Red River of the North Basin

BASIN TECHNICAL AND SCIENTIFIC ADVISORY COMMITTEE

(BTSAC)

Briefing Paper #3:

Water Management Options for Surface Drainage

CONTENTS

INTRODUCTION

Floods of varying scale and severity are relatively common in the Red River of the North Basin (Red River Basin). During and after a given flood event, there commonly are public statements that directly infer or imply that the region's flooding problems are caused by the extensive network of surface and subsurface agricultural drainage systems in the Red River Basin. Although such statements are often dismissed as rhetoric or opinion, the underlying questions regarding agricultural drainage and its relationship to flooding in the Red River Basin have largely remained unanswered.

ND - MN Joint Drainage Committee

In an attempt to objectively address the questions surrounding the relationship between agricultural surface drainage and flooding and ultimately develop more effective and equitable water management policies in the Red River Basin, the MN Red River Watershed Management Board (RRWMB) and the ND Red River Joint Water Resource District (RRJWRD) formed a MN-ND Joint Drainage Committee, which framed a series of agricultural drainage study directives including:

- What are the impacts of agricultural drainage on flooding?
- How should agricultural drainage systems be designed to maximize benefits while minimizing adverse impacts?

The RRWMB and the RRJWRD commissioned the International Water Institute (IWI) early in 2010 to establish an objective process to study artificial drainage and its relationship to peak watershed flows in the Red River Basin (US) and develop management recommendations for local land and waters managers in the Red River Basin.

Basin Technical and Scientific Advisory Committee (BTSAC)

The IWI established a Basin Technical and Scientific Advisory Committee (BTSAC) comprised of technical representatives from organizations with an interest and/or statutory role in agricultural drainage management in the Red River Basin. The BTSAC is facilitated by the IWI and funded by the RRWMB and the RRJWRD. Participation on the BTSAC is exclusive with stakeholder organizations identified by the IWI. The IWI contacted the stakeholder organizations asking for a technical representative to serve on the BTSAC. When considering the makeup of the BTSAC, the goal was to strategically identify stakeholder organizations that would appoint an accredited (formal education in hydrology, engineering, soil science, natural resources management, etc.) representative to serve with their peers and address the questions posed by the RRWMB and the RRJWRD. BTSAC's role is to assemble, review, and summarize relevant scientific information, use best professional judgment, and initiate studies (if necessary) to draw conclusions and make water management recommendations for consideration by local land and water managers in the Red River Basin.

As an initial task, the RRWMB and the RRJWRD directed the BTSAC to investigate the relationship between subsurface (tile) drainage systems and peak watershed flows and develop management recommendations to mitigate impacts from *subsurface* drainage systems during flood events. This first BTSAC subsurface drainage study concluded early in 2012 with two Briefing Papers describing the known effects of subsurface drainage on peak watershed flows and outlining a series of subsurface drainage management recommendations for landowners and local water managers in the Red River Basin (http://www.rrbdin.org/archives/649).

STUDY SCOPE

At the conclusion of the first BTSAC subsurface drainage study, the ND-MN Joint Drainage Committee re-convened with the Red River Basin Commission's Drainage Committee to further discuss issues related to agricultural drainage. Following a series of ND-MN Joint Drainage Committee meetings, the RRWMB and the RRJWRD requested the IWI to reconvene the BTSAC (Appendix A) to develop recommendations to:

1. Determine how to best manage the existing surface drainage system to increase or maintain drainage benefits, reduce flood flows, and decrease downstream flood damages.
2. Determine best strategies for future surface drainage system improvements/modifications to maintain or improve drainage benefits, reduce flood flows, and decrease downstream flood damages.

The BTSAC defined and undertook a number of steps deemed necessary to address the request for recommendations from the ND-MN Joint Drainage Committee including:

1. Perform a search of existing scientific literature to understand the relationship between artificial surface drainage and flooding.
2. Review and, if necessary, refine existing hydrologic models to clarify relationships between ditch design, culvert size, and flooding.
3. Review current engineering design practices for agricultural drainage systems being applied in the Red River Basin (US).
4. Develop management recommendations and rationale for consideration by local land and water managers.
5. Develop a final report for distribution.

For the purposes of this report, BTSAC defines agricultural surface drainage as the current system of man-made artificial ditches and altered natural waterways in the Red River Basin that convey water from the land surface for the purposes of agricultural production. The study scope focused on hydrology and hydraulics including general physical principles and associated cause and effect relationships of agricultural drainage system components. The primary audiences for this report include the RRWMB, the RRJWRD, their member watershed and water resource districts and technical advisors.

The BTSAC did not address environmental, social, or economic aspects of agricultural surface drainage. Implementation of site specific or system-wide changes in surface drainage design or management may require consideration of these factors.

LITERATURE SUMMARY

There is a substantial body of literature and data regarding research and analysis of flows and flood events for natural and artificial waterways which serves as a foundation to understanding the modern-day hydrologic and hydraulic conditions in the Red River Basin (Appendix B). From the literature, BTSAC derived and affirms the following summary statements regarding the relationship between flooding and artificial surface drainage systems:

- Climate (weather) is the major hydrology driver, especially during large scale flood events, in relation to rainfall and/or snowmelt distribution and intensity.

- Trend analyses studies of surface drainage effects on flooding have failed to conclusively attribute Red River Basin floods to increased surface drainage.
    - Historical data indicate that floods as large as, or larger than those currently occurring in the Red River Valley, occurred at times before modern agriculture and drainage.
    - There are many factors affecting floods and it is difficult to determine effects from the individual factors using trend analyses.
    - The most comprehensive review papers have indicated that situations of both flood peak/flow reduction and increase can occur from surface drainage, depending on the point of reference, local hydrology, and the sequence of climatic events.
- Most recent papers investigating anthropogenic (originating from human activity) effects on flooding have attempted to disaggregate only a broader category of "land management change effects" from climate. The papers reviewed included only subcategories of various factors affecting flooding where surface drainage and tile drainage are usually discussed as composite and not disaggregated. Although papers have generally established some flood effect from land use changes, determining the relative effects of land use and climate are difficult and make associated generalizations problematic.
    - Trend analyses studies have indicated that combined climate and land use changes have resulted in larger annualized flow volume.
- Hydrologic reasoning supported by the literature concludes that reducing floodwater runoff which otherwise would have entered the waterway during a flood event can result in flood peak and flow reduction, and vice versa.
    - Effects of retention (longer-term) and detention (short-term) storage will decrease with increasing flood intensity and decreasing flood frequency based on storage volume compared to the total flood volume.
    - Even a small percentage of flow/volume reduction may have a beneficial effect at some locations during large flood events.
- Increasing drainage conveyance capacity tends to increase flood peaks downstream, unless flow timing at the point of interest is altered to decouple flood peaks.

- The effects of surface drainage conveyance are greatest with small flood events and lesser with large flood events (due to ditch capacity relative to flood volume and peak flow).

BEST MANAGEMENT PRACTICES RECOMMENDATIONS FOR AGRICULTURAL SURFACE DRAINAGE SYSTEMS

In general, any water management practice which vacates surface or soil storage during low flow periods, and from which or through which release of waters can be controlled, limited, or reduced during flood events will be beneficial for flood reduction through enhancement of usable storage. An example, provided in the previous BTSAC report on subsurface drainage (BTSAC 2012), is controlled tile drainage wherein water is removed (assuming conditions allow) through slow drainage prior to or over winter following a wet fall, and outlets are closed during spring flood events. In this situation, pre-drainage creates and allows for use of soil porosity for additional water storage that would not have been available without drainage. Similar scenarios may be inferred for surface waters where earlier release and controls allow for floodwater storage (retention or detention) of surface waters in drained areas which would otherwise have had limited floodwater storage available prior to and during the flood event. However, floodwater storage will have limited and situational benefits if controls are not present and operated for flood control, and may in some situations contribute to flooding. An example would be where wet soil conditions in the pre-flooding period reduce soil profile storage, and surface drainage infrastructure expedites free movement of runoff during flood events. In addition, agricultural surface (and subsurface) drainage systems which connect previously unconnected land to the river system will contribute to flooding unless drainage infrastructure is designed and used to prevent release of water during flood events.

Various water management strategies including reducing flood volume, increasing conveyance, and increasing temporary storage have been extensively studied and successfully applied to reduce runoff and alter the amount and timing of surface water conveyance to mitigate downstream flood damages (Anderson and Kean 2004 and Anderson et al. 2007). In addition to the specific recommendations that follow, BTSAC affirms these established flood damage reduction strategies and recommends their appropriate implementation throughout the Red River Basin to reduce surface runoff from drainage systems and decouple coincidental flood peak timing at downstream problem areas.

The BTSAC best management practices recommendations are based on scientific literature, results of hydrologic and hydraulic modeling, and the collective experience of BTSAC members.

Uniform Surface Drainage Design Guidance

The majority of agricultural drainage systems in the Red River Basin are owned by private landowners and administered by local or state jurisdictions; either independently or through some form of Joint Powers Agreement. In recent times, agricultural surface drainage systems have often been engineered to contain estimated peak discharge (the flow during maximum flood stage or depth during a given frequency of flood event) while culverts have been sized to pass peak discharge essentially unimpeded for much larger events. The design capacity of surface drainage systems is driven by the landowners' acceptable level of risk (and willingness to pay) while the size of culverts within the drainage system is dependent on the use and importance of the road or highway it passes water under. The result is a mishmash of Red River Basin surface drainage systems that have different design capacities of both channels and culverts.

The BTSAC developed a Uniform Surface Drainage Design Guidance (design guidance) for the Red River Basin (Appendix C) that includes consistently balanced design capacities of both channels and culverts. The design guidance is predicated on BTSAC model results and the BTSAC philosophy of "adequate and equitable." "Adequate" refers to the amount of agricultural drainage provided by a given surface drainage system and the acknowledgment that Red River Basin landowners have the right to adequate, but not more than adequate drainage, in accordance with drainage and reasonable use laws. "Equitable" refers to the equal distribution of positive and negative effects of agricultural surface drainage throughout the drainage system and the entire Red River Basin.

The BTSAC recommends:

- The design guidance should be considered when permitting or improving both public and private surface drainage systems in agricultural areas of the Red River Basin.
- Every available opportunity should be utilized to retrofit existing Red River Basin drainage systems using this design guidance.
- Where the design guidance cannot be applied, other means to mitigate flood damages should be implemented in the watershed.

Most crops grown in the Red River Basin can tolerate standing water for a period of 24-48 hours (see Crop Water Tolerance Literature Review Section in Appendix C). In order to address the BTSAC's adequate and equitable philosophy, the primary objective of the design guidance is to remove water from a 10-year summer rainfall event before crop/flood damage occurs. During larger events (events with greater than a 10 year return period), some longer inundation with the potential for crop/flood damage is expected. During these larger events, the design guidance would - as equitably and practically - apportion the potential for crop/flood damages throughout the drainage system by widely distributing floodwaters on agricultural land for a practicable period of time during major (primarily spring) flood events.

If the design guidance is applied, *and culverts are appropriately sized according to the design guidance throughout the watershed of the drainage system*, no further surface drainage system flood mitigation is needed because the agricultural surface drainage system can be considered self-mitigating. For those agricultural surface drainage systems where the design guidance cannot be applied, BTSAC recommends the implementation of established flood damage reduction strategies to reduce flows and decouple flow timing at downstream damage centers. The most effective mitigation strategy is temporary gated floodwater storage in the middle and late runoff areas (Anderson and Kean 2004).

Flood Storage

Flood storage can also further reduce flood damages in drainage systems where the design guidance is applied.

Although there are many types of floodwater storage, the most effective are those with "gated" outlet structures that are strategically located and have the capacity to store floodwaters until they can be released without adding to flood damages downstream. Gated storage is preferred over un-gated storage (Anderson and Kean 2004).

Maintain Non-Contributing Areas

Adding water that would normally not have a pathway to enter the hydrologic system during flood events tends to increase downstream flood peaks.

BTSAC recommends maintaining non-contributing areas in the watershed. Drainage of non-contributing areas should be discouraged wherever possible. If non-contributing areas are drained, other strategies to mitigate the additional downstream flow contribution (e.g. temporary floodwater storage) from these areas must be implemented to mitigate any downstream impacts from the additional water added to the flood hydrograph.

Subsurface Drainage Management

Since subsurface drainage systems increase total annual water volume from fields and have the potential to increase downstream flood peaks, the BTSAC reaffirms the subsurface management recommendations to mitigate flood impacts from subsurface drainage systems including the installation and operation of controls to increase temporary storage during flood events whenever possible (BTSAC 2012).

Outreach and Education Strategy

There is currently no basin-wide governance in place to uniformly establish policy, adopt, and/or enforce the BTSAC recommendations in the Red River Basin. However, the RRWMB and the RRJWRD were formed to provide a more comprehensive perspective for water management and flood damage reduction:

- The RRWMB was created by an act of the Minnesota legislature in 1976 to provide an organization with a basin-wide perspective concerning flooding. Historically, the activities of the RRWMB have centered on flood control. Previous efforts in dealing with the flooding problem within the Red River Basin consisted of single projects within a localized area, planned with primary regard to local benefits. The RRWMB actively promotes a basin-wide perspective for water management. The RRWMB's mission is to *institute, coordinate, and finance projects and programs to alleviate flooding and ensure the beneficial use of water in the watershed of the Red River of the North and its tributaries.*
- The RRJWRD was formed in 1979 to address flooding problems in the Red River Valley in North Dakota. The majority of water resource districts in North Dakota are established along county boundaries. The RRJWRD's mission is to *provide a coordinated and cooperative approach to planning and implementing a comprehensive water management program in the Red River*

Valley. Particular attention is devoted to the development of water detention projects for the purpose of flood damage reduction.

Participation/membership in both the RRWMB and the RRJWRD is voluntary. There are also local water management entities (e.g. counties) independent from these originations that have jurisdiction over drainage systems. Comprehensive adoption and implementation of BTSAC surface (and subsurface) water management options requires voluntary action by the respective local watershed districts (MN), water resource districts (ND), and other local and state drainage jurisdictions in the Red River Basin. Garnering participation and cooperation will require an aggressive, targeted, and sustained outreach campaign by the RRWMB and the RRJWRD.

The BTSAC recommends the RRJWRD and the RRWMB establish and fund an outreach strategy that promotes comprehensive water management practices in the Red River Basin through the adoption of the BTSAC recommendations for surface (and subsurface) drainage. The outreach strategy should include efforts to engage the respective audience groups:

- Local Water Managers (watershed and water resource districts, and counties)
- Landowners
- Drainage Engineers
- Local and State Road Authorities and Engineers
- Public/Media

Local water managers, landowners, engineers, local and state road authorities, the public, and the media must have a comprehensive understanding of the BTSAC recommendations along with information products (e.g. brochures, presentations) supporting their implementation. Landowners must be engaged and informed by their local watershed and water resource districts or some designated entity (or individuals) of the underlying rationale and logic of BTSAC recommendations. Engineers (public and private) and road authorities must understand, embrace, *and apply* the uniform design standards when working in the Red River Basin. Drainage and road engineers are critical advisors to water managers for implementations of this design guidance. The public and the media should be informed and engaged whenever possible with a consistent and comprehensive message regarding BTSAC surface and subsurface drainage recommendations. Creating and highlighting examples of successful implementation of the design guidance at drainage system and subwatershed scales are expected to be important for its broad adoption.

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The IWI gratefully acknowledges the funding and support provided by the RRWMB and the RRJWRD. Their support of the BSTAC process is evidence of their ongoing commitment to comprehensive water management in the Red River Basin.

The IWI would also like to thank the individual BTSAC members and their respective organizations who participated in the BSTAC process. The BTSAC members always strived to address the longstanding and complex water management issues with science-based objectiveness and integrity.

APPENDIX A: BTSAC MEMBERSHIP

Stakeholder Organization	**BTSAC Representative**
MN Red River Watershed Management Board	Charlie Anderson
City of Fargo, ND	Mark Bittner
MN Red River Watershed Management Board	Nate Dalager
US Fish and Wildlife Service	Josh Eash
ND Red River Joint Water Resource District	Damon DeVillers
International Water Institute	Charles Fritz
ND Red River Joint Water Resource District	Randy Gjestvang
MN Natural Resources Conservation Service	Dave Jones
US Army Corps of Engineers	Scott Jutila
MN Board of Water and Soil Resources	Al Kean
ND Red River Joint Water Resource District	Chad Engels
US Geological Survey	Rochelle Nustad
ND Natural Resources Conservation Service	Dennis Reep
ND State Water Commission	Bill Schuh
MN Department of Agriculture	Rob Sip
MN Corn Growers	Adam Birr
Red River Basin Commission	Jeff Lewis
Ducks Unlimited	Roger Smith
MN Department of Natural Resources	Jim Solstad
MN Red River Watershed Management Board	Dan Thul

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APPENDIX C. RED RIVER BASIN UNIFORM SURFACE (OPEN DITCH AND DITCH CROSSING) DRAINAGE DESIGN GUIDANCE

Introduction

This document is intended to provide drainage design guidance for engineers and drainage technicians involved in the design and management of surface drains (open ditches) within agricultural areas of the Red River of the North Basin (Red River Basin). The design guidance establishes a uniform standard for evaluating the capacity of existing and proposed drainage systems throughout the basin.

Agricultural drainage ditches require an adequate outlet to function properly. The frequent recurrence of major floods has also heightened concern regarding the general lack of adequacy of the Red River and its major tributaries to handle increased drainage flows, especially during spring flood events. Widespread drainage and channel improvements tend to increase downstream flood peaks and flows; therefore, a methodology for drainage design which recognizes potential adverse flow impacts and minimizes those impacts is needed. The goal of this design guidance appendix is to present a self-mitigating drainage design that can be applied to both new and existing drainage systems. The underlying philosophy of the design guidance is that efficient and highly productive agriculture relies on adequate drainage; however, more than adequate drainage may unnecessarily burden downstream interests.

Flood-related agricultural damages are primarily caused by rainfall events that occur during the growing season. Epic Red River Basin floods that have caused extensive and widespread damages to infrastructure, urban areas, and farmsteads are primarily the result of spring snowmelt events. This guidance seeks to optimize the drainage system to remove water quickly following frequently occurring summer rainstorm events and retard the flow of water during relatively infrequent major (primarily spring) flood events, thereby mitigating the most serious adverse impacts.

The assumptions used in developing the design guidance are that runoff comes from typical cropland in the Red River Basin and that properties affected by temporary detention within the drainage system are also typical cropland. *Any use of the guidance in other areas should account for the differing circumstances.*

Design Guidance Goal and Objectives

A review of available literature indicates most Red River Basin crops can tolerate standing water for a period of 24 to 48 hours (Attachment A). The goal of the design guidance is remove backwater from intensively farmed land over a period of about 24 hours following a 10 year 24 hour summer rainfall event. The primary objectives of the design guidance include:

- Remove excess water from a field before it causes extensive crop damage.
- Minimize the potential for damages to roads
- Prevent overflow onto lands in ways likely to cause frequent and severe erosion of cultivated soil.

For larger than 10 year rainfall events, crop damages should be expected but, in the interest of fairness, the damages should be distributed as equally as practical throughout the drainage system. The design guidance would provide widely distributed storage to reduce downstream flooding within the Red River Basin by storing as much water on agricultural land as practicable for as long as practicable during major (primarily spring) runoff events. This is accomplished by a careful and consistent balance of channel and culvert capacities. The capacity of the ditch system is a blend of channel conveyance and culvert conveyance. In general, channel conveyance (the capacity to transport water) increases rapidly with increasing depth of flow. Conversely, once a culvert is flowing full its conveyance increases slowly as headwater depth increases. Balancing culvert and ditch design results in a ditch system that keeps flows from greatly exceeding channel capacity. Channel size should be thought of as a means of providing adequate flow capacity and culvert size should be thought of as a means of restricting flow to closely match channel capacity. The excess water is temporarily stored as equally as practical on fields throughout the drainage system.

The flow control provided by a theoretical culvert is illustrated by the performance curves resulting from a typical trapezoidal ditch about 4 feet deep with an upstream drainage area of a little more than 3 square miles (Figure 1).

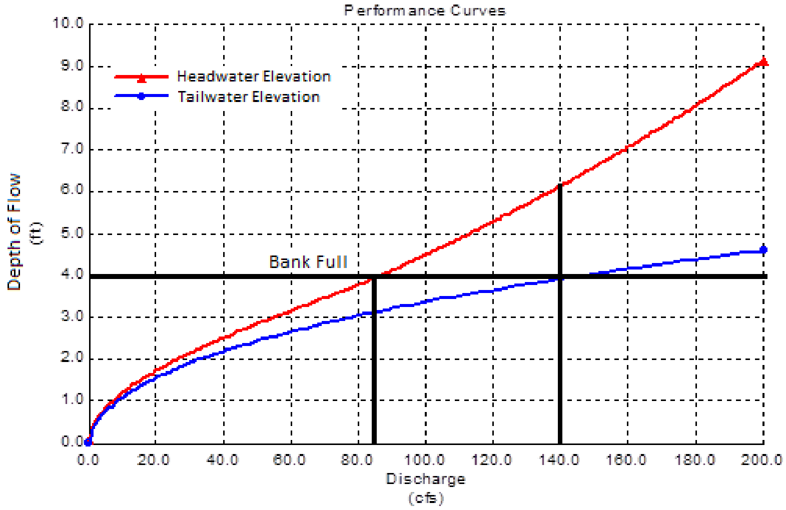


Figure 1. Flow Control provided by a Theoretical Culvert (assuming no road overtopping).

The ditch would be bank full immediately upstream of the culvert at a design flow of about 85 cubic feet per second (cfs). Immediately downstream of the culvert there would be about 0.8 feet of freeboard. When flows increase above 85 cfs, field storage begins to occur upstream of the culvert. As flows upstream of the culvert continue to increase, the actual flow through the culvert does not increase at the same rate; flows through the culvert increase at a reduced rate due to the temporary storage effect. The design strategy sizes the culvert with sufficient head loss (headwater elevation minus tailwater elevation) so that the culvert will retard flow increases to more closely match downstream channel capacity. In this example, the flow through the culvert would not exceed the downstream channel capacity of about 140 cfs until the upstream depth reaches about 6 feet (probably a 25 to 50-year flood event). Without the culvert in place, the flows would be much greater. The excess water volume is temporarily stored upstream of the culvert.

This approach differs substantially from frequency-based ditch and road design methods. Ditches are often designed to contain estimated flood peak discharges while culverts have often been sized to pass (almost unimpeded) peak inflows during much larger flood events. Ditch design capacity has depended primarily on landowners' acceptable level of investment. Culvert sizes have depended primarily on the importance of the road. The result is a mishmash of ditch and culvert sizes throughout the basin.

The benefits and challenges of bringing culvert capacities more in line with ditch capacities have been addressed in Technical Paper 15 (http://www.rrwmb.org/files/FDRW/TP15.pdf). The drainage engineer should refer to this paper for more detailed discussion and analysis.

Design Guidance Methods

The best currently available design methodology would utilize HEC-HMS to develop inflow hydrographs and HEC-RAS to route flows down the ditch. However, a preliminary design can easily be done using regional design capacity curves and the steady state design procedure outlined below. If necessary, the preliminary design can be fine-tuned later by modeling.

Background information regarding the development of these design guidelines is attached. Review of the background information will be beneficial to determining how well the general guidelines apply in specific situations and how to develop site specific parameters for modeling projects.

Steady State Design Procedure

The steady state design procedure steps can be expected to produce acceptable results when site topography and soils are close to normal for agricultural land in the Red River Basin. Assumed normal would be a curve number of about 73.5, a primary slope of about 5 feet per mile (parallel to the drain), a secondary slope of about 2 feet per mile (perpendicular to the drain), with 2 foot high roads (2 feet above field elevation). Steady state design procedure steps include:

1. Determine the required ditch and culvert design capacity. The design capacity (Qd) can be determined by the equation $Qd = K * A^{0.96-0.02 lnA}$, where A is the drainage area in square miles and K is selected from the Drainage Design Coefficient K map (Figure 2). Design curves for three random K values are shown in Figure 3. The steady state design flow is substantially less than the peak discharge rates predicted by frequency analysis because the design goal is not to carry 10 year peak flows without flooding. The goal is to control the duration of flooding of crop land to 24 hours. Also, the peak flows within the system will exceed the design flow during a 10 year flood, but these flows are moderated by the storage provided upstream from each road crossing and are substantially less than peak flows predicted by frequency based analysis.

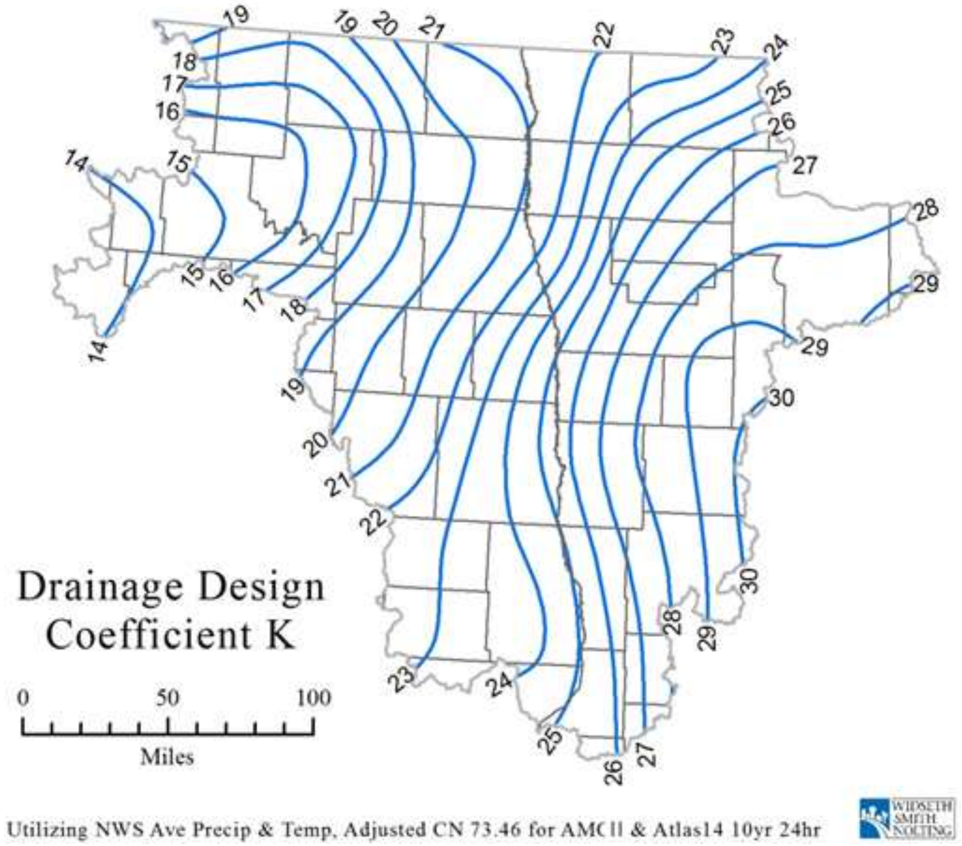


Figure 2. Drainage Design Coefficient K.

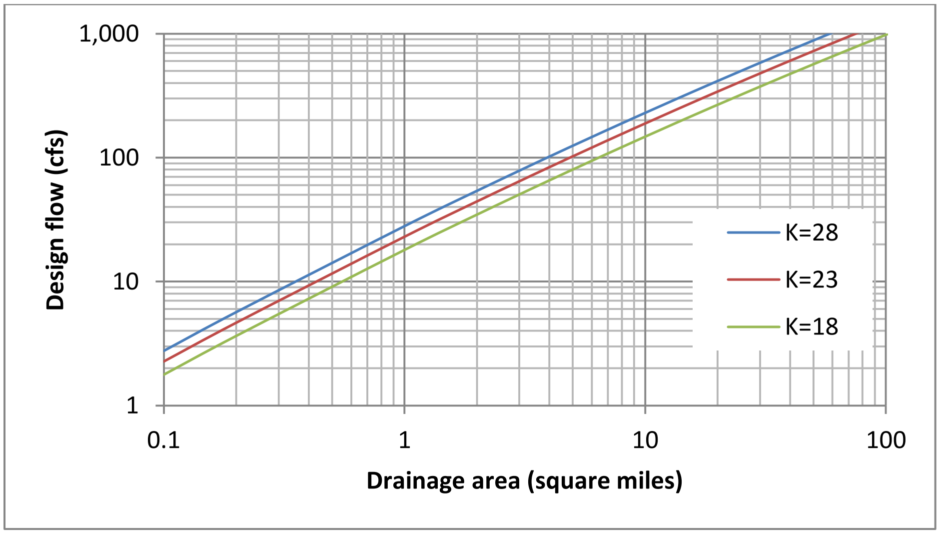


Figure 3. Design Curves for Three Random K Values.

2. Beginning with the downstream reach, and using normal depth analysis, design a channel to convey the design flow about ½ to 1 foot below field elevation (i.e. freeboard) immediately downstream of the next upstream road crossing.
3. Design the culvert at the next upstream road crossing to convey the design flow with about ½ to 1 foot of head loss to match the downstream freeboard provided by the channel design. The resulting water surface elevation (headwater elevation) upstream from the culvert should be at field elevation (note: ½ to 1 foot should work well except where there are very low gradient reaches or where there are closely spaced culverts in series. Then the head loss may need to be less but, regardless, the headwater elevation should always be at the field elevation). Under typical conditions, the result will be about ½ to 1 foot of head loss across the culvert with the downstream water surface profile having ½ to 1 foot of freeboard and the upstream water surface profile having no (or nearly no) freeboard.
4. Design successive upstream reaches and culverts using the same procedure.
5. Include intermediate culverts if they are needed for field access or if necessary to achieve the desired water surface profile. Consider, however, that field access crossings are often too low to provide flow control without overtopping unless field dike work is included. If there is no dike work, excess flows should overtop the field approach rather than break into the field in order to avoid property damage resulting from field erosion.
6. Check the potential for road overtopping. A preliminary 50-year estimate can be determined by the following formula: $Q50 = 2KA^{(0.96- .02\ln A)}$. Check each road crossing to determine if it would overtop at that flow. If so, the road may need to be raised or some other measure may need to be considered to protect the road.
7. Check the storage potential upstream from each crossing. The 50-year flow estimate is based on a minimum storage of about $3 * K$ acre-feet per square mile, distributed throughout the watershed. If that amount of storage is not available, consider raising roads or adding storage at other crossings within sections that have less storage. A desired outcome is that storage is equally distributed and provided by each section of land within the drainage area. However, to some extent, less storage in one section can be made up for by greater storage in another section. Modeling may be necessary to determine optimization. Note that any area which contributes water to the ditch project must also have properly sized culverts to control inflows to the ditch project by providing upstream storage during flood events. Culverts throughout the drainage area, but not along the course of the ditch

that is being constructed, should be checked and resized as necessary to pass design flows using the same methodology or simply with ½ to 1 foot of head loss.

Unsteady Flow Model Design Procedure

When conditions differ significantly from basin normal; typical cropland curve number of about 73.5, a primary slope of about 5 feet per mile (parallel to the drain), a secondary slope of about 2 feet per mile (perpendicular to the drain), with 2 foot high roads (2 feet above field elevation), it may be warranted to develop the final design using unsteady flow models following the procedures outlined below.

1. Using HEC-HMS, or other suitable hydrologic model, develop inflow hydrographs for each subwatershed area within the drainage basin.
    a. Determine the curve number of each subwatershed for Antecedent Moisture Condition II (normal) based on soil types and expected land cover.
    b. Determine an adjusted curve number, based on annual precipitation and temperature, for each subwatershed following the methodology presented in Attachment B.
    c. Apply an appropriate aerial reduction factor for large drainage areas to the point precipitation estimate given by Atlas 14. Aerial reduction factors can be found in TP 40 and TP 49. These may be overly conservative. Reanalysis of the aerial reduction effect is anticipated to be completed in 2016.
    d. Using the adjusted curve numbers and rainfall depths, develop hydrographs representing inflows to the ditch system from each of the subwatersheds where they enter the ditch. Inflows should be developed for the 10 year and 50 year, 24 hour rainfall events and any other events of special interest.
2. Using HEC-RAS, or other suitable hydraulic model, develop an unsteady flow model of the ditch system.
3. Adjust ditch and culvert design to achieve the goals of adequate but not more than adequate drainage during a 10 year, 24 hour rainstorm event.
    a. The duration of backwater flooding on intensively farmed agricultural land should be about 24 hours.
    b. Head loss at culverts should be sufficient (typically ½ to 1 foot) to have a controlling effect during periods of high flow.

4. If necessary, make adjustments to prevent road overtopping during the modeled 50 year, 24 hour rainstorm event.
    a. Raise road. This will both increase culvert capacity and upstream storage capacity.
    b. Add storage capacity at other areas upstream.
    c. Culvert size may be increased as a last resort, but storage loss may need to be made up elsewhere.

Dikes and Trapped Culverts

In general, landowners acknowledge a responsibility to temporarily store their own water during flood events. However, landowners commonly take issue with the idea of storing someone else's water that arrives on their land from upstream locations. A common response to controlling the amount of water that backs out of a ditch system through an open field ditch has been to install trapped culverts (a one-way obstruction installed to prevent water from flowing through the culvert) through ditch spoil banks, dikes, and roads. This practice can be counter to the design guidance methodology because it could result in losing flood plain connectivity. The design guidance is based on the principal of equity, in other words, all landowners have the responsibility to provide their share of flood storage during major runoff events. The intent of the design guidance method is to equally distribute the flood storage responsibility from upstream to downstream so that downstream landowners are not unfairly impacted by upstream drainage.

Open side inlet culverts installed through spoil banks, dikes, and roads can have several beneficial functions. First, they can be sized to control the flow which enters the ditch system. Second, they protect the ditch side slope from erosion. Third, they prevent field erosion by preventing head cutting where water enters the ditch. Lastly, they provide connectivity to the adjacent floodplain through barriers such as spoil banks, dikes, and roads.

Trap gates installed on side inlet culverts can block floodplain connectivity and are therefore counter to this design guidance. Nevertheless, there are special circumstances where the use of trap gates is warranted. One example is where breakout flows near the upper end of a reach wash across a section causing extensive field erosion damage and sediment delivery as the breakout flow reenters the stream near the lower end of the reach. Another example is where the field elevation in a particular location is lower than the design flow elevation. In this case, a trap gate will prevent upstream flows from inundating the low lying field until the design flow is exceeded. Finally, trap gates may be needed to prevent the flooding of nearby structures; however, ring diking the structure is preferred over a trap gate in order to preserve floodplain storage. Great care should be taken to ensure trap gates don't prevent floodplain connectivity for flows that exceed the design flow by designing the elevation of the spoil bank or dike in conjunction with the ditch design so that the spoil bank or dike will be just overtopped during the 10 year design event thereby creating flood plain connectivity during larger events.

If trap gates are used, flood plain connectivity above the 10 year design event can be assured by removing the excess spoil bank immediately upstream of the road crossing at each mile line so that water above the design head water elevation leaves the channel cross-section and goes into storage. In most cases, this will require removing the spoil bank to field elevation for a lineal distance of approximately 50 feet. In some cases, the design flow elevation may be higher than field elevation due to the local topography. In these cases the excess spoil bank would only be removed to the design flow water surface elevation (i.e. some remnant of the spoil bank would remain).

Typical Results of Design Method

Changes in the 10 year, 24 hour (3.6 inch point precipitation) flood hydrograph leaving 1, 8, and 28 square miles are shown in the figures 4, 5, and 6. Peak flows are reduced. Temporary flooding occurs in lower parts of each section, but is of short duration. The results shown in figures 4, 5, and 6 are modeled results of the steady state design method. As shown, the flood duration at 28 square miles is about 34 hours. This is greater than the design goal of 24 hours. This specific ditch design could be improved by adjusting ditch and culvert dimensions within the model to reduce the duration. Consider, however, that the model assumed 3.46 inches of rainfall over the entire 28 square mile basin, which may be conservative.

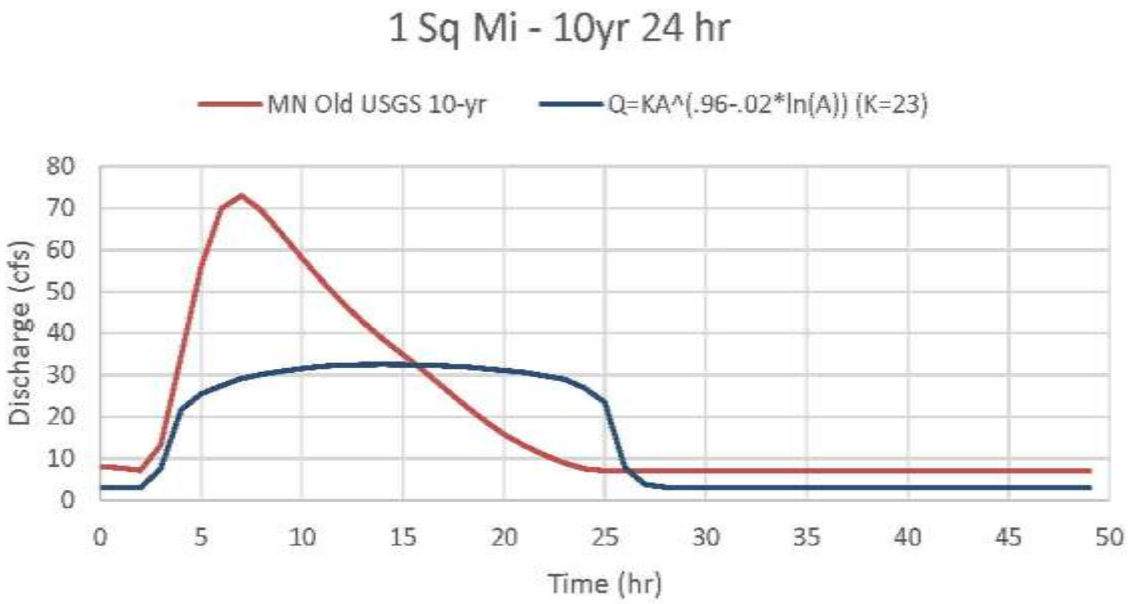


Figure 4. 10 Year 24 Hour Summer Flood @ 1 Square Mile.

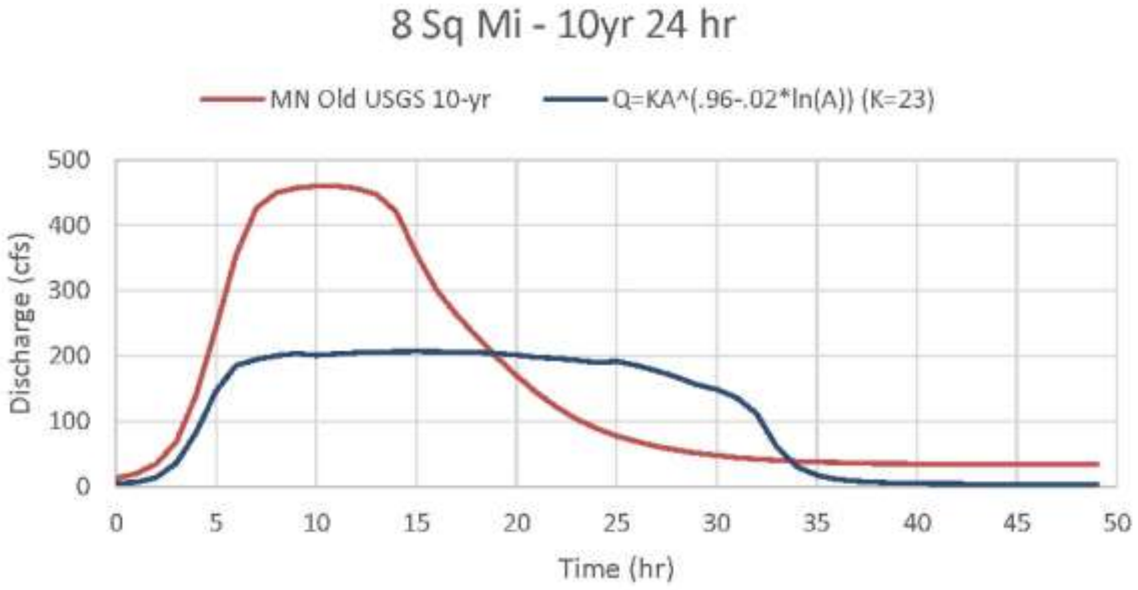


Figure 5. 10 Year 24 Hour Summer Flood @ 8 Square Miles.

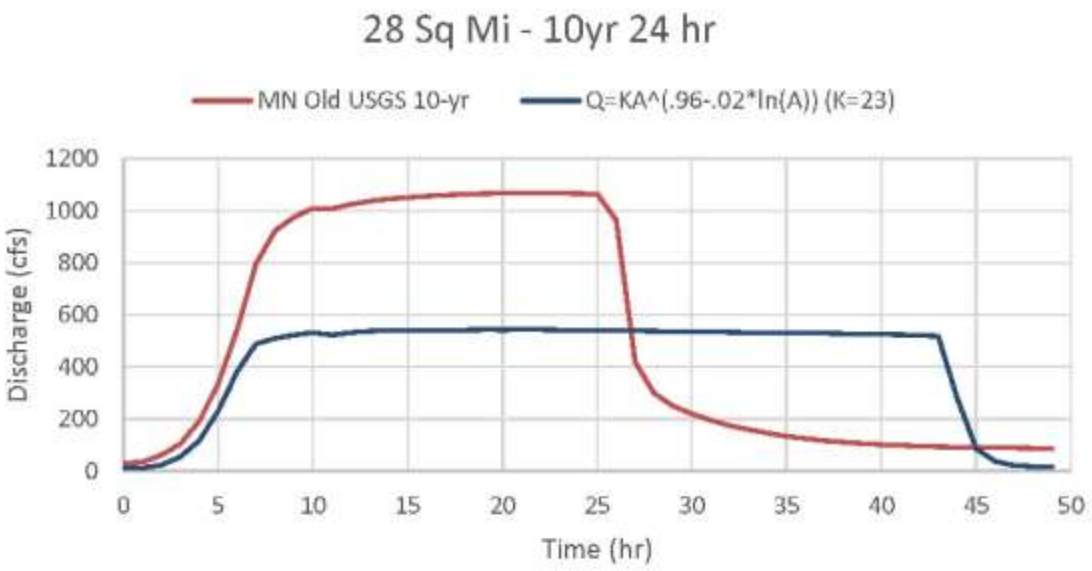


Figure 6. 10 Year 24 Hour Summer Flood @ 28 Square Miles.

The effects on larger floods (50 year and 100 year) is shown in figures 7 and 8. At 5 square miles, peak flow is reduced by 50%. At 25 square miles the peak flow is reduced by 45%. The percent reduction is expected to continue to diminish as drainage area increases.

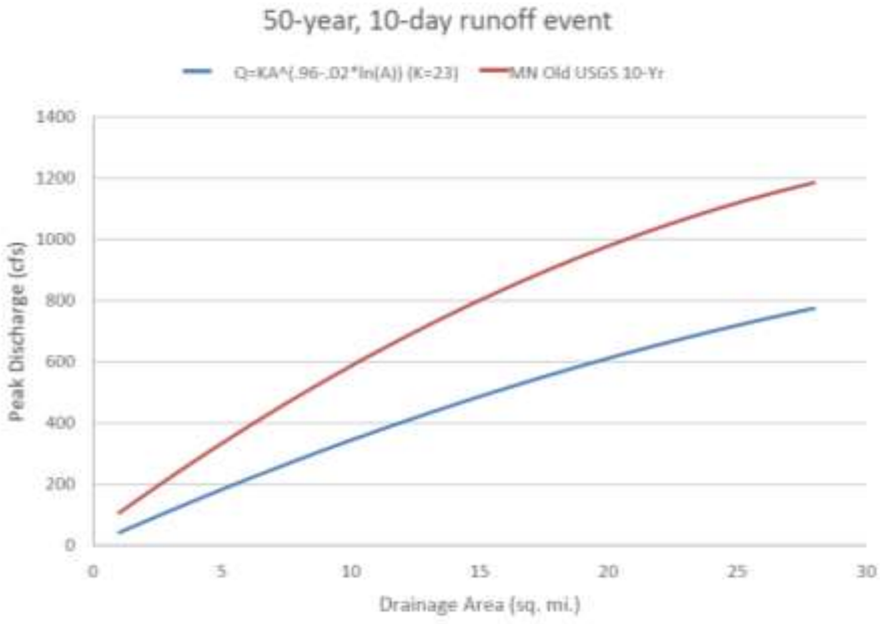


Figure 7. 50 Year 24 Hour Runoff Event.

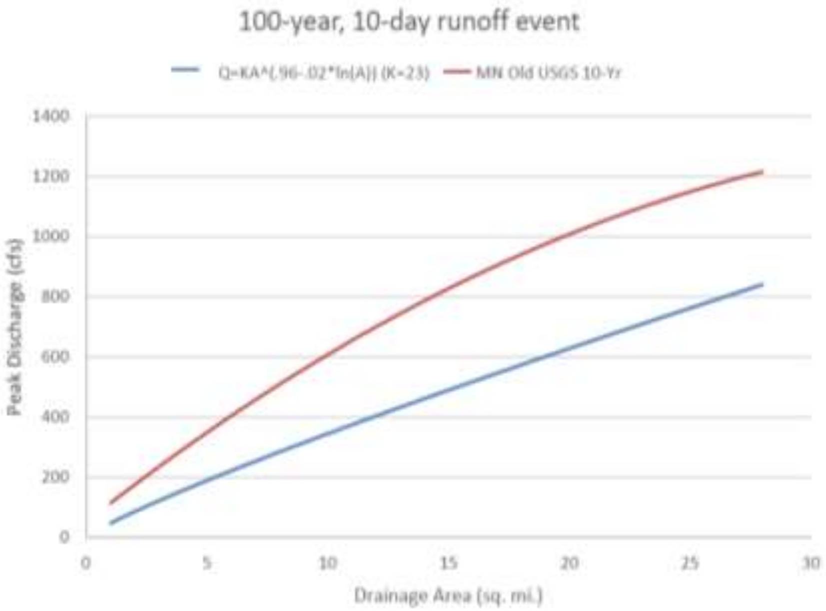


Figure 8. 100 Year 10 Day Spring Runoff Event.

Historic Perspective

While substantially different from frequency based peak flow design, the recommended design guidance capacity is not that different from historic recommendations (Figure 9). Guidance provided by SCS (NRCS) and others has recommended K values of 21 to 27cfs at 1 square mile drainage area in the Minnesota portion of the Red River Basin.

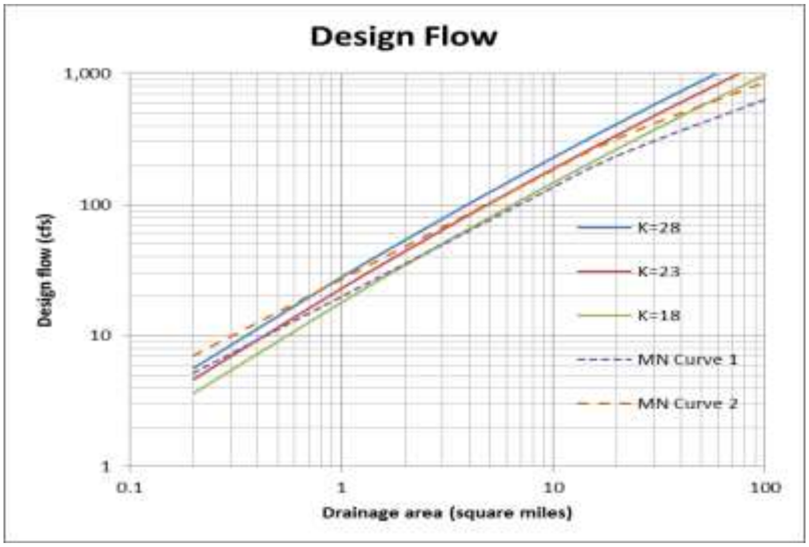


Figure 9. Design Flow/Drainage Area for Comparison.

What is different is the use of culverts to control peak flows during larger runoff events. Soil Conservation Service (NRCS) and others have deferred to highway engineering standards for the sizing of culverts. Certainly, highway safety standards should not be violated by the drainage engineer. But the safety standard can be met by means other than greater culvert capacity. In the case of this guidance, it is provided by controlling flows. The result of which is increased, not diminished, safety of the associated road crossings.

Attachment A: Crop Water Tolerance Literature Review/Summary

Butzen, Steve. Flooding Impact on Crops. Pioneer Hi-Bred Int'l. Online at https://www.pioneer.com/home/site/us/agronomy/crop-management/adverse-weather-disease/flood-impact/[URL accessed July 2014].

Coulter, Jeff, Seth Naeve, Dean Malvick, and Fabian Fernandez. 2014. Considerations for Flooded Corn and Soybean. Minnesota Crop News, Univ of Minnesota Extension. Online at http://blog.lib.umn.edu/efans/cropnews/2014/06/considerations-for-flooded-corn-and-soybean.html [URL accessed July 2014].

Lauer, Joe. 2008. Flooding Impacts on Corn Growth and Yield. Agronomy Advice. Univ of Wisconsin Agronomy Dept. Online at http://corn.agronomy.wisc.edu/AA/pdfs/A056.pdf [URL accessed July 2014]

Malvick, Dean. 2014. Soybean and Corn Seedling Diseases Increase With Flooded and Wet Soil Conditions. Minnesota Crop News, Univ of Minnesota Extension. Online at http://blog.lib.umn.edu/efans/cropnews/2014/06/soybean-and-corn-seedling-dise.html [URL accessed July 2014].

Nielson, R.L. Effects of Flooding or Ponding on Corn Prior to Tasseling. 2014. Corny News Network, Purdue Extension. Online at http://www.agry.purdue.edu/ext/corn/news/timeless/pondingyoungcorn.html [URL accessed July 2014].

Ransom, Joel. 2009. Flooding Impacts Winter Wheat. NDSU Agriculture Communication, North Dakota State Univ Extension Service. Online at http://www.ag.ndsu.edu/news/newsreleases/2009/april-20-2009/flooding-impacts-winter-wheat/ [URL accessed August 2014].

Scott, H.D., J. DeAngulo, M.B. Daniels, and L.S. Wood. 1989. Flood Duration Effects on Soybean Growth and Yield. Agron. J. 81:631-636.

Wiersma, Jochum. 2009. Losses in Wheat due to Flooding and Waterlogging. Minnesota Crop News, Univ of Minnesota Extension. Online at http://blog.lib.umn.edu/efans/cropnews/2009/06/losses-in-wheat-due-to-floddin.html [URL accessed August 2014].

Excerpts

Corn

- Young corn can survive flooded condition lasting for about 2 days under warm temperatures (at or above mid-70^{0}F) to 4 days under cooler temperatures (at or below mid-60^{0}F).

- Corn younger than about V6 is more susceptible to ponding damage than is corn older than V6.

- Corn plants should show new leaf development within 3 to 5 days after water recedes.
- Surface crusts forming as the soil dries increases the risk of emergence failure for recently planted crops.
- Deposition of mud or crop residues on plants as the water subsides can reduce photosynthesis and can encourage the development of fungal and bacterial diseases in damaged plant tissue.
- Flooding and saturated conditions also restrict root development, thereby reducing the crop's ability to take up water and nutrients and tolerate drought stress later in the season.
- Nitrogen loss will occur in fields where N from fertilizer or organic N from the soil was present in nitrate form before the soils became excessively wet.
- Water saturated conditions in fine-textured soils cause N loss through denitrification and can lose as much as 5% per day when the soils remains saturated with water under warm soil conditions.
- Prolonged periods of wet soil conditions favor the development of seedling blight diseases in young corn seedlings caused by *Pythium* fungi.
- Diseases such as common smut and crazy top may also become greater due to flooding and cool temperatures.

Soybean

- Soybean is generally sensitive to excess water but the most important factors related to survival include duration of flooding, temperature during the flood, rate of drying after the flooding event, and growth stage of the crop during the flood.
- Yield losses seldom noted in fields flooded for 48 hours or less; however 4 days or more of flooding stresses the crop, delays growth, and causes the plant to be shorter with fewer nodes.
- Higher temperatures during flooding cause the plant to deplete stored energy more quickly.
- Flooded clay soils results in greater yield reductions than silt loam soils when flooded for the same period of time.
- Flooding is more detrimental during reproductive phases of development.
- Indirect effects of flooding include root diseases, N deficiency, and other plant nutrient imbalances.
- Prolonged periods of wet soil conditions can damage soybean seedlings or start infections in the early summer caused by root rot *(Phytophthora)*.

Wheat

- Flooding and waterlogging leads to a depletion of oxygen from the root zone which affects several physiological processes related to uptake of water, transport of nutrients, and root/shoot hormone relations.
- Wheat can tolerate 3 to 4 days of flooding and/or waterlogged soils before grain yield is impacted negatively as long some of the leaves are above the water level.
- Higher temperatures increase the risk of crop damage.
- Extended periods of waterlogging reduce leaf elongation, kernel number, and subsequent grain yield.
- Yield losses of 20 to 50% are reported in the literature when waterlogging occurs for more than 10 days.
- Differences exist among different wheat varieties in waterlogging tolerances possibly due to the ability of the variety to initiate adventitious roots of the first node.
- Data on the effect of flooding on winter wheat when ambient temperatures are below 40 degrees Fahrenheit is limited however the effects described above under midsummer conditions take longer to impact plant tissues.

Sugar Beet

After an extensive literature search, little if any data or information was readily available for water tolerances of sugar beets in the Red River Valley. However, information exists for sugar beet water needs during the growing season in irrigated settings in Idaho, Michigan, Montana, and Nebraska. The following information is relevant to the Red River Basin:

- Too much water can result in root rot when soil temperatures are high and plants are exposed to saturated soils for several days due to lack of oxygen movement into root tips. This can occur in low areas of fields where water stands in shallow depths for extended periods of time.
- Foliage wilts can occur suddenly and/or permanently, and the sugar beet taproot will disintegrate. Rotted roots also may have a fermentation odor, which is also due to lack of oxygen in the soil surrounding the root zone.
- Root diseases often result from extreme or heavy rainfall. Diseases can include *Aphanomycetes*, *Rhizoctonia* or *Pythium*. Excess soil moisture and damaged roots allow the disease a pathway to enter into the sugar beet.
- Sugar beets damaged from heavy rainfall will often exhibit stunting, yellowing and an increase in root diseases. High intensity rainfalls are damaging to young crops and in addition, high temperatures associated with excess moisture increases crop damage.
- When conditions are too wet, a condition called "sprangling" occurs. The result is the sugar beet being on top of the ground or soil in the row. Because of this condition, defoliating equipment will knock the sugar beet out of the row and reduce the efficiency of the harvest equipment.

Attachment B: Uniform Drainage Design Guidance Parameters

Drainage Design capacity formula

The drainage design capacity formula takes the familiar form:

$$Q_d=KA^X$$

Where:

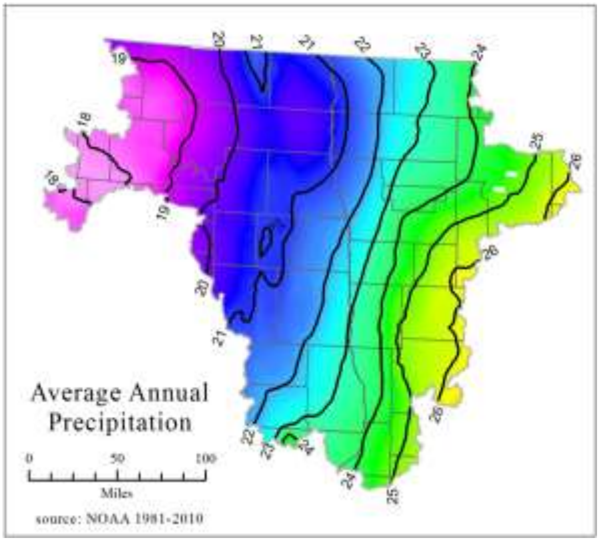
- "Q_d" = the drainages system design flow in cubic feet per second (cfs).
- "A" = the drainage area in square miles.
- "K" = the parameter that is equivalent to the design flow (cubic feet per second) at one square mile. It is directly proportional to the drainage coefficient (DC) (K=26.89*DC)
- "X" = the parameter that reduces the flow per square mile as drainage area increases.

Determine K

The Basin Technical and Scientific Advisory Committee (BTSAC) goal is to provide equal event protection at any location within the basin. Therefore, K needs to reflect differences across the basin in both event rainfall amount and antecedent moisture condition. Event rainfall amounts tend to increase from northwest to southeast. Antecedent moisture tends to increase from west to east. Other topographic and soil variations may also need to be factored in. The following analysis assumes typical or average basin topography and soils.

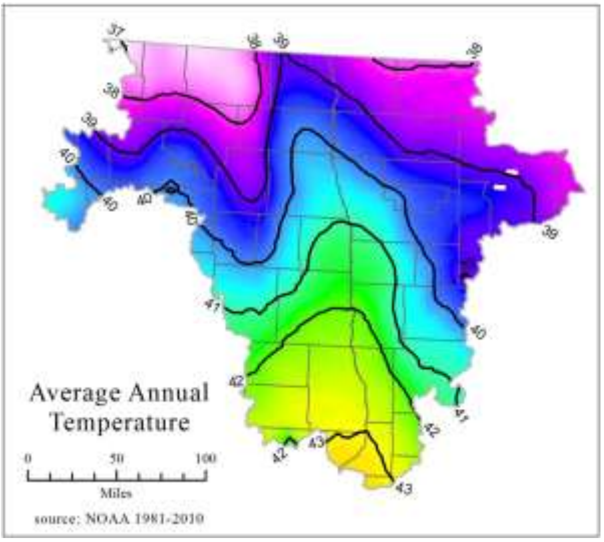
Antecedent moisture condition is not a measured variable. There are no available data to directly estimate an antecedent moisture condition. Although not directly calculated, spatial variation of antecedent moisture condition can be inferred by considering other climate-related variables that are measured such as runoff, precipitation, and temperature. Spatial variation in antecedent moisture conditions should also rely on engineering judgment and experience provided by over 100 years of basin drainage with observations of what works well and what doesn't.

The Natural Resources Conservation Service (NRCS) and the United States Geological Survey (USGS) periodically publish runoff maps based on measured stream flows. However, there is currently no method to regularly update runoff maps to reflect changing conditions. Even if regularly updated runoff maps were created by NRCS and USGS, it is not obvious that they would be appropriate to use in estimating runoff from agricultural lands since the measured flows would also reflect evaporative losses from lakes and wetlands and the influence of other non-agricultural land uses. Therefore, the runoff estimates used in developing the drainage design curves are based only on precipitation (Figure 1) and temperature (Figure 2). Average annual precipitation for the period 1981-2010 varied from a low of about 18 inches in the west to a high of about 26 inches in the east. Average annual temperature over the same period varied from a low of about 37 degrees in the north to a high of about 43 degrees in the south.



source: NOAA 1981-2010

Figure 10. Average Annual precipitation.



source: NOAA 1981-2010

Figure 11. Average Annual Temperature.

The Soil Conservation Service (Natural Resources Conservation Service) Curve Number method is used to estimate runoff. The average curve number for the US portion of the Red River Basin is 74.51. The average curve number for agricultural land in the basin is 73.46.

The curve number used to estimate storm runoff needs to be adjusted to reflect different antecedent moisture conditions. The SCS (NRCS) "National Engineering Handbook, Section 4 – Hydrology (NEH4)" describes three antecedent moisture conditions: wet, normal, and dry. The effective curve number of these three relative conditions is depicted in Figure 3. An adjustment to curve numbers that reflects relative dryness across the Red River Basin can be made using the following formula (note that this formula is based on experience and judgment of water resource engineers in the Red River Basin. There is no mathematical derivation of the formula):

$$CNadj = \frac{P}{25} * \frac{43}{T} * (CN\ II - CN\ I) + CN\ I$$

Where:

- *CNadj* = AMC adjusted Curve Number
- *CN II* = Curve Number for Antecedent Moisture Condition II (normal)
- *CN I* = Curve Number for Antecedent Moisture Condition I (dry)
- *P* = Average Annual Precipitation (inches)
- *T* = Average Annual Temperature (degrees Fahrenheit)

For the basin average curve number for agricultural land of 73.46, CN I = 54.46, the equation can be reduced to:

$$CNadj = 32.68 * \frac{P}{T} + 54.46$$

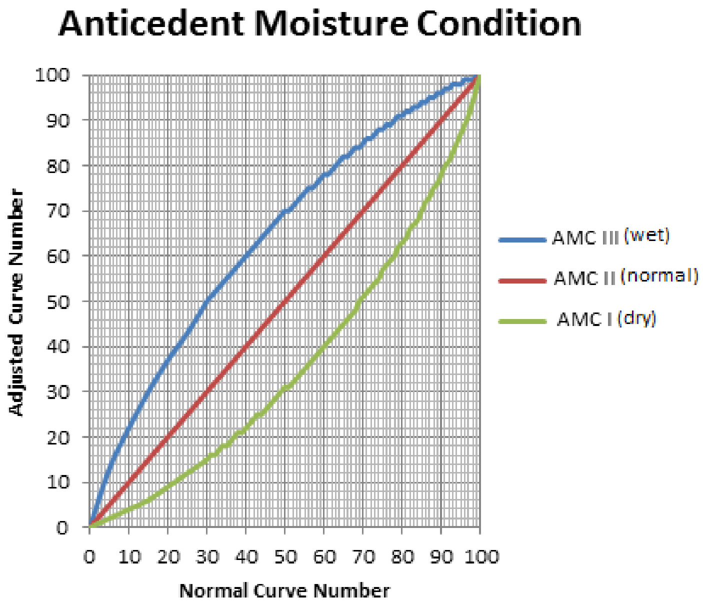


Figure 12. Curve Numbers of Three Relative Conditions.

The estimated 10-year-24-hr rainfall, based on National Oceanic and Atmospheric Administration Atlas 14 (Atlas 14), varies from about 3 inches in the northwest to about 3.75 inches in the southeast (Figure 13). Applying Atlas 14 rainfall and using the Adjusted Curve Numbers results in the 10 year 24 hour runoff (Figure 14).

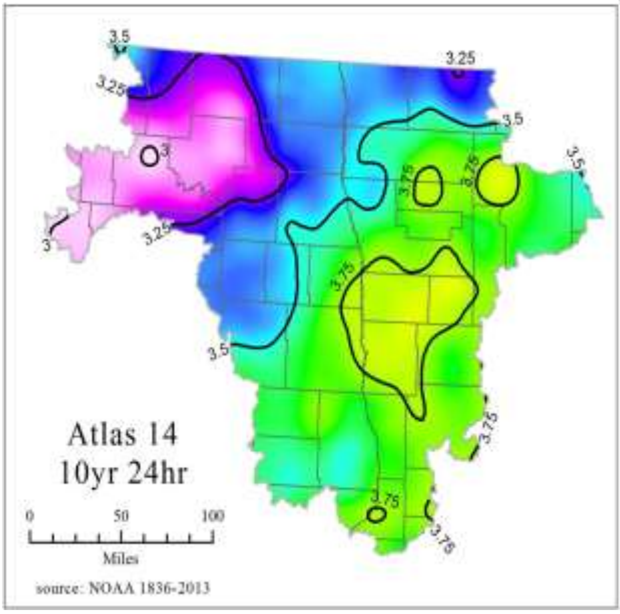


Figure 13. 10 year, 24 hour Rainfall.

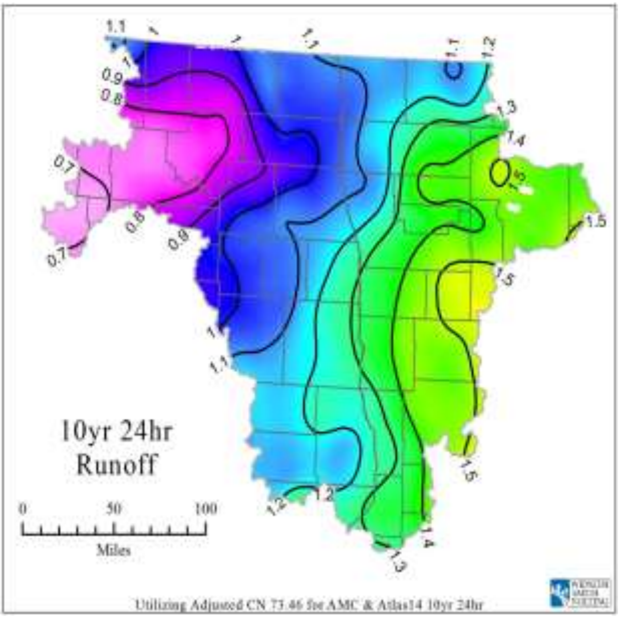


Figure 14. 10 year, 24 hour Runoff.

K should vary in direct proportion to the runoff amount. The HEC-HMS models used to develop runoff hydrographs were based on a 10 year, 24 hour rainfall depth of 3.6 inches and Curve Number 75 developing 1.37 inches of runoff. The HEC RAS models used to evaluate ditch design methods show that, with drainage coefficient (DC) =1 inch/day, the goal of 24 hour inundation is met. A DC of 1 is equivalent to a K of 26.89. Therefore, the resulting distribution of K drainage design coefficient (Figure 6) can be determined by the following equation:

$$K = 26.89 * \frac{R}{1.37}$$

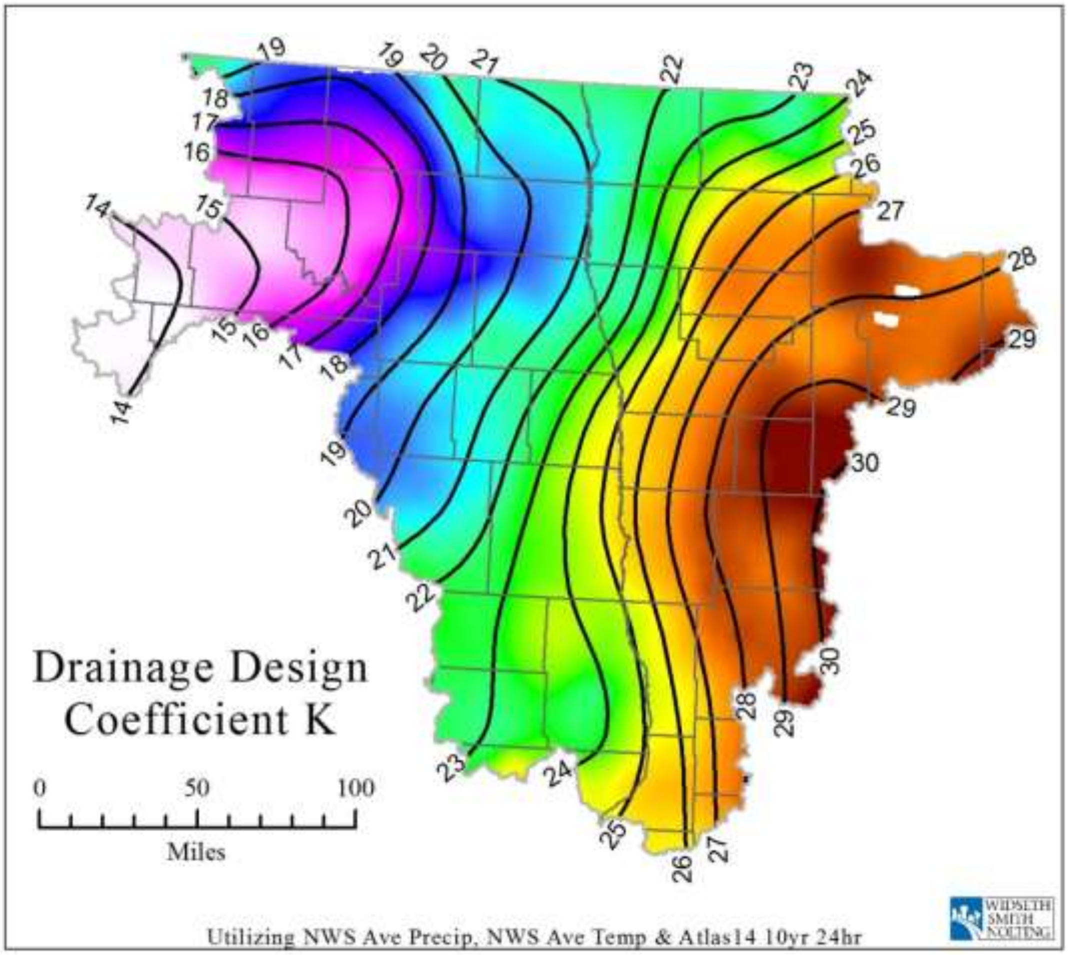


Figure 15. RRB Drainage Design Coefficient K.

<u>Determine "X"</u>

"X" should be reduced as drainage area increases to reflect aerial reduction from point precipitation given in Atlas 14 and the effect of travel time, both of which are related to the size of the drainage area. Aerial reduction from point precipitation and the effect of travel time may also be related to shape and orientation of the drainage area, but this can only be accounted for on a specific project basis. Most regression derived equations for peak flow have "X" values ranging from about 0.6 to 0.8. Drainage design modeling of 28 square mile hypothetical drainage area suggests 0.90 to 0.96. Below is the formula determined for "X" (note that this formula is based on a curve fitting analysis that reasonably matches model derived results for small drainage areas and 10 year flood flows of large watersheds) and the relationship of "X" to drainage area (Figure 7):

$$X = 0.96 - .02(\ln A)$$

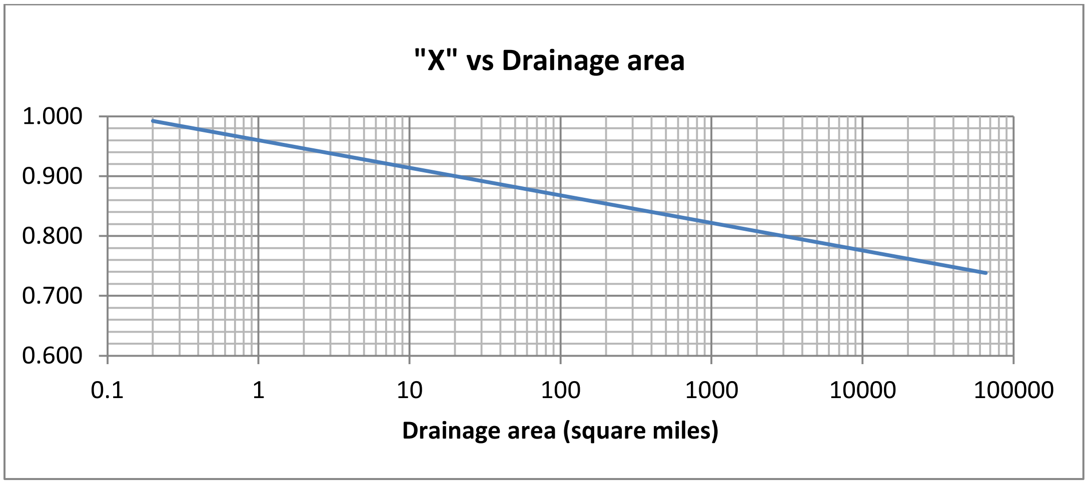


Figure 16. Exponent "X" Varies with Drainage Area.

Resulting Design Capacity Curves

The resulting regional equation for surface drainage design capacity is used to develop regional design flow curves (Figure 8):

$$Q_d = KA^{.96 - .02(\ln A)}$$

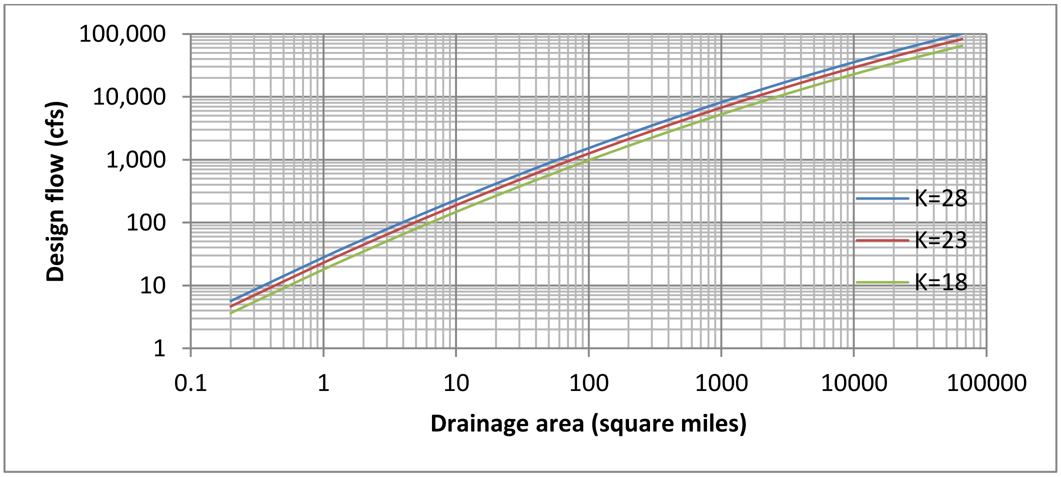


Figure 17. Drainage Design Discharge Curves.