Culvert Sizing
for Flood Damage Reduction

Phase 1 – Preliminary Guidelines

Red River Basin Flood Damage Reduction Work Group
Technical and Scientific Advisory Committee
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Purpose

Technical and Scientific Advisory Committee (TSAC) Technical Paper No. 11, "Red River Basin Flood Damage Reduction Framework" (May 2004) identifies a number of measures for increasing temporary floodwater storage to reduce downstream flood damages. Culvert sizing is one of these measures. Technical Paper No. 11 provided limited guidance for implementation of culvert sizing. The purpose of this technical paper is to provide more detailed culvert sizing guidelines for flood damage reduction and prevention in the Red River Basin.

Phased Process for Development of Guidelines

In order to systematically develop and test guidelines for culvert sizing, the TSAC recommended the following 3-phase process.

Phase 1: Develop preliminary guidelines based on: 1) modeling of a hypothetical watershed that is representative of average conditions in the Red River Basin; 2) applicable experience to date in the Red River Basin and; 3) TSAC analyses and deliberations. Invite a representative of MnDOT to participate in TSAC deliberations and development of preliminary guidelines. This phase includes sensitivity analyses of some key variables affecting culvert sizing including average land slopes, duration of temporary storage and hydrologic design methods.

Phase 2: Use preliminary guidelines to size culverts for one or more existing drainage areas within the Red River Basin having representative characteristics and test the results by modeling. Validate, revise or clarify guidelines, as appropriate.

Phase 3: Assist a watershed district to apply culvert sizing guidelines to a proposed pilot project and monitor the results. Further verify, revise and/or clarify the guidelines, as appropriate.

This technical paper presents the Phase 1 hypothetical modeling results and includes preliminary guidelines for culvert sizing in the Red River Basin.

Definition and Purpose of Culvert Sizing

Culvert sizing is the design of conduits through road embankments to help manage runoff timing and peak flows within a drainage network. Culvert sizing provides short-term temporary storage within channels and on adjacent lands upstream from road crossings. It is most applicable for small drainage areas (up to approximately 30 square miles).

The purpose of culvert sizing is to reduce or prevent flood damages by better utilizing distributed temporary storage and the metering of runoff, without causing a significant increase in the risk of flood damage where runoff is temporarily stored. Culvert sizing not only reduces downstream flood peaks, it also provides a more uniform level of flood protection within a drainage system. This flood damage reduction and prevention measure typically will result in smaller culverts and bridges, thereby reducing associated costs. Culvert sizing is best implemented through a subwatershed design approach (all culverts sized at the same time, within a subwatershed). However, it can also be implemented through an incremental approach (one road crossing at a time), using appropriate design considerations.

Culvert sizing is similar to the Waffle® Plan in that both techniques utilize temporary storage upstream of road embankments. However, these techniques are different in that the duration of temporary storage resulting from culvert sizing (24 to 48 hours) typically is much shorter than for the Waffle® Plan, operation is automatic (ungated), and no additional land rights acquisition is typically envisioned for culvert sizing.

Why Culvert Sizing is Important

Miles of Drainage Systems and Numbers of Culverts and Bridges

Minnesota has more than 21,000 miles of channelized streams and publicly administered drainage ditches (Surface Hydrology of Minnesota, MDNR). There are also tens of thousands of miles of natural watercourses and private drainage ditches in Minnesota, as well as untold miles of roadside ditches. These watercourses provide agricultural, urban, and transportation infrastructure drainage, as well as local flood control. Most, if not all, of these watercourses intersect the vast network of local, state, federal and private roadways. A culvert inventory conducted by the Bois de Sioux Watershed District in Eldorado Township of Stevens County and Dollymount Township of Traverse County identified 799 culverts and bridges within these two adjacent townships. This represents an average of 10.5 culverts per square mile. This example includes field access roads and driveways, not all of which have temporary storage potential. However, it serves to illustrate the substantial potential to affect both peak flows and structure costs through culvert sizing.

Current Design Methods

The primary hydraulic design standards currently used for culverts and bridges are based on risk assessment at individual crossings to minimize adverse impacts of road overtopping and other potential damages associated with stage increases. Common practice may also consider maintaining at least as much flow capacity as currently exists and/or providing flow capacity based on the peak flow for a selected flood frequency and maximum allowable head loss through the culvert or bridge. These design methods typically do not consider temporary storage upstream from the culvert or bridge.

The current design method used for many drainage ditches is also based on flood frequency, or peak flows computed as a generalized function of drainage area and other factors. Typical design flood frequencies for drainage ditches are 5 to 10 year events. Larger capacity is generally considered better, to the extent that the costs can be justified and the outlet of the associated drainage system can be considered adequate. This design method also does not consider temporary storage upstream from culverts and bridges.

As a result of these design methods, there often is a reduction of temporary storage in drainage systems, particularly in the upstream reaches. The associated acceleration of runoff can result in higher peak flows downstream and unequal levels of protection along the length of drainage systems. Problems tend to show up near the confluences of drainage systems and at locations where there is an abrupt reduction in slope. Flooding in these problem areas initiates a trend toward the need for larger flow capacities downstream, or other measures, to reduce flood damages.

Since 1977, the USGS has periodically developed regression equations for estimating the magnitude and frequency of floods for small watersheds in Minnesota, based on stream gaging records. The resulting estimates of peak flow in the Red River Basin for a given flood frequency have increased over time. Figure 1 illustrates the results of the 1977, 1987 and 1997 USGS regression equations for a 10-yr. event at a location without upstream lake or wetland storage. The peak flow increase may have been caused in part by current drainage ditch and conduit design methods, trends in precipitation and/or land use changes that increase runoff. Because the USGS regression equations are often used for culvert, bridge and drainage channel design, there tends to be a continuation of the trend toward increased flood peaks over time.

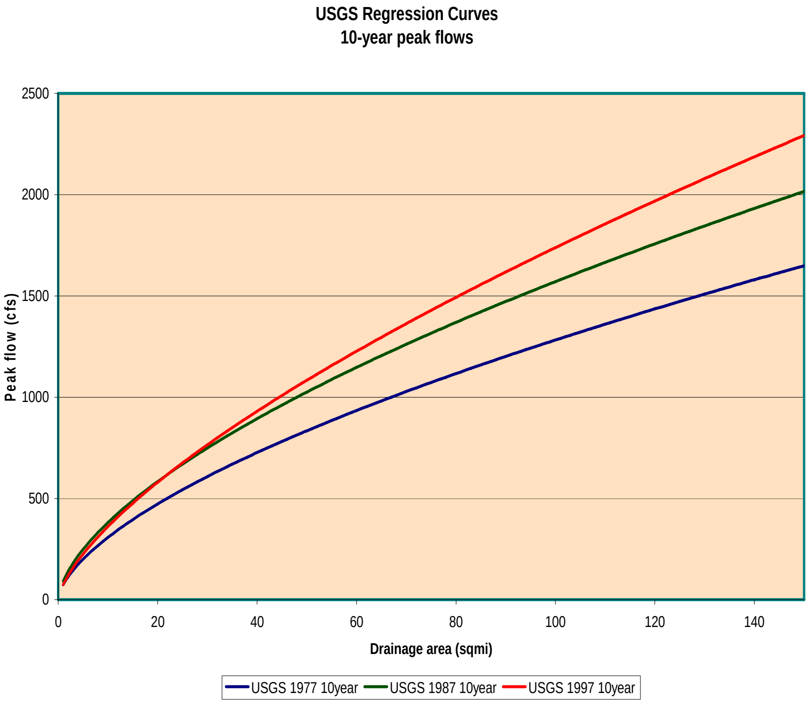

Figure 1. USGS – Peak Flows for Small Watersheds in Minnesota

Ongoing Drainage System Improvements

Although much of the land in Minnesota has substantial artificial drainage to enable or enhance crop production, protect road embankments and convey urban runoff, drainage systems in Minnesota are not fully developed. Drainage continues to be improved and expanded. Surface drainage channels and culverts are often designed using the methods discussed above, which result in larger capacities than for design methods used in previous periods. Therefore, the future without culvert sizing is expected to involve increasing channel and culvert sizes. This trend will lead to additional loss of temporary storage and increased peak flows downstream. Culvert sizing provides one way to maintain or increase distributed temporary storage within drainage systems for flood damage reduction and prevention.

Predominance of Small Drainage Areas

Natural and artificial drainage systems typically are dendritic (i.e. branching). This results in many more low stream order, or headwaters, miles of watercourses than higher stream order, or mainstem, miles. As a result, there are many more small drainage areas (subwatersheds) than large drainage areas (watersheds or basins). Figure 2 illustrates the number of subwatersheds in the Mustinka River watershed having less than 5 square miles, 5 to 15 square miles and greater than 15 square miles of drainage area. Increased metering of runoff from many subwatersheds can add up to a large metering effect at the watershed and basin scales.

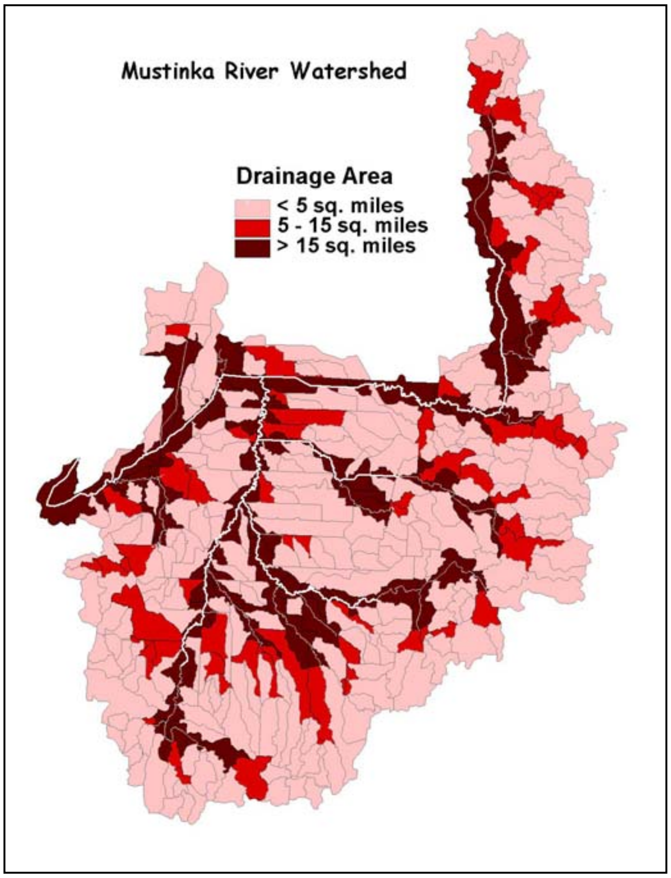

Figure 2. Mustinka River Subwatershed Sizes

TSAC Technical Paper No. 11 indicates that culvert sizing is most effective at achieving Red River mainstem peak flow reduction benefits in addition to local benefits when implemented in the “middle” and “late” runoff timing areas relative to the main stem. Within “early” runoff areas relative to the main stem of the Red River, culvert sizing might have a negative effect on mainstem flood peaks, due to the delayed timing effects of short-term storage. However, culvert sizing could help to provide the local benefit of more equitable levels of drainage and flood protection within these areas. Note that culvert sizing in conjunction with drainage improvement may be a way to prevent a potential increase in downstream flood peaks associated with an improvement.

Opportunities to Reduce Road Overtopping and Washouts

Road overtopping for extended periods of time, and associated washouts, are often major components of flood damage. Although culvert sizing (typically downsizing) might appear to increase the potential for road overtopping and associated flood damages, better utilization of distributed temporary storage in the many headwaters areas of drainage systems can reduce the overall potential for road overtopping within a drainage system. Culvert sizing is also expected to provide overall cost reduction for culverts.

Guiding Principles for Culvert Sizing

The following guiding principles were utilized to develop preliminary culvert sizing guidelines:

- risk to highways should not exceed current standards in terms of safety and maintenance;
- risk to developed properties upstream of road crossings should not exceed accepted standards;
- benefits of drainage should be equitable throughout the drainage system;
- the drainage system should detain water in excess of downstream channel capacity, to the extent practical;
- the responsibility to temporarily store excess water on cropland should be uniformly distributed throughout the drainage system, to the extent practical;
- detention of water on cropland for most rainfall events should be no longer than 24 to 48 hours to avoid crop damage;
- the recommended design methodology should be easy to apply, yet comprehensive enough to provide safe roads and an equitable and effective drainage system; and
- guidance should provide an incremental approach to implement culvert sizing one site at a time, in addition to a subwatershed approach, and provide for transitioning from the incremental approach to the subwatershed approach over time.

Hydrologic and Hydraulic Design Methods and Flood Damage Considerations

It has been customary in bridge and culvert design to treat hydrology and hydraulics independently. First the flow rates are estimated using one or more of several accepted hydrologic methods. Second, the bridge or culvert is designed to pass that flow within one or more of several hydraulic design criteria, such as a maximum head loss (increase in water level / stage) and/or maximum flow velocity. This approach assumes that the bridge or culvert will have no effect on flow rates. This is only true if the bridge or culvert is so large that it does not cause any increase in water level on the upstream side. As a practical matter, there is always some stage increase. But if the stage increase does not result in a significant increase in upstream storage, the reduction in flows will be negligible. In traditional road design, negligible effect on hydrology is considered a desirable outcome. Therefore, the assumption of no significant effect on flow rates is not unwarranted for this design approach.

Culvert sizing takes an opposite design approach. The culvert is expected to have an effect on stage and temporary storage and the resultant peak flow reduction is a desired outcome. The goal is to reduce the peak flow as much as possible without causing significant damage. This is achieved by providing short-term storage of water in the channel and on the land upstream from the road crossing.

This approach requires a good understanding of potential flood damages and how best to address them. In rural agricultural areas, potential damages fit into four general categories:

1. crop or other vegetation damages,
2. erosion and sedimentation damages,
3. damage to roads (including safety issues), and
4. damage to buildings and contents.

Crop damage is primarily related to the duration of flooding. Most crops can tolerate inundation for 24 to 48 hours. Therefore, the design criteria for agricultural drainage should relate to an average flow rate over a comparable time period, rather than to instantaneous peak flows as currently used in many drainage ditch designs and most culvert designs. This is exactly the approach used in subsurface tile drainage design, for which capacity is stated in terms of a drainage coefficient, or removal rate, the units of which are inches of runoff removed per day. Commonly used subsurface drainage coefficients are 1/8 to 1/2 inch per day. Similarly, surface drainage (i.e. agricultural open ditch) design curves with a long record of use in the Red River Basin (NRCS Minnesota Drainage Guide Curves 1 and 2) are equivalent, at one square mile, to a drainage coefficient of ¾ inch and 1 inch per day, respectively. By comparison, regression equations commonly used to estimate design flows for culverts are based on peak flows and would be equivalent, at one square mile, to a 5-inch drainage coefficient. This is obviously a more rapid removal rate than required to avoid crop damages associated with duration of flooding.

Erosion and sedimentation damages are generally related to high flows. In particular, severe field erosion is often associated with out-of-bank flows, particularly breakout flows downstream from road crossings. Out of bank flows occur when channel capacities are exceeded. To avoid overloading the downstream channel, culverts through road crossings can be used to restrict flows to more closely match channel capacity. Temporary out of bank storage created by culvert sizing is backwater that gradually moves into and out of storage with low velocity that typically is not erosive. If channel capacities are much less than recommended by culvert sizing guidelines (i.e. have a drainage coefficient less than ¾ inch per day), consideration should be given to increasing channel capacity.

Road damages are primarily related to peak flow. If peak flows are high enough to cause the road to overtop, traffic is disrupted and road washouts can occur, creating significant safety issues and substantial repair costs. Rapid washout can quickly release temporary storage causing even higher peak flows and potentially initiating a domino effect of road washouts downstream. A common response to road washouts has been culvert replacement with a larger capacity, based on the premise that overtopping proves that the culvert is too small. However, there are three other equally likely causes of overtopping. First, the road may be too low, not allowing culvert capacity to fully develop before overtopping occurs. Second, there may be an inadequate amount of temporary storage upstream. Third, the outlet channel may be too small. Storage capacity can be increased at the site by raising the road. However, the problem may be a lack of temporary storage farther upstream. This is one of the risks associated with culvert sizing done on an incremental basis. Until culverts upstream have been properly sized to provide enough distributed storage, flow at downstream culverts may remain high. It may be necessary, particularly on heavily traveled roads, to include measures to protect against damages. This might be accomplished by including an armored overflow section or a two-stage culvert inlet that would allow a major increase in capacity as the water level approaches the road elevation.

Damage to buildings (typically farmsteads) is primarily related to peak stage. If there are buildings upstream from a road crossing, their vulnerability to flooding if the culvert is downsized must be evaluated. A common method of providing protection is to set the road overtopping elevation (potentially with an armored overflow section) below the building elevation, thereby providing a positive relief mechanism. If that is not practical or acceptable, a higher capacity two-stage culvert design may be considered. In some cases, it may be more practical at these locations to simply use a larger culvert even though this may give up some temporary storage capacity. In the Red River Basin, ring dikes are often constructed around vulnerable building sites to protect against peak flood stage. This practice can assist the implementation of culvert sizing.

Culvert Sizing Experience to Date in the Red River Basin

Culvert sizing as a technique to increase distributed temporary storage and control downstream peak flows has been applied in various ways in several watershed districts in the Red River Basin. In 1987, the Red Lake Watershed District developed "normal culvert sizing guidelines for agricultural areas". These guidelines are based on a 1-inch drainage coefficient and have been used by the watershed district in its permitting program for bridges and culverts.

The Middle-Snake-Tamarac Rivers Watershed District has used culvert sizing in managing legal drainage systems under its jurisdiction. Flows are controlled both entering and within the ditch system by providing culvert capacity related to ditch design capacity.

The Bois de Sioux Watershed District has required flow control as a condition of drainage improvement permits since 1989. The applied standard has been a 1-inch drainage coefficient. The required flow control has typically been provided by culvert sizing at downstream road crossings. Permit applicants have generally accepted flow control as a reasonable tradeoff for drainage improvements that might otherwise adversely impact their downstream neighbors. Road authorities have been cooperative in assisting landowners in implementing flow control. The District's culvert sizing guidelines have become a standard of fair and reasonable use often referred to in local dispute resolution. Interestingly, there have been no documented instances of significant damages associated with the adoption of this standard.

The Two Rivers and Roseau River Watershed Districts have both used a 1-inch drainage coefficient as a standard in reviewing permit applications since 1996.

Modeling of Hypothetical Drainage Systems

General

Unsteady flow models were developed for two hypothetical drainage systems to help develop and evaluate preliminary culvert sizing guidelines, using the U.S. Army Corps of Engineers Hydrologic Engineering Center – River Analysis System (HEC-RAS) model. Use of hypothetical drainage systems simplified the modeling effort and eliminated the need to obtain field data for this phase of guidelines development. Detailed descriptions of the models and results are presented in Appendix A.

The first hypothetical watershed consisted of a main ditch with three branches, having a total watershed area of 28 square miles. This model was based on a topographic slope of 5 ft./mile from east to west and 2 ft./mile from south to north and assumed that the drainage ditches were along the north and west sides of sections with culverts in the northwest corners. This watershed model was used to begin the development and testing of preliminary guidelines. The second hypothetical watershed model consisted of a single reach with a total drainage area of 10 square miles. This model was used to test the impact of varying the topographic slope and the ditch size. Four scenarios were simulated using the 28 square mile watershed model:

1. **Future conditions without culvert sizing.** This scenario models the effect of applying current commonly used peak flow design criteria for ditches and culverts in the watershed.
2. **Future conditions assuming no overbank flooding.** This scenario models the effect of containing all flows within the ditch. It illustrates the impacts on peak flows of achieving the 1998 Red River Basin Mediation Agreement goal of providing 10-year flood protection to prime agricultural lands by utilizing only conveyance improvements. This represents a worst-case future scenario for peak flows.
3. **Future conditions with culvert sizing.** This scenario models the effect of sizing ditches and culverts to achieve temporary out-of-channel storage upstream from roads for a maximum of 24 hours for the 10-yr., 24-hr. storm event. Road overtopping potential was evaluated for the 50-yr. event. The performance standards also included preventing out-of-channel flow at the upstream end of 1-square mile sections for up to the 50-yr. event, to avoid the potential for associated field erosion. This model was also used to evaluate the effects of temporary out-of-channel storage for up to 30 hours. The results of this 30-hour scenario were used to develop preliminary culvert sizing design guidelines.
4. **Future conditions using preliminary culvert sizing guidelines.** This scenario tested the effects of applying the preliminary design guidelines.

Four additional variations were evaluated using the 10 square mile watershed model:

1. Main channel slope = 5 ft./mile;
2. Main channel slope = 10 ft./mile;
3. Main channel slope = 2 ft./mile;
4. Main channel slope = 5 ft./mile with smaller ditch size.

For all scenarios, both the 10- and 50-yr., 24-hr. storms were evaluated. The 50-year, 10-day event was evaluated for scenarios 1, 3 and 4.

Summary of Key Findings

1) Using culvert sizing to create temporary storage of runoff upstream from roads for up to 24 hours for the 10-yr., 24-hr. summer flood reduced peak flows by 41% at 1 square mile of drainage area, 33% at 8 square miles and 11% at 28 square miles. This is based on comparing the future with culvert sizing (Scenario 3) to the future without culvert sizing (Scenario 1). For the 50-yr., 24-hr. storm, culvert sizing reduced peak flows by 63% at 1 square mile, 39% at 8 square miles and 18% at 28 square miles.
2) Using culvert sizing to create up to 30-hour duration of temporary storage upstream from roads for the 10-yr., 24-hr. summer flood, the reductions in peak flows were 60% at 1 square mile, 44% at 8 square miles and 23% at 28 square miles of drainage area. Again, this is based on comparing the future with culvert sizing (Scenario 3) to the future without culvert sizing (Scenario 1). The corresponding reductions in peak flows for the 50-yr. summer flood were 75% at 1 square mile, 49% at 8 square miles and 28% at 28 square miles.
3) Restricting all flows for the 10-yr., 24-hr. summer flood to the channel (i.e. Scenario 2 no temporary overbank storage) <u>increased</u> the peak flows by 0% at 1 square mile of drainage area, 28% at 8 square miles, and 75% at 28 square miles. This is compared with the ditch and culvert sizes for the future without culvert sizing scenario.

4) Culvert sizes based on the preliminary culvert sizing guidelines are about 1/5 at 1 square mile to 1/2 at 25 square miles the size of culverts designed using the commonly used peak flow and maximum headloss design method. This is based on comparing Scenario 3 to Scenario 1 for the 28 square mile watershed models.
5) For these modeling scenarios, with the top of roads 2 feet above the adjacent ground elevations, there was no road overtopping for the future without culvert sizing (Scenario 1) or the future with culvert sizing (Scenario 3, including both the 24-hr. and 30-hr. temporary storage durations). This was true for both the 10-yr. and 50-yr. events.
6) Using the 10-square mile hypothetical watershed model with preliminary guidelines applied, for a main channel slope of 2 ft./mile, more temporary storage is available upstream from road crossings per unit of increased floodwater stage compared to a main channel slope of 5 ft./mile. As a result, the reduction in peak flows is greater with culvert sizing on the flatter slopes. However, the flood duration increases somewhat.
7) For a main channel slope of 10 ft./mile, there is less available storage per unit of increased floodwater stage compared to a main channel slope of 5 ft./mile. As a result, the duration of flooding and reduction in peak flows is somewhat less with culvert sizing on steeper slopes. Unless roads are raised, or intermediate temporary storage is made available, the modeling results indicated that both the 10-yr. and 50-yr., 24-hr. floods would overtop 2-ft. high roads for a main channel slope of 10 ft./mile. The modeling results indicated that raising roads approximately 1.5 ft. (to 3.5 ft. above the adjacent ground surface) would prevent overtopping up to the 50-yr., 24-hr. flood.
8) Using the design guidelines for culvert sizes, but with a lower capacity ditch design, reduced peak flows slightly and increased flood durations significantly.

Culvert Sizing Implementation Approaches and Guidelines

General

The following implementation approaches and guidelines are intended for use in agricultural areas of the Red River Basin where the upstream drainage area is agricultural and the potential damages are predominantly agricultural or rural. They are based on “average” conditions. The user is cautioned regarding the potential need to adjust the design when conditions deviate substantially from average.

As previously indicated, there are two general approaches to implementation of culvert sizing. They are herein referred to as the **subwatershed approach** and the **incremental approach**. The subwatershed approach is to resize all of the culverts and bridges within a subwatershed at the same time. This approach may be applied in the establishment of a new drainage system or subsystem, or the improvement of an existing drainage system. The subwatershed approach involves the least risk and may, therefore, be designed for the greatest benefit. The incremental approach is to resize culverts one at a time as they are in need of replacement. This approach will gradually achieve the benefits of distributed temporary storage, but may require a more conservative design in replacing culverts downstream from areas where sufficient upstream temporary storage has not yet been provided. Ideally, the long-term result of the incremental approach is the same as the subwatershed approach.

Subwatershed Approach

In the subwatershed approach, all of the culverts, road heights, and drainage channels are considered and, to the extent practical, may be altered to provide the desired results. Design criteria may include:

1. Outflows limited to downstream channel capacities.
2. Road overtopping limited to greater than the 50-year flood frequency.
3. Protection provided for buildings or other flood prone property improvements to the 100-year flood frequency.
4. Cropland flooding (temporary storage) duration limited to normal crop tolerance (24 to 30 hours) for the 10-year frequency summer rainfall.
5. Temporary storage distributed as uniformly as possible throughout the subwatershed.
6. Flowing water confined to channels to minimize field erosion.

Recommended Design Guidelines for Subwatershed Approach

A. Choose a design drainage capacity for the subwatershed. State in terms of removal rate (i.e. inches per day) as opposed to peak flow design frequency. A removal rate of one inch per day worked well in modeling average conditions in the Red River Basin. One inch per day would be provided by a design flow in cubic feet per second equal to 27 times the drainage area in square miles. A slightly more sophisticated design removal rate equation of $Q=27A^{0.96}$, where Q = flow in cubic feet per second (cfs) and A = drainage area in square miles, was derived by modeling the hypothetical drainage system. At one square mile, the capacity would be 27 cfs, which is equivalent to a drainage coefficient of one inch per day. The exponent in this equation, 0.96, reduces the design flow to somewhat less than a linear increase relative to drainage area. For example: if the drainage area increases by a factor of 2, the design capacity would increase by a factor of 1.95. This works because not all of the water gets to the downstream end of a subwatershed at the same time. This equation has been tested by modeling to 28 square miles with good results. It may be a higher flow rate than necessary for larger drainage areas, due to the lower probability of getting a uniform heavy rainfall over a large area.

B. Design the channels to carry the design flow with ½ to 1 foot of freeboard.

C. Design the culverts to pass the design flow with ½ to 1 foot of head loss. Note that the head loss, combined with the comparable channel design freeboard above, results in the water surface being at or near ground level upstream from the culvert at the design flow.

D. Check road overtopping potential. Based on regression analysis of the modeling results, the 50-yr. flows can be represented by the formula $Q_{50}= 52.5A^{0.868}$. If the road would overtop with 50-yr. flows, first consider raising the road. If raising the road is not practical, look for opportunities to increase upstream storage. If increasing upstream storage is infeasible at this time, use risk assessment methods to determine if the resulting frequency of overtopping is acceptable. If not, then increase the culvert size, but only to the extent necessary to meet risk assessment requirements.

E. Check flow velocities at outlets and inlets of culverts for 50-yr. event and design for erosion protection, as necessary.

F. Check potential for additional temporary storage. Consideration should be given to raising the road above the 50-yr. level. This would provide a margin of safety to handle larger floods or to make up for areas of the subwatershed that have less storage potential. The amount of design temporary storage (based on the model) is about 85 acre-feet per square mile. To the extent practical, each section of the drainage area should provide its share of storage capacity. But when that is not possible, it can be provided elsewhere. Even if some areas of storage may be used less frequently than others, it is still beneficial.

G. Use modeling, if necessary, to fine tune the design. Although this involves substantially more engineering work, it may be justified in subwatersheds with a variety of topography, or where there are significant other areas of flood storage or particularly important roads.

Incremental Approach

As previously defined, the incremental approach involves sizing culverts one at a time as they are in need of replacement. Ideally, the incremental approach would lead to the same result as the subwatershed approach, over time. However, designers need to consider the potential short-term risks associated with the incremental approach. These risks are greatest when replacing culverts with large drainage areas before most of the upstream culverts have been properly sized. It is recommended that the designer consider the acceptability of this risk using the standard highway risk assessment methods based on traffic count and other factors. Many rural roads meet risk assessment criteria even with frequent overtopping. Over time, as culvert sizing implementation progresses, overtopping risks will diminish and typically will be much less than generally considered acceptable by highway design standards.

Size of drainage area is an important factor (but seldom considered) for assessing risk. The amount of water that could pass over a road increases greatly with increasing drainage area. Therefore, the potential for washouts to occur also increases greatly. Culvert sizing should become more conservative, in terms of design overtopping frequency, as drainage area increases.

Recommended Design Guidelines for Incremental Approach

The recommended design guidelines for an incremental implementation approach are essentially the same as for the subwatershed approach. Ways to reduce and/or manage risks associated with incremental implementation include:

1. Delay the replacement. It is often a choice to replace or refurbish an existing crossing. Refurbishing can buy time, during which upstream culverts may be replaced.
2. Design for future downsizing. For example, a crossing might include a long life permanent culvert and a relatively short life temporary culvert. The temporary culvert would eventually be removed. Another alternative would be to eventually block a portion of the culvert opening.
3. Raise the road overtopping elevation. Raising the road will increase the maximum head loss through the culvert, which will increase its flow capacity. For example, increasing head loss from 2 feet to 3 feet would increase its capacity by about 20%. At the same time, raising the road increases upstream storage capacity, which will reduce peak flows. As upstream culverts are replaced, the extra storage will seldom be used, but will continue to provide an additional margin of safety to the system.
4. Provide a 2-stage inlet on a larger culvert. This will restrict flows to the desired rate until the headwater reaches a critical elevation. Then the flow capacity will automatically increase.

Developing a culvert size master plan for a subwatershed may be the best strategy for implementing the incremental approach for culvert sizing. The master plan would provide the long-term sizes for all culverts within a subwatershed, based on one study. This may be a service that could best be provided by watershed districts and/or county drainage authorities. Incremental implementation by road and drainage authorities would utilize these culvert sizes, to the extent practical, or utilize road, culvert and inlet designs that could be retrofit in the future to achieve the master plan culvert size after adequate distributed temporary storage is achieved upstream. This strategy should enhance acceptance and implementation of culvert sizing for flood damage prevention and reduction, because the master plan would clearly define the goal of a more equitable level of drainage capacity within the subwatershed and control of flows downstream.

Other Design Considerations

The above implementation approaches and design guidelines were developed based on average conditions in the Red River Basin. Obviously, conditions will be encountered that deviate substantially from average. Some of these are discussed below.

Flat Slopes

Gravity flow of water occurs due to a difference in water elevation (head). This difference is largely dependent on the slope of the land, which determines the head available to move the water. In a waterway with culverts, some of the head is used to push water through the culverts and some is used to carry water down the channel between culverts. The above guidelines recommend using ½ to 1 foot of head loss through each culvert. Obviously this will not work if there is insufficient slope to provide that head loss through the culvert and still have enough to move water down the ditch. The minimum practical slope to move water down the channel is about 1 to 1½ feet per mile. Head loss through the culvert should be reduced, to the extent practical, from that recommended above, if necessary to maintain at least 1 to 1½ feet of head per mile of channel without crossings.

Steep Slopes

Control of flows by culvert sizing requires temporary storage capacity upstream from each culvert equivalent to about 85 acre feet per square mile. The amount of water that can be stored upstream from a road grade is diminished as slope is increased. Reduced storage capacity would have to be compensated by increased flows. This would be highly undesirable, especially as it would affect flatter sloped areas downstream. Every effort should be made to provide the requisite storage and hold the line on culvert sizes through steep sloping areas. This may require adding intermediate storage by developing crossings or other storage areas within each section in addition to providing for the most temporary storage practical at section line roads.

Soil Texture

Soil texture affects the amount of runoff. It could be argued that fine textured soil areas should have larger culverts to allow for the naturally higher runoff rates. On the other hand, the need to control runoff rates is greatest from high runoff areas. Higher runoff volumes would require greater storage capacity and longer durations. Greater storage capacity is not expected to be a problem in the Red River Basin, because fine textured soils tend to occur on the flattest slopes, where substantial temporary storage typically can be achieved by small increases in stage upstream from roads.

Coarse textured soils have naturally lower runoff rates. It could be argued that they should have correspondingly smaller culverts. However, because the runoff rates are lower, controlling these flows more than the recommended culvert sizing methodology would be of little consequence. Having more complex culvert sizing guidelines may not be worth the extra effort. On the other hand, it would not make sense to increase culvert sizes in these areas if existing culvert sizes are working well. In this regard, the culvert sizes recommended by the guidelines above should be considered maximums.

Land Use

As with soil texture, land use affects runoff rates. Because land use can change over time, it would be very difficult to incorporate this consideration into culvert sizing design guidelines. To the extent that land use changes are elements within the landowner's control, the benefits of reduced runoff rates may provide an incentive for applying runoff reducing practices.

Fish Passage

Culvert downsizing will generally result in increased flow velocities through the culvert, which can be undesirable where fish passage is a concern. However, the duration of increased flow velocities for culvert sizing using the above guidelines is approximately 24 to 30 hours. When culvert sizing is utilized in the headwaters areas of drainage systems, fish passage may not be a concern.

Summary of Key Principles, Benefits, Challenges and Recommendations

Key Principles

In discussions and implementation of runoff management measures for flood damage reduction and prevention, some generally accepted principles are often applied, including:

- manage runoff as close to the source as possible;
- timing, volume, peak flows, stage and velocity are key aspects of runoff management;
- the doctrine of reasonable use of land includes a right to drainage that does not unreasonably harm others downstream;
- adequacy of the outlet is critical for drainage design and general runoff management, but subject to interpretation.

This technical paper suggests adding the following principles for management of excess runoff in the Red River Basin:

- distributed temporary storage that best utilizes the interaction between drainage networks and road networks can substantially reduce downstream peak flows, flood stages, breakout flooding, and associated flood damages;
- the duration of temporary storage on agricultural lands generally should be limited to 24 to 48 hours to avoid crop damage, but should also be utilized to achieve the benefits of distributed temporary storage;
- equitable drainage benefits throughout a drainage system, in terms of level of protection, is a reasonable design criteria, particularly for artificial drainage systems; and

- a removal rate (drainage coefficient) design methodology is appropriate for both subsurface and surface drainage in agricultural areas, because this methodology considers both rate and duration of runoff.

Key Benefits

Culvert sizing provides substantial opportunity in the Red River Basin to increase distributed temporary storage to help achieve the following key benefits:

- reduced peak flows,
- associated flood damage reduction and prevention,
- anticipated lower overall costs for culverts and drainage systems, and
- more equitable levels of flood protection within drainage systems.

The predominant current design methodologies for culverts (and drainage ditches) tend to underutilize distributed temporary storage, particularly within small drainage areas. Because there is a predominance of small drainage areas (subwatersheds) within larger watersheds, culvert sizing can create a large amount of distributed temporary storage.

Key Challenges for Implementation of Culvert Sizing

- Modifying the predominant current paradigms for design of culverts and roadways, as well as drainage ditches, to achieve widespread distributed temporary storage of runoff. There are many federal, state and local road authorities involved, as well as many drainage system administrators and designers. Fears about negative impacts to road safety, road maintenance and crop production should be expected.
- Implementation of this runoff management and flood damage reduction measure will require ongoing leadership to provide information and education, to pilot adoption of this measure and to refine implementation based on experience. Several successful pilot efforts are already in place in the Red River Basin.
- In many instances, incremental implementation will be necessary over a long period of time before the goal of full implementation of culvert sizing within subwatersheds is achieved.

Key Recommendations

- Drainage and road authorities, as well as their engineering assistance providers, should become familiar with the subwatershed and incremental approaches of these preliminary culvert sizing guidelines and the associated implementation experience to date in the Red River Basin.
- Drainage authorities should consider applying these guidelines within their jurisdictions.
- TSAC should lead implementation of Phase 2 for application of the preliminary culvert sizing guidelines to one or more representative drainage areas within the Red River Basin to verify, revise and/or clarify these guidelines.

Appendix A - Modeling of a Hypothetical Drainage System

Methods and Approach

The purpose of this modeling exercise was to test the concepts of culvert sizing and help develop and evaluate design guidelines. Use of hypothetical drainage systems simplified the modeling effort and eliminated the need to obtain field data. It was also possible to test the effect of varying watershed slope and ditch capacity.

Two hypothetical watersheds were evaluated. The first watershed consisted of a main ditch with three branches, having a total watershed area of 28 square miles (Figure 1). This model was primarily used to test the concepts of culvert sizing and to begin the development of design guidelines. The second hypothetical watershed model consisted of a single reach with a total drainage area of 10 square miles. This model was used to test the impact of varying slope and ditch size. In both models, only one culvert location at the outlet of each square mile was included.

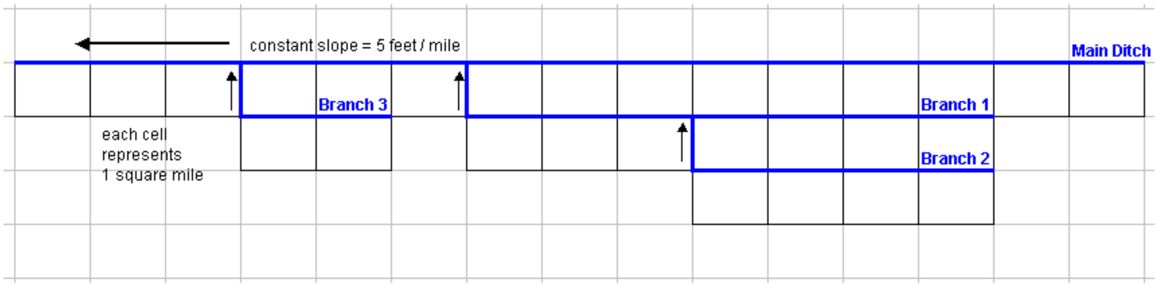

Figure 1. Plan view of 28-square mile hypothetical watershed

The U.S. Army Corps of Engineers Hydrologic Engineering Center – River Analysis System (HEC-RAS) model was used for this study. This program was primarily selected for its unsteady flow analysis capabilities. An unsteady flow analysis computes channel and culvert hydraulics while routing inflow hydrographs through the channel and floodplain network, including flow into and out of floodplain storage. Model parameters and assumptions are listed on page 16 of this Appendix.

Four scenarios were simulated using the 28 square mile watershed model:

1. **A peak flow based design without culvert sizing** (hereafter referred to as “without culvert sizing”). This is one possible scenario of future conditions – and not necessarily a worst-case scenario. The future is unknown, but estimated assuming current ditch and culvert design continue to be applied and widely established. The NRCS “20-40” rule (*MN Drainage Manual*) was used to establish ditch dimensions downstream of confluences.

2. **Future conditions assuming no overbank flooding.** This scenario evaluates the impact of achieving the 1998 Red River Basin Mediation Agreement goal of providing 10-year peak flow flood protection to agricultural lands by confining all runoff within a large

ditch. This is the upper limit of potential future conditions that rely only on drainage improvements to provide local flood damage reduction.

3. **Future conditions with culvert sizing**. The without culvert sizing model was used as the starting point for this scenario. Using a trial and error approach, culverts sizes and ditch dimensions were adjusted until the following performance standards were met:
   - Cropland flooding: 24-hour maximum following the 10-year, 24-hr storm event;
   - Road overtopping: For all road classes, no overtopping following the 50-yr, 24-hour event; and
   - Ditch design: Keep flow (50-year, 24-hour event) within ditch at the upper end of section, i.e., culvert tailwater, to prevent breakout flow and associated erosion.

   A variation of this scenario was developed with additional culvert downsizing to test a 30-hour cropland flood duration standard.

4. **Using preliminary design guidelines**. As described later in this appendix, the modeling results of the "with culvert sizing scenario" were used to develop the preliminary design guidelines. A fourth model was developed in which both ditch dimensions and culvert sizes were set using the preliminary design standards. Neither the culvert sizes nor ditch dimensions were adjusted in an attempt to achieve the stated performance standards.

Four additional variations were simulated using the 10 square mile watershed model:
1. Main channel slope = 5 ft/mile;
2. Main channel slope = 10 ft/mile;
3. Main channel slope = 2 ft/mile
4. Main channel slope = 5 ft/mile w/ smaller ditch size.

- for all scenarios, both the 10- and 50-year, 24-hour storms were run. The 50-year, 10-day event was also run for selected scenarios.

Findings

Significance of temporary storage

One square mile: The results of this hypothetical model study suggest that the potential for increased temporary storage is likely greatest at the upstream end of a drainage system. A culvert design strategy based on peak flow (assumed future conditions) results in essentially no attenuation of the peak flow at one square mile (Figure 2). As shown in Figure 3, the 10-year summer flood remains within the channel (minimum ditch depth and bottom widths were assumed to be four feet).

The overbank storage created by the culvert sizing strategy results in a significant reduction in peak flow. The maximum pool extends approximately 1600 feet upstream of the culvert. It is this temporary ponding of runoff that causes the significant reduction in the downstream peak flow.

Increasing the duration of that temporary ponding from 24 to 30 hours results in a very small incremental increase in the upstream depth of ponding with a substantial further reduction in peak flow.

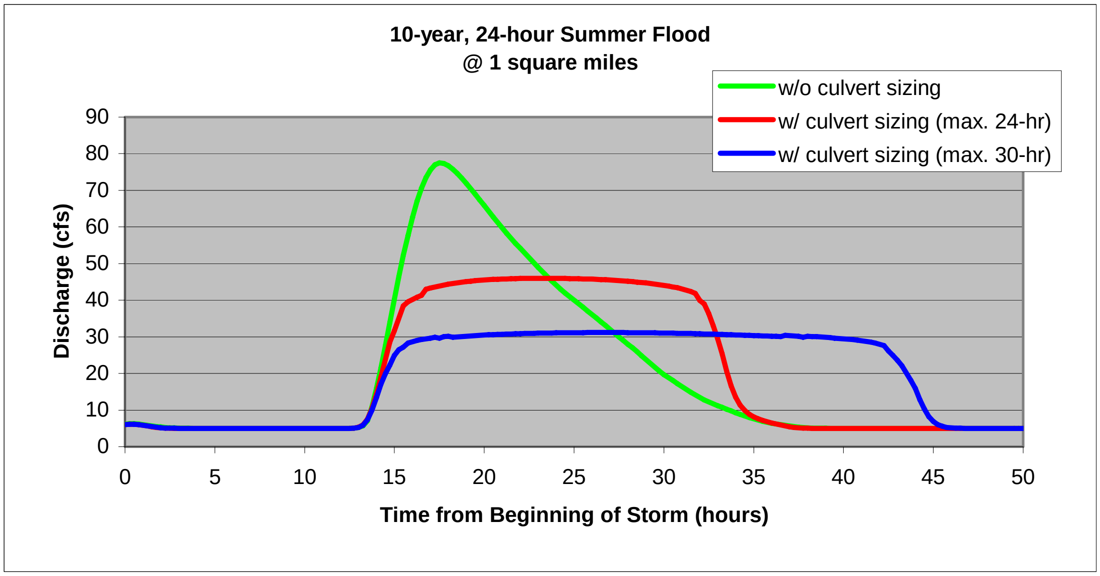

Figure 2. Discharge hydrographs at 1 square mile.

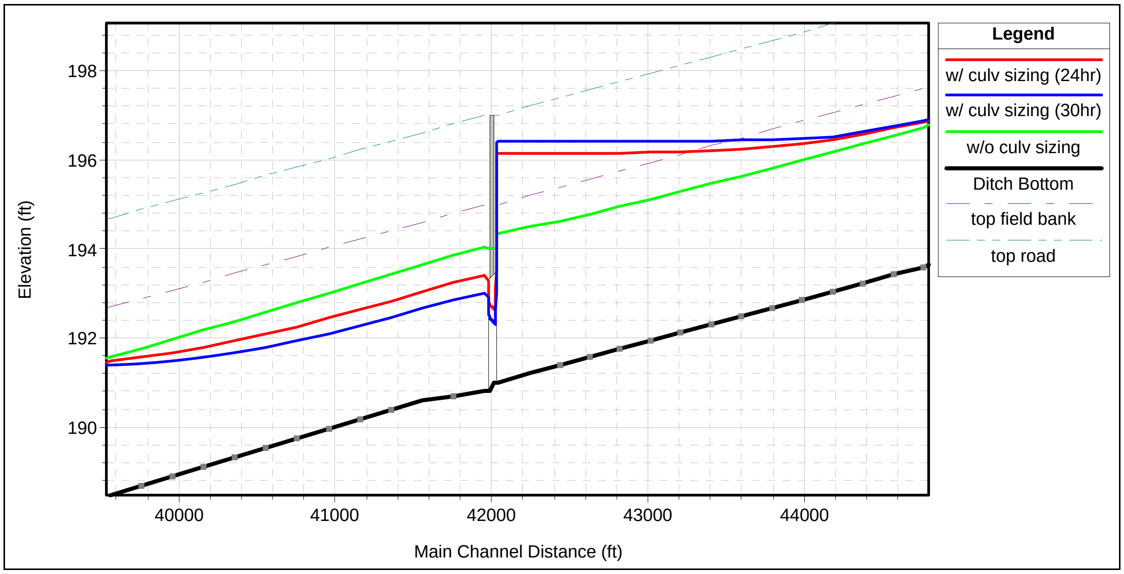

Figure 3. Water surface profile at 1 square mile (10-year, 24-hour storm)

Eight square miles: When comparing conditions with and without culvert sizing, the percent reduction in peak flow becomes smaller moving downstream along the drainage system. The corresponding discharge hydrograph and water surface profile plots at eight square miles are shown in Figures 4 and 5. There is relatively little head loss at the culvert for the future conditions w/o culvert sizing scenario. But the water surface profile is at, or slightly above the top of bank for the entire length of channel for this 10-year summer event (Figure 5).

Both of the "with culvert sizing" scenarios continue to show ponding on the upstream side of the culverts, with flow remaining within the channel on the downstream side of the culvert. This is one of the objectives of culvert sizing so as to minimize the potential for serious erosion caused by out-of-channel flow. Water "backing up" on the upstream side of a culvert generally does not have the same erosive potential.

The hydrograph for the "no overbank flooding" scenario was also added to Figure 4. The general shape of this hydrograph is essentially the same as the one-square mile inflow hydrograph shown in Figure 2. This indicates that essentially no attenuation of peak flow is occurring. The flattened shape of the without culvert sizing hydrograph indicates that out-of-channel flow/storage is having the effect of reducing the peak flow.

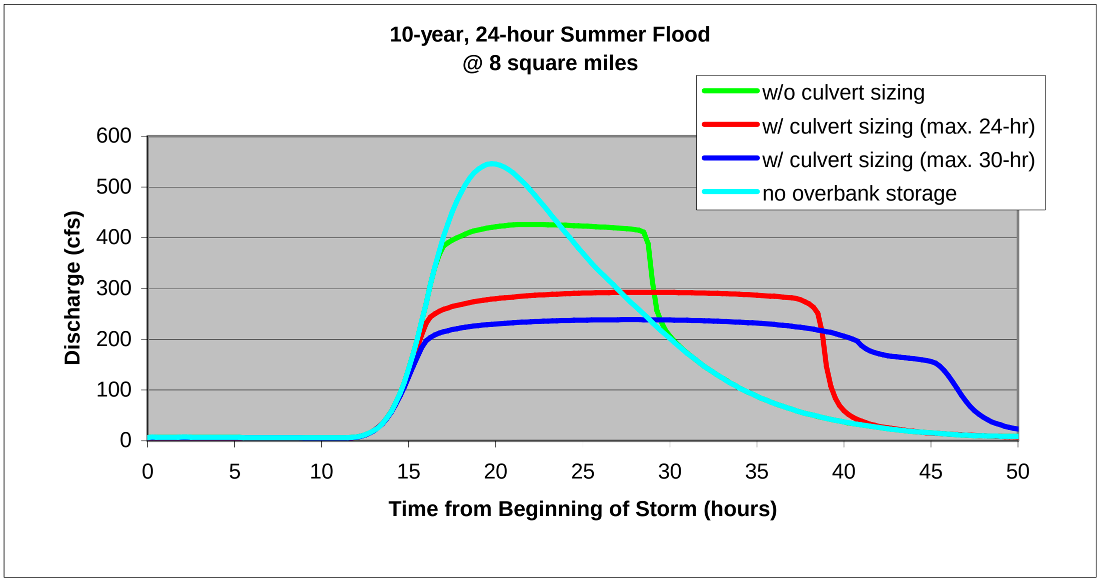

Figure 4. Discharge hydrographs at 8 square miles.

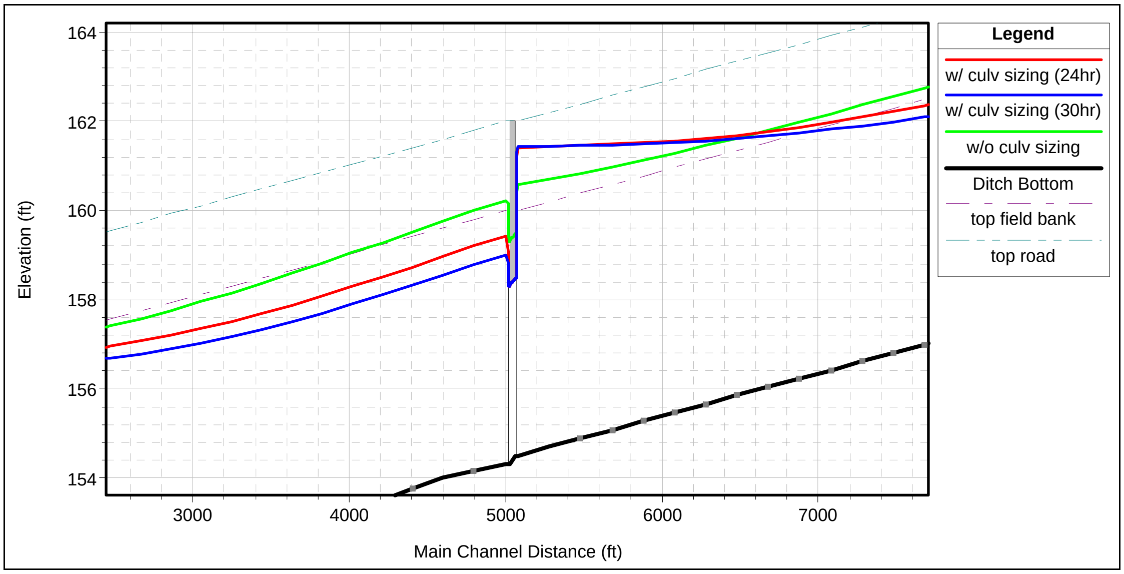

Figure 5. Water surface profiles at 8 square miles (10-year, 24-hour storm).

Twenty eight square miles: Finally, discharge hydrograph and water surface profile plots are presented in Figures 6 and 7 for the downstream end of the hypothetical watershed (28 square miles). The "no overbank storage" hydrograph has retained the same general shape as the one-square mile inflow hydrograph, whereas the other three hydrographs have a similar "boxed" shape. The with culvert sizing scenarios include temporary storage of flow by design. Storage also occurs in the without culvert sizing scenario, but not by design.

The "no overbank storage" scenario results in a peak flow almost twice the other scenarios that include temporary storage. In reality, it's generally not practical to keep all flow within a channel for an extended reach. Flooding will occur somewhere along the ditch or downstream tributary. The culvert sizing strategy seeks to equitably distribute the storage throughout the entire system.

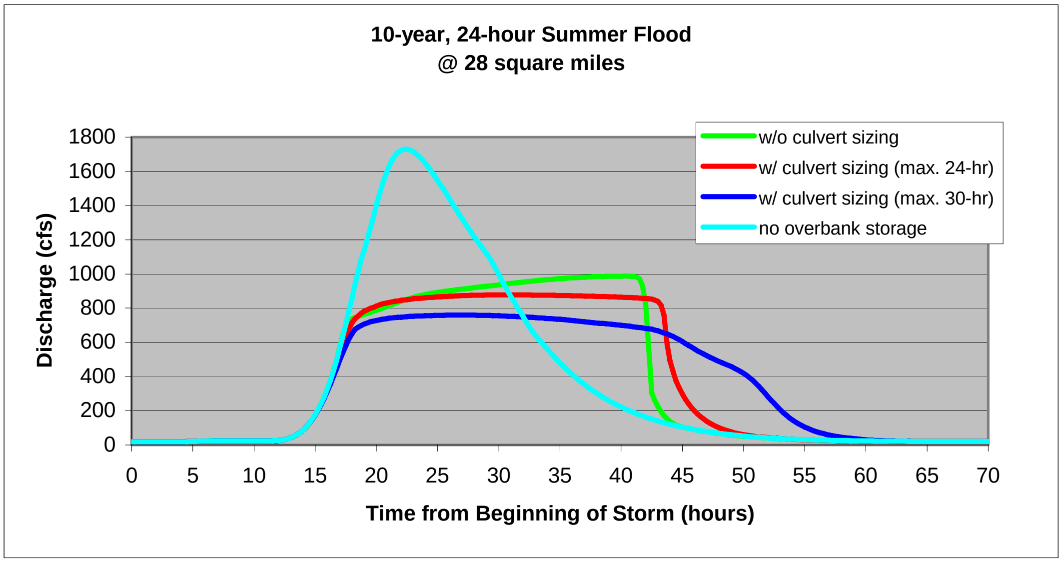

Figure 6. Discharge hydrographs at 28 square miles.

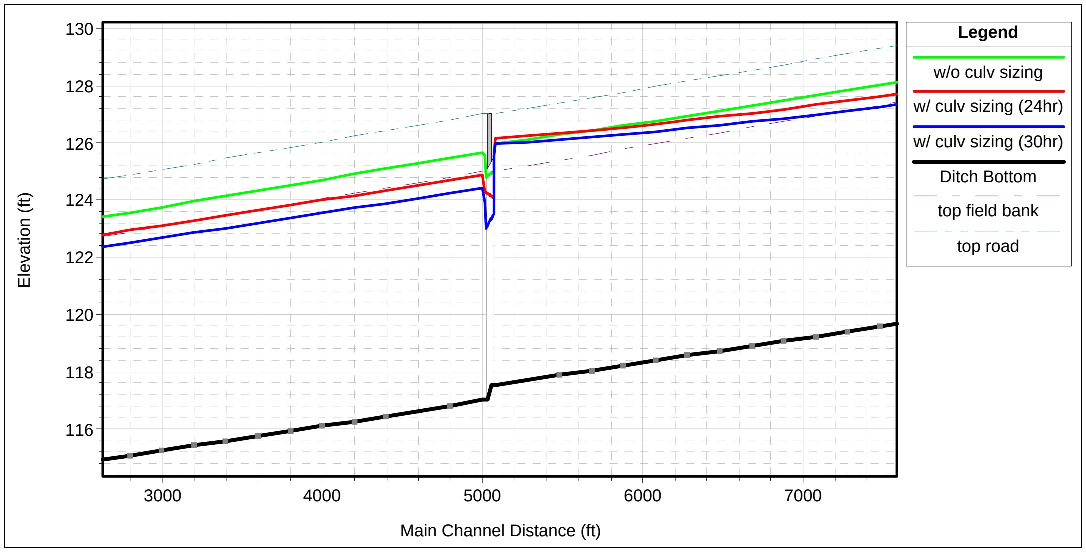

Figure 7. Water surface profiles at 28 square miles (10-year, 24-hour storm).

Similar results were found with the 50-year, 24-hour storm and the 50-year, 10-day event. Computed peak flows for all culverts along the main ditch are shown in Figures 8a, 8b and 8c, and summarized in Table 1.

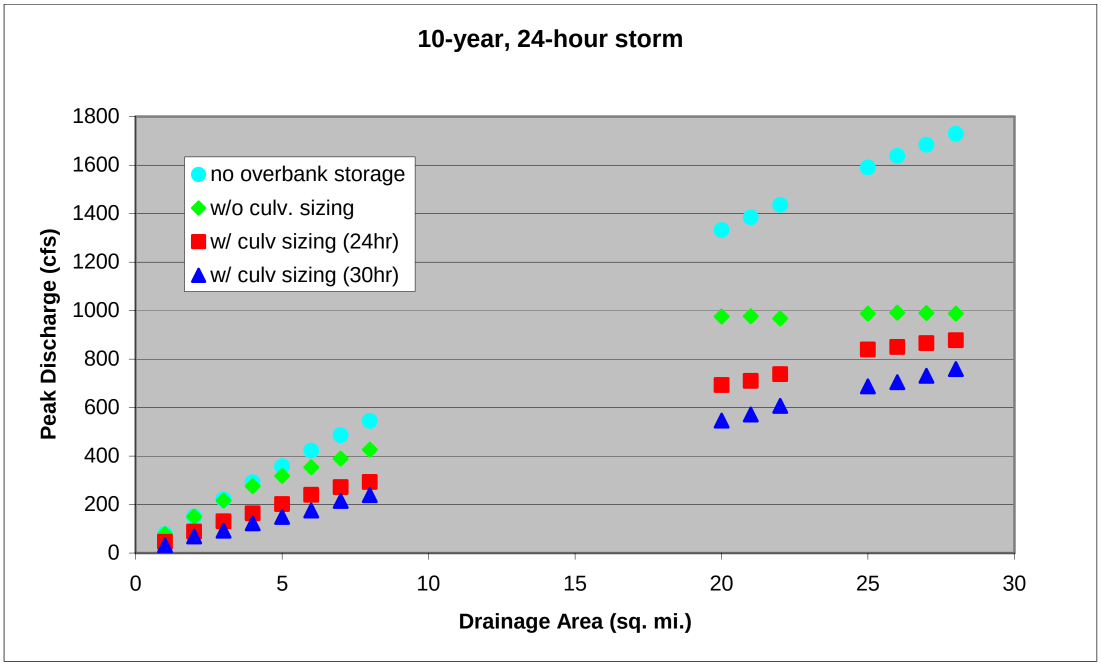

Figure 8a. Peak discharge rates for the 10-year, 24-hour storm.

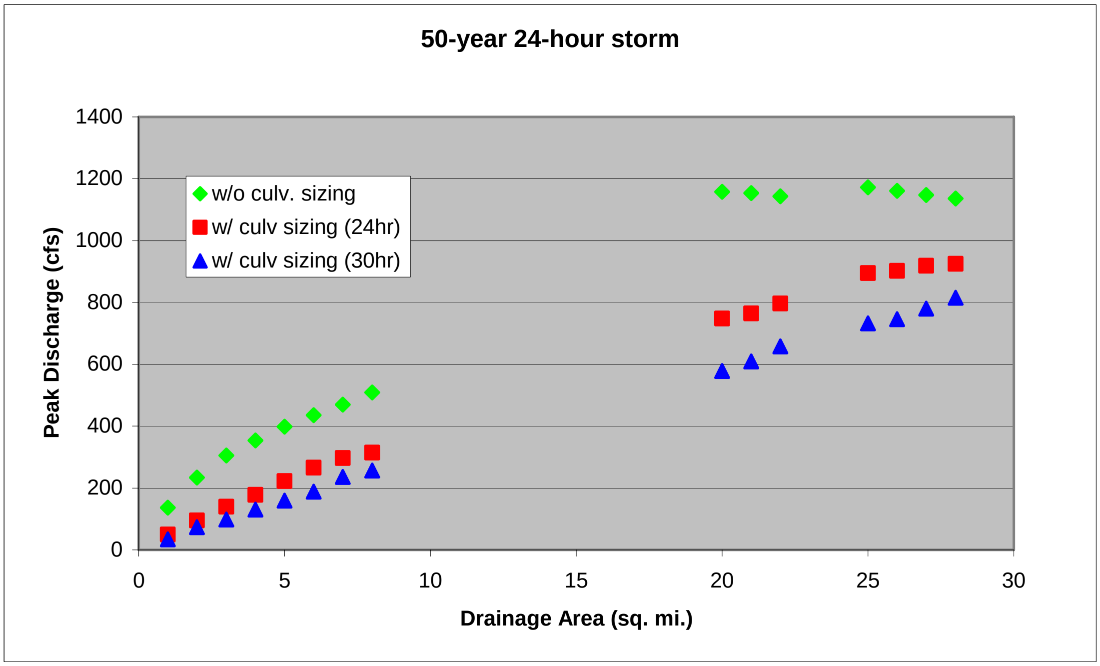

Figure 8b. Peak discharge rates for the 50-year, 24-hour storm.

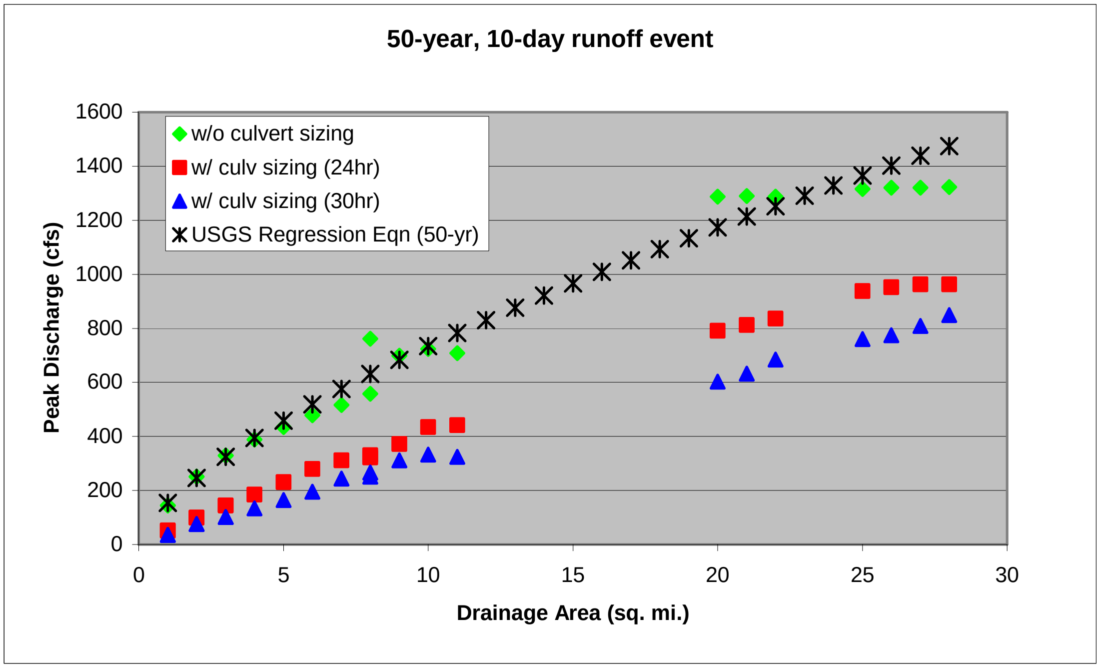

Figure 8c. Peak discharge rates for the 50-year, 10-day event.

Table 1

Summary of Computed Peak Discharge Rates

	Peak Discharge (cfs)			
	1 sq mi.	8 sq. mi.	20 sq. mi.	28 sq. mi.
▪ 10-year summer storm				
• No overbank storage	78 cfs	550 cfs	1330 cfs	1730 cfs
• w/o culvert sizing	78	430	980	990
• w/ culvert sizing (24-hr)	46	290	690	880
• w/ culvert sizing (30-hr)	31	240	550	760
▪ 50-year summer storm				
• w/o culvert sizing:	136	510	1160	1140
• w/ culvert sizing (24-hr)	50	310	750	930
• w/ culvert sizing (30-hr)	34	260	580	820
▪ 50-year 10-day				
• w/o culvert sizing:	145	558	1290	1320
• w/ culvert sizing (24-hr)	51	330	791	963
• w/ culvert sizing (30-hr)	35	266	603	849

Duration and depth of overbank flooding

Duration of flooding: The duration of overbank flooding is generally longer for the with culvert sizing scenario than without culvert sizing (Figure 9). The difference decreases in a downstream direction. As expected, the duration of flooding is greater for the 50-year flood than the 10-year flood. Due to the much greater total volume of runoff with the 50-year, 10-day event, the duration of flooding was up to twice as long as the 50-year, 24-hour event.

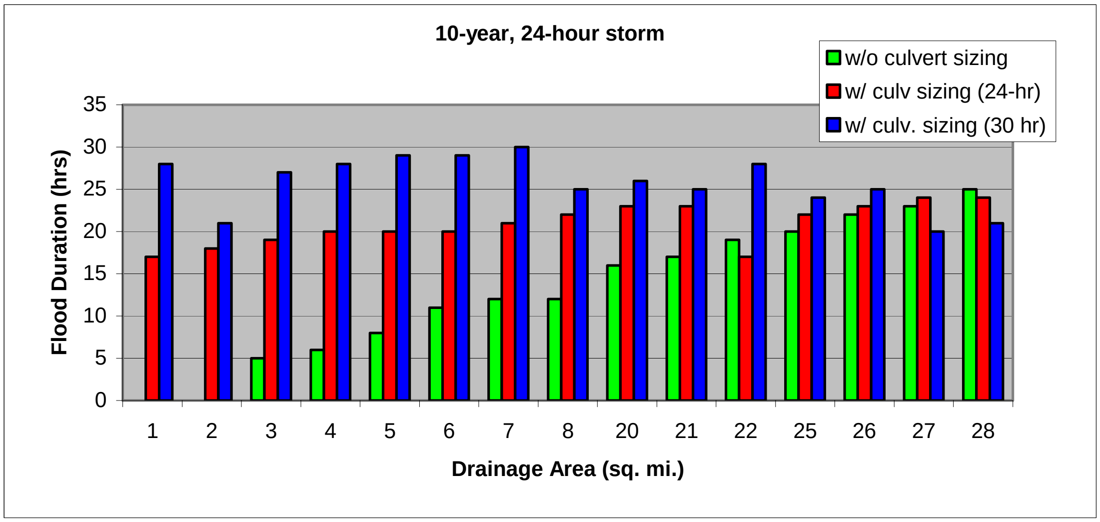

Figure 9. Duration of flooding, 10-year summer flood.

Figures 10a, 10b, & 10c show the water level (stage) hydrographs at 1, 8, and 28 square miles, respectively. Both the 10-year and 50-year summer floods are shown for future conditions without culvert sizing and with culvert sizing (24-hour duration standard). Also shown on the figures are the top of road elevations and top of ditch bank (field side) at the culvert.

Depth of flooding: At one and eight square miles, the depth of flooding with culvert sizing is greater than the without culvert sizing scenario – as would be expected. At the downstream end of the system (28 square miles), the reverse is true.

Road overtopping: There was no overtopping of the roads at any of the modeled culverts for either the with- or without culvert sizing scenarios for either of the summer storm events. However, at several culverts for the computed 50-year summer event, the computed water level was very close to overtopping. Roads did not overtop because simulated height of the roads (2 ft) provides just enough storage to reduce the peak flows and prevent overtopping. It's also likely that the uniformity of design for all culverts within the drainage system also contributed to this result.

Culvert size differences

Culvert sizes based on a culvert sizing strategy range from one-quarter (at one square mile to one-half (at 28 square miles) of the size of culverts for the future conditions without culvert sizing scenario. Selected culvert dimensions are shown below, as well as the total waterway openings in Figure 11.

		w/ culvert sizing	
Drainage area	w/o culvert sizing	24-hr standard	30-hr standard
1 sq. mi.	2–48" round (25 ft^2)	1–30" round (4.9 ft^2)	1–24" round (3.1 ft^2)
8	2 – 10x5 box (100 ft^2)	1 – 8x5 box (40 ft^2)	2-48" round (25 ft^2)
25	3 – 10x7 box (210 ft^2)	1 – 14x7 box (98 ft^2)	1 – 14x6 box (84 ft^2)

Maintaining flow within the downstream channel

At drainage areas greater than four square miles, the model results for the 10-year 24-hour flood for the future conditions without culvert sizing scenario indicate that peak flows exceed the channel capacity downstream of the culverts.

Flows generally remain within the channel downstream of culverts for the with culvert sizing scenario, even during the 50-year summer flood (Figure 12). This performance standard was achieved with a sizeable ditch, and by lowering the channel grade by one-half foot at the downstream side of the culvert. This objective was not met with a smaller ditch size, as discussed later in this report.

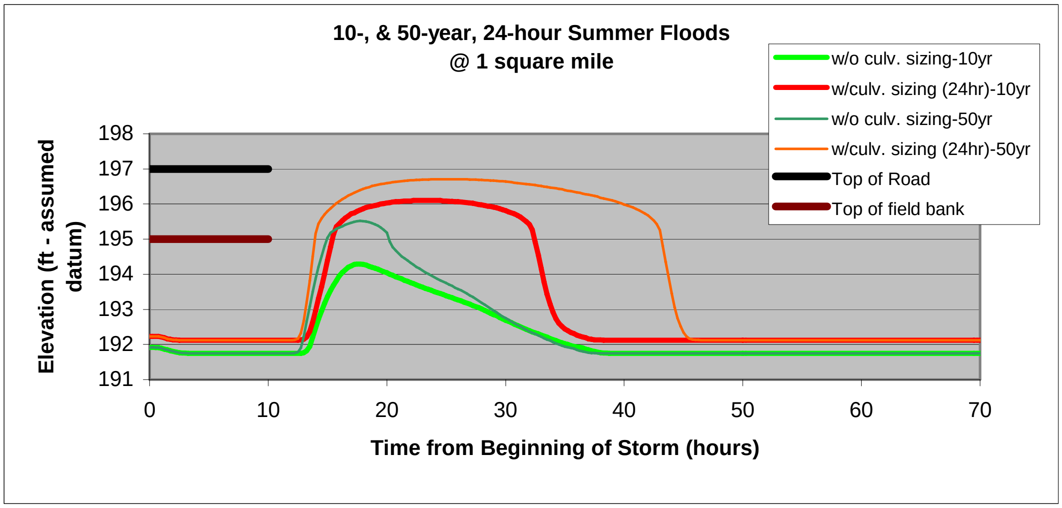

Figure 10a. Stage hydrographs at one square mile

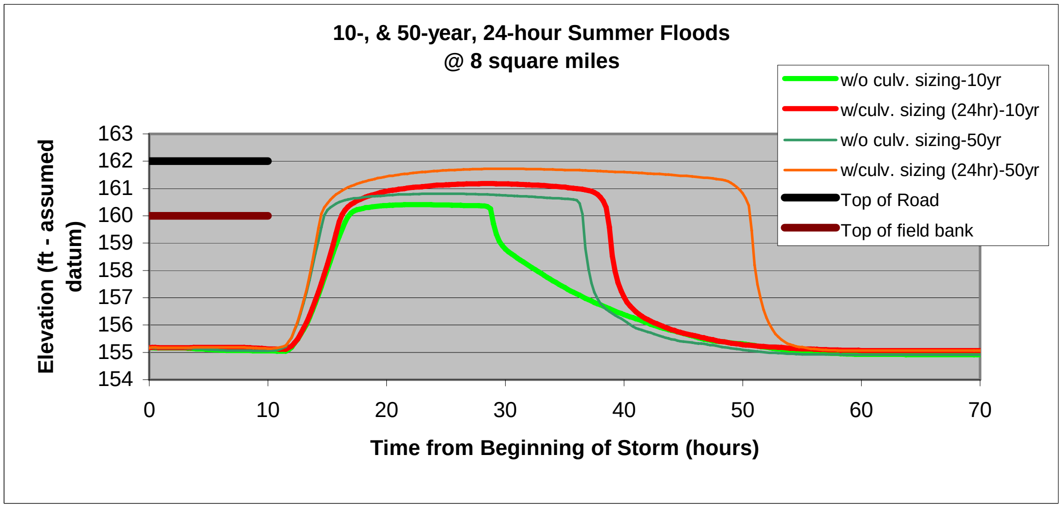

Figure 10b. Stage hydrographs at eight square miles

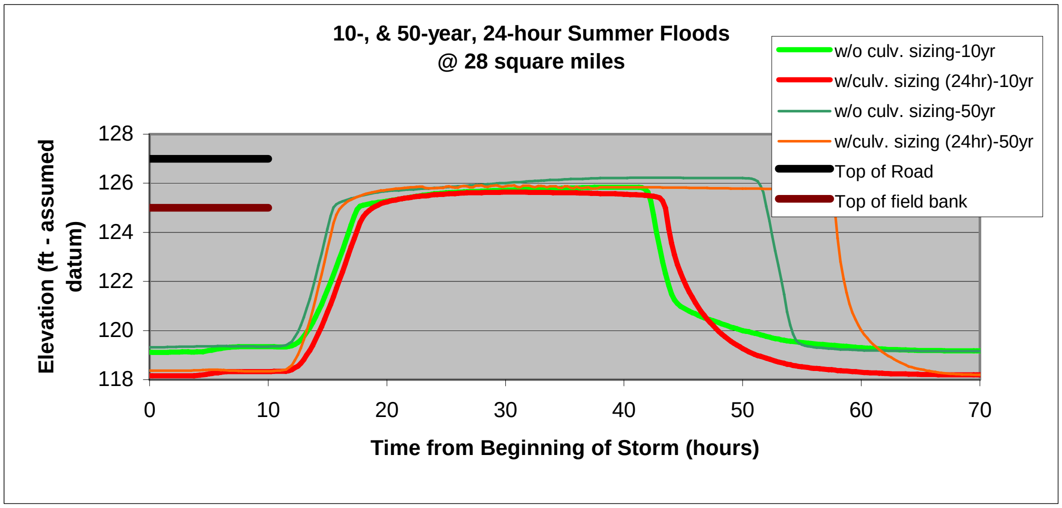

Figure 10c. Stage hydrographs at 28 square miles

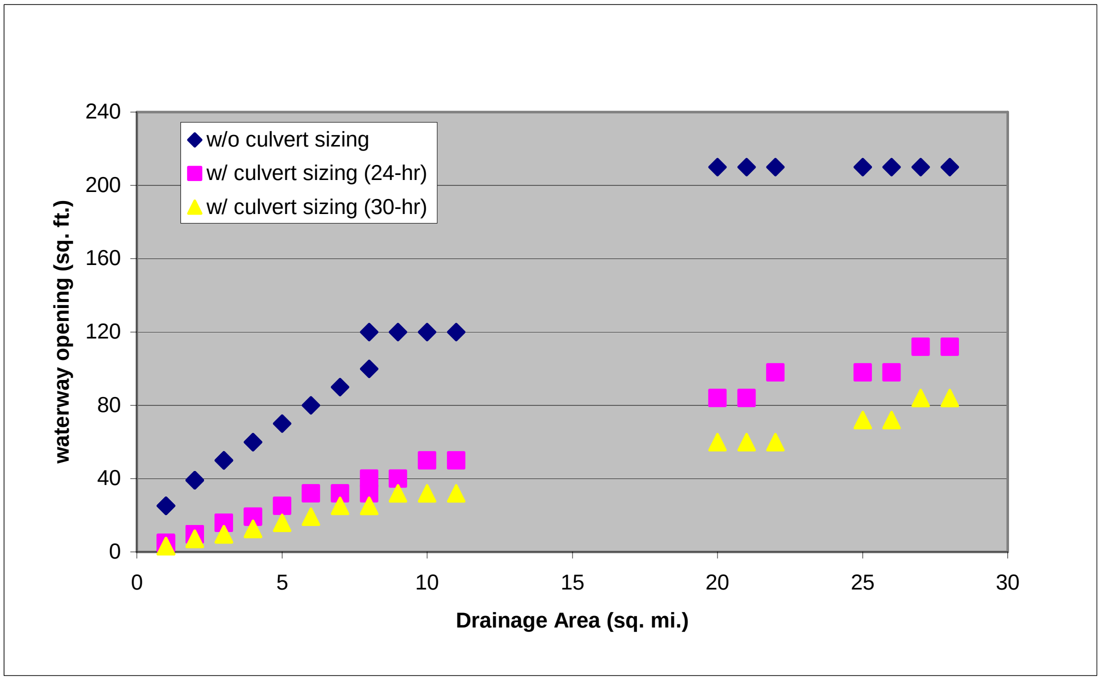

Figure 11. Culvert sizes (total waterway opening)

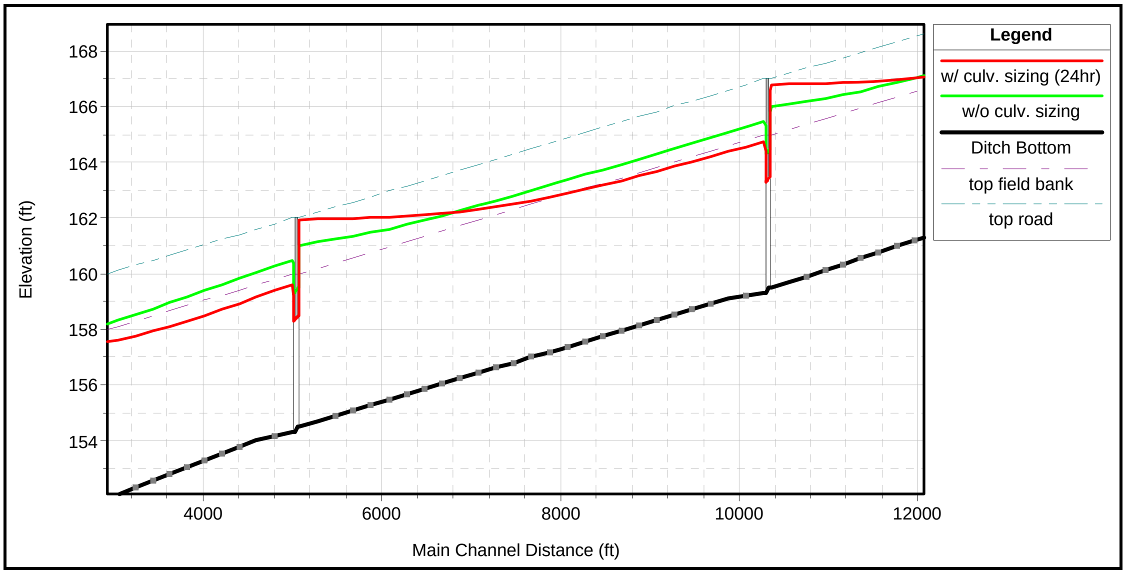

Figure 12. Water surface profiles at eight square miles (50-year, 24-hour flood)

Preliminary design guidelines

The above results were used in developing the preliminary design guidelines. The preliminary design guidelines identified on pages 10 and 11 of the main report were tested using the same 28-square mile drainage network. Design discharges were based on the equation $Q=27A^{0.96}$ (derived by analysis of data from the model) for both the ditch and culvert design.

A normal depth analysis (i.e., Manning's equation) was used to determine the ditch dimensions, adding one foot of freeboard. As with the initial model, the ditch grade was typically dropped one-half foot on the downstream side of most culverts. This somewhat flattened the grade to the next downstream culvert. Culvert sizes were set such that computed steady state head loss was generally between 0.5 and 1.0 foot.

This new model was run with both a steady flow, and unsteady flow analysis. The steady state profiles using the two design equations: $Q=27A^{0.96}$, and $Q=52.5A^{0.868}$ were computed using the HEC-RAS model. An example profile plot of the steady state analysis is shown as Figure 13.

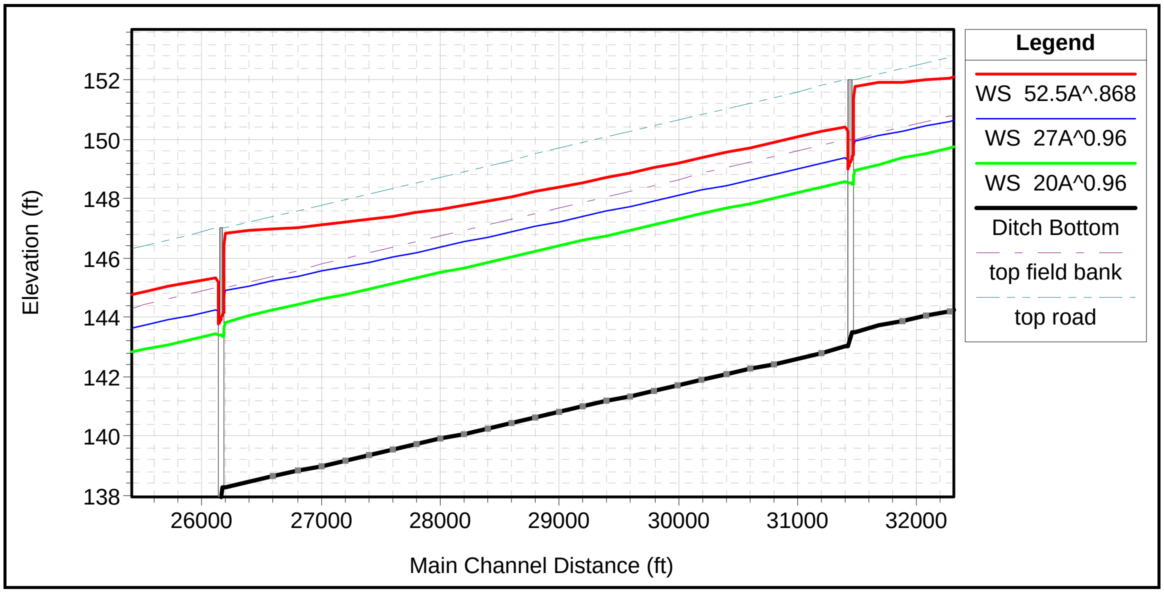

Figure 13. Design water surface profiles with steady state analysis.

Figure 14 shows the results of the unsteady flow analysis for the drainage system designed using the preliminary design guidelines. As discussed above, this figure also shows the equation fitting the peak flow results for the 50-year, 10-day event, as well as the SCS Design Curve No. 2 and curves representing the 10-year and 50-year USGS regression equations assuming zero lake and wetland storage.

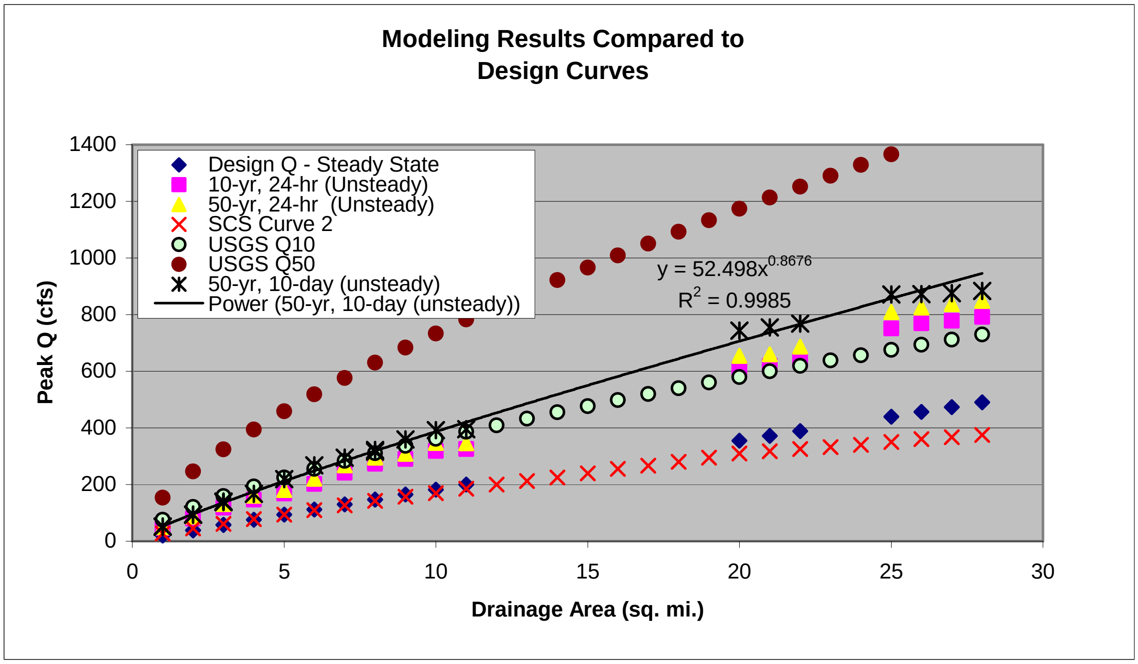

Figure 14. Peak flow using preliminary design guidelines.

While the design was primarily based on a steady state analysis, the performance of the ditch system was evaluated using an unsteady flow analysis. The results found an increasing duration of out-of-bank flooding in the downstream direction, in particular for the 50-year, 10-day event (Figure 15). At the downstream six culverts, the flood duration exceeded the 24-hour performance standard during the 10-year summer event, but did not exceed the 30-hour standard.

The computed peak level was not over the top of any of the roads for the 50-year, 24-hour flood. However, most of the roads were overtopped by less than 0.2 feet for the 50-year, 10-day event.

The computed water surface profile was generally within the channel immediately downstream of the culverts, except along the lower reach of the main stem and the lower reaches of the larger tributaries (both the 10- and 50-year 24-hour events). The computed flow exceeded the bank full capacity along the lower reach (>20 square miles) of the main ditch with the 50-year, 10-day event.

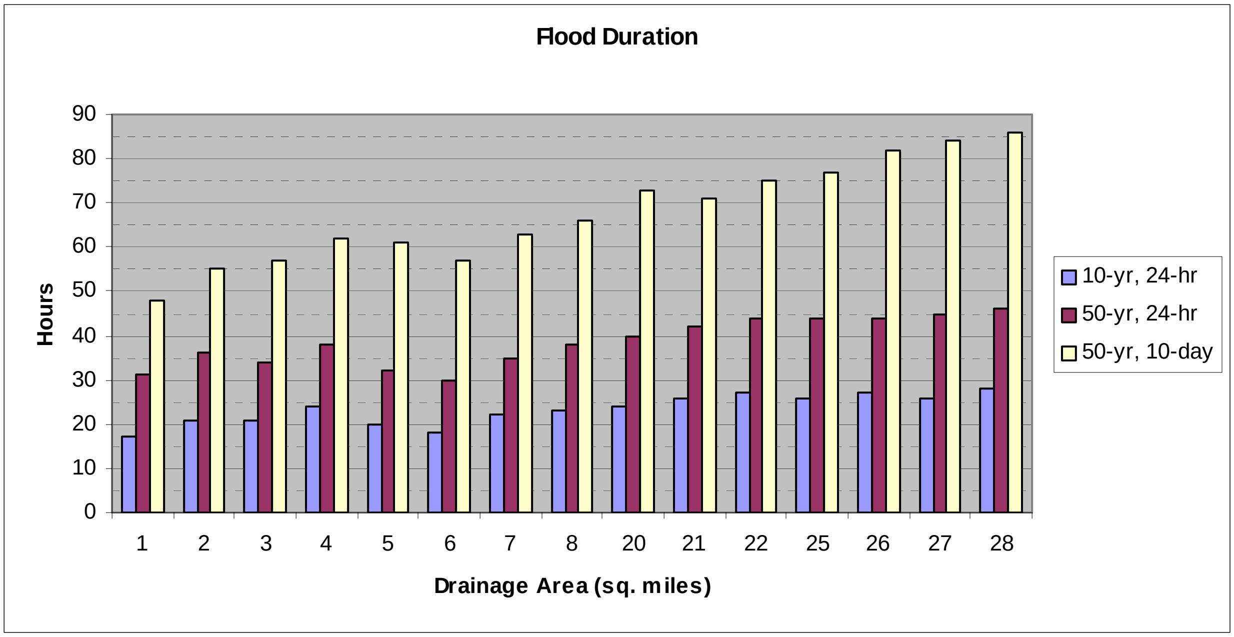

Figure 15. Flood durations – design guidelines.

Effect of varying main channel slope

All of the above results are based on the 28-square mile hypothetical watershed, which was assumed to have a constant main channel slope of five feet per mile. A smaller 10-square mile hypothetical watershed model was developed to assess how well the preliminary design guidelines work in a watershed with a flatter slope (2 ft/mi), a steeper slope (10 ft/mi), and the same slope (5 ft/mi) but with a smaller ditch dimension. The ditch / culvert design procedure was generally the same as used for the "Preliminary Design Guidelines" model. The design of the smaller ditch was based on the SCS Drainage Curve #1 with 0.5 feet of freeboard.

Predictably, the unsteady flow model results for the 2 ft/mile main channel slope found considerably more storage, lower peak flows, and longer flood durations. Peak flood levels were below the top of roads.

The reverse was found with the 10 ft/mile scenario. The smaller amount of available storage resulted in higher peak flows and shorter flood durations. The model results found that the 10-year summer flood would overtop the 2-foot high roads. A subsequent model run found that raising roads 1.5 feet (i.e. to 3.5 feet above natural ground elevation) provided enough additional storage to eliminate overflow during the 50-year summer storm.

The smaller ditch resulted in approximately 10% lower peak flows, with considerably longer flood durations.

Table 2

Summary of Results for Varying Watershed Slope and Ditch Size

Peak Discharge (cfs)

	10-yr, 24-hour flood			50-year, 24-hour flood		
Main Channel Slope	1 sq.mi.	5 sq.mi.	10 sq.mi.	1 sq.mi.	5 sq.mi.	10 sq.mi.
2 ft/mile	36	150	270	37	160	300
5 ft/mile (larger ditch)	46	170	310	50	180	340
5 ft/mile (smaller ditch)	46	150	260	50	160	310
10 ft/mile	61	220	370	110	430	560
10 ft/mile w/ road raise	61	190	380	70	210	430

Flood Duration (hours)

Main Channel Slope						
2 ft/mile	22	29	17	42	48	31
5 ft/mile (larger ditch)	18	26	22	31	41	37
5 ft/mile (smaller ditch)	18	31	38	31	48	58
10 ft/mile	11	22	24	18	26	29
10 ft/mile w/ road raise	11	23	22	21	36	31

HEC-RAS Model Parameters and Assumptions

Watershed:

- Size: 28 square. miles; 1 square mile cells.
- Ditch slope (east to west): 5 feet per mile
- Cross slope (south to north): 2 feet per mile
- Assume local inflow enters ditch at bottom of section (northwest corner).

Hydrology

- Unit hydrograph
  - Compute Tc using MN Hydrology Guide procedures.
  - Adjust Clark's R until Qpeak matches USGS regression eqn. (R ≈ 1 → 1.5*Tc).
- Curve Number = 75
- No baseflow
- No point rainfall reduction for watershed size
- Events
  - 10-year, 24-hour (rainfall = 3.6"; runoff = 1.37")
  - 50-year, 24-hour (rainfall = 4.7"; runoff = 2.20")
  - 50-year, 10-day event, CN adjusted to generate 5.0" of runoff

Ditch Design

- 4:1 road side slopes; 3:1 field side slopes
- 4' minimum bottom width
- 4' minimum depth
- Size using 1997 USGS Q5 regression equation w/ minimum 1.0 ft freeboard at normal depth
- Manning's "n" based on hydraulic radius (R) and table in SCS Drainage Manual
  - Generally using n=0.04

Road / Culvert Design

- concrete culverts
  - K_e=0.5
  - 50' long
  - n=0.013
  - downstream culvert invert = 0.2' below u.s. invert
  - culvert crown generally ≤ 0.5' above ground level
  - contraction / expansion coefficients: 0.3 / 0.5
- road height = 2 ft. above ground
- Culvert design standards (w/o culvert sizing)
  - 25-yr flood: 0.5' h_L; maximum 5 fps
  - 50-yr flood: 1.0' h_L; maximum 6.5 fps