of excessive sediment and nutrients in ditches and streams include the incorporation of best management practices (BMPs), which include structural and non-structural controls and operating procedures designed to prevent or reduce non-point source pollution. Drainage BMPs include, but are not limited to, grassed side-inlet waterways, energy dissipation devices/structures, and riparian vegetation/buffers, buried rock inlets, erosion control fabric, and constructed wetlands (Wilson, 2004, Yates et al., 2007). However, in landscapes drained by subsurface tile-drains, water can by-pass constructed wetlands and buffer strips unless they are located within an active floodplain. Therefore, another potential way to mitigate sediment and nutrient pollution is by an alternative ditch design that more closely resembles a natural stream. Historic work by Wolman and Miller (1960) defined the term "effective discharge" as the stream flow that transports the greatest amount of sediment over time, forming and shaping the bed and banks. Channel shape is a function of the sediment transport rate and frequency of occurrence for a given stream flow discharge. Low-flow discharges occur frequently, but are not effective at transporting large amounts of sediment. Extreme events, which have the greatest power to form a channel and transport the most sediment, occur infrequently. The effective discharge for natural streams in the Midwestern USA is generally associated with the discharge at the bankfull stage, which has a recurrence interval between 1.4 and 1.6 years (Rosgen, 1996).

Christner et al. (2004) point out that traditional agricultural ditches are designed to carry their maximum anticipated flow when they are filled to 80% of their design depth. Return intervals corresponding with these discharge values occur infrequently, and are typically greater than 50 years. Traditional ditch design does not allow for the effective movement of sediment, and the resulting accumulation of sediment requires costly periodic clean-out maintenance. This design also lacks an active floodplain which limits the interaction of water and vegetation and any concordant nutrient attenuation. The two-stage ditch design has the potential of improving both sediment continuity and ecological function (Ward et al., 2004). This design is based on the natural fluvial processes that occur in response to the construction of an oversized trapezoidal channel (Simon Stage IV and V), in which a small effective discharge channel is formed by building an active floodplain within the ditch itself (Ward et al., 2004). The channel is sized to convey the effective or bankfull discharge with benches that serve as active floodplains for frequent flood peaks; however, the ditch geometry will still contain the more infrequent flood peaks (figure 2).

The process by which an active floodplain is formed within the ditch in response to over-widening was also observed by Christner et al. (2004). Judicial Ditch #8 in central Minnesota was over-widened to accommodate the protection of a new bridge. The new and wider channel allowed for the development of a low-flow channel that meandered and establish its own dimension, pattern and profile, along with an active floodplain within the ditch geometry. The new effective discharge channel allowed for the natural movement of sediment, the growth of vegetation, and improved channel development

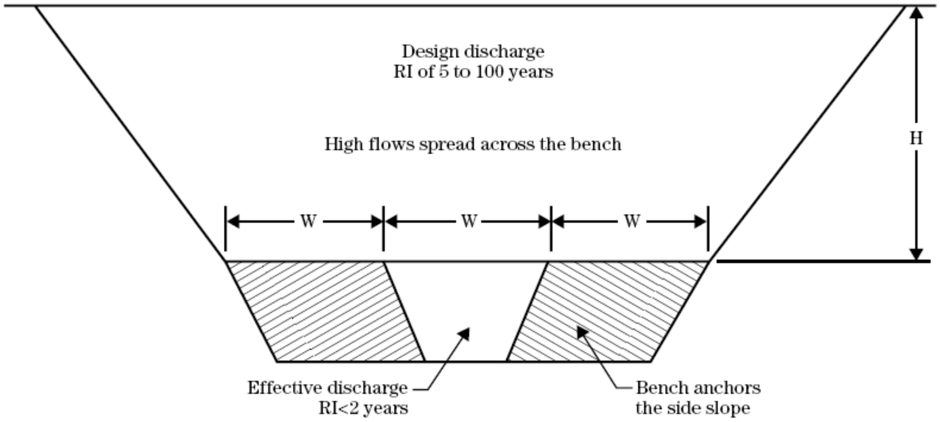


Figure 2: Two-stage ditch geometry (Source: USDA NRCS)

which created a combination of runs, riffles and pools, all of which created better habitat for fish. As a result, Judicial Ditch #8 had the 2nd highest fish IBI score of all streams measured in the Minnesota River Basin in 2003. The same ditch also demonstrated the third highest qualitative habitat evaluation index score and some of the lowest values of nitrogen (nitrite + nitrate), total phosphorus, and total suspended solids of all the channelized streams surveyed in 2003 in the Minnesota River basin by the MPCA (Anderson, 2008).

Despite initial construction costs and the increased width of the ditch system, which would require the surrender of agricultural land, the benefits of a two-stage ditch are several-fold. The initial function of water conveyance is not negatively impacted, the two-stage channel is more capable of transporting sediment more effectively that the traditional design, and overall ditch stability is improved, thereby reducing the need for costly maintenance. Furthermore, because the two-stage channel is more likely to retain its design shape, it is easier to predict its flood protection performance. In addition, there is a potential to improve habitat due to increased vegetation on the benches, water depth variation, and improvements to the substrate due to the ability of the stream to transport sediment (NRCS, 2007). Finally, the two-stage ditch may also be useful for improving water quality due to nutrient assimilation (Ward et al, 2004).

In 2008, a joint project between the MPCA, University of Minnesota, Mower County Soil and Water Conservation District and the Nature Conservancy designed and constructed a two-stage ditch near the Iowa border in southern Minnesota. The MADRAS procedure identified channel instability over a 2-km reach. Because the assessment yielded a score higher than 30, the ditch system warranted a more detailed investigation. Ditch channel morphology was surveyed using a total station to develop channel cross-sections and a longitudinal profile. The data was then used to create an overview design of a two-stage ditch which was presented to the landowners. The landowners agreed to the two-stage ditch concept and nearly 2-km of trapezoidal ditch was re-shaped into two-stage geometry in October, 2009.

CONCLUSIONS Ditch management for improved water quality will be required by the USA TMDL process to meet water quality standards. MADRAS offers a means for local units of government to identify high priority ditches and develop a repair or restoration plan. Given the need to insure water conveyance and improve water quality, the two-stage ditch design appears to offer channel bank stability in critical reaches, sediment transport under low-flow conditions and nutrient attenuation.

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