Does Increased Rainstorm Intensity Pose Risks to County Infrastructure? A study from Nicollet and Sibley Counties in Minnesota

By

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Under the supervision of Laura Triplett

ABSTRACT

Based on observations over the past 30 years and results of climate models, climate scientists predict that the Midwest will receive more rainstorms of higher intensity in the coming years. South-central Minnesota, is underlain by clay-rich soils that limit the infiltration rate of water; therefore, agricultural practice has evolved to rely on systems of open drainage ditches that rapidly remove water from cropland. These drainage systems, common in south-central Minnesota counties like Nicollet County and Sibley County, not only pass between fields but also under important infrastructure such as roads through culverts. We know little about how increased storm intensity might affect this infrastructure, so this study aims to evaluate the impact of intense rainstorms on agricultural ditches and related infrastructure. To do this, a HEC-RAS hydrologic model coupled with the HEC-GeoRAS toolbar in ArcMap was employed. Three model scenarios were used to assess the ditch system under conditions of average flow, 2-year flood, and 20-year flood discharge volumes. The results showed that during the 2-year flood discharge scenario, three of the 34 culverts in the watershed flooded and the same culverts were flooded during the 20-year flood discharge scenario. All three of the flooded culverts lay within fields and not beneath a major county road. These preliminary results suggest that the small culverts beneath field access roads may need to be updated as storm intensities increase. The results of this study also highlight potential weaknesses in the ditch system that would benefit from further modeling involving sediment and groundwater factors.

ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

FIGURES AND TABLES

INTRODUCTION

Open drainage ditches (***Figure 1***) can be found all over southern Minnesota and are an important structure for growing crops like corn and soybeans in regions where natural soils drain slowly. These structures swiftly drain water from agricultural fields to avoid flooding and standing water, which can lead to ruined crops (Needelman et al. 2007). Ditches receive water that flows out of drainage tiles beneath the fields, and transport it to natural streams and rivers. Open drainage ditches usually have a "V"-shaped cross-section and have vegetation growing on both sides (***Figure 1***). In southern Minnesota, known for its sprawling agricultural fields, it is not uncommon to see this type of drainage ditch between fields and occasionally crossing beneath roads when necessary.

Figure 1. This is an example of an open drainage ditch in south-central Minnesota.

Southern Minnesota is dominated by corn and soybean agriculture. For water to be drained from agricultural fields relatively quickly, drainage ditches were implemented to collect the excess water and direct it toward larger streams and rivers. These ditches usually follow the path of what were once natural streams and gullies and by straightening and deepening them, farmers have enabled the water to drain more quickly and predictably off the fields. However, during rain events these ditches can fill quickly in some areas, leading to possible flooding hazards surrounding infrastructure such as roads. One example of infrastructure being damaged occurred in June 2014 in Belle Plaine, MN. Sibley County Road 6 (Scenic Byway) was washed out (***Error! Reference source not found.***) after approximately 7.6 inches of rain fell in a single storm (Ruud, 2014). Another instance where infrastructure was severely damaged by flooding occurred in Courtland, MN in June 2016 when 506th Street was completely washed out (***Error! Reference source not found.***) (Buletti, 2016).

Schottler et al. (2014) determined that precipitation that was once being captured in depressional areas and lost to evapotranspiration is now being transported to rivers by ways of artificial drainage. Therefore, the artificial drainage leads to the residence time for the water both on the landscape and in the watershed to be decreased and the amount of water flowing to the receiving water to be increased. Following this logic suggests that as more intense rainstorms occur, the more water will be flowing through the open drainage ditches. In the near future, this region of the United States is predicted to receive more intense rainstorms with increased precipitation based on 30 years of observations and climate models (Groisman et al. 2001, Groisman et al. 2004, and Kunkel et al. 2013). This leads to the ultimate research question of this

Figure 3. (Above) Road washout in Belle Plaine, MN in 2014. (Ruud, 2014)

Figure 3. (Left) Road washout in Courtland, MN in 2016. (Buletti, 2016)

study; does increased rainstorm intensity pose risks to county infrastructure (roads and drainage ditches)?

In order to determine the impact that greater rainstorm intensities may have on agricultural ditches and county roads a hydrologic model, Hydrologic Engineering Center-River Analysis System (HEC-RAS), was used. A model was chosen as the best way to represent the impact of increased rainstorm intensities due to the fact that it is better for planning and allows you to manipulate one or more variables at a time. In this way, we can model scenarios of multiple rainstorm sizes and their respective effects on the ditch system.

GEOLOGIC SETTING

During the last glaciation, which occurred more than 10,000 years ago, much of what is now Minnesota was covered with glaciers. As they melted and retreated, unsorted sediment that had accumulated within the glacier as it scoured across the earth’s surface was deposited as till. The till filled in pre-existing valleys and the glaciers smoothed peaks, which created a flatter terrain (Wall, 2014).

The surficial geology of south-central Minnesota is dominated by glacial and post-glacial deposits associated with the Des Moines Lobe. This glacial lobe originated from the northwest and flowed southeastward, reaching as far south as present-day Des Moines, Iowa. The sediment carried by the Des Moines lobe is sand-, silt-, and clay-rich (Meyer et al. 2012). This surficial geology controls the ability of rainfall and snowmelt to infiltrate present-day soils. Clay-rich soils, in particular, do not let water infiltrate very well due to fine grain size and the long and platy shape of the grains.

The area for this case study, which is representative of the Nicollet and Sibley County regions, is a small watershed, Eight Mile Creek (***Figure 4***). Approximately 14.1% of the watershed is composed of Canisteo-Glencoe complex, which is characterized as poorly drained. Another large percentage of the watershed is composed of poorly drained Canisteo clay loam contributing about 7.6%. Both of these soil types can be considered prime farmland if drained (Soil Survey, 2018 and Jackson, 1994).

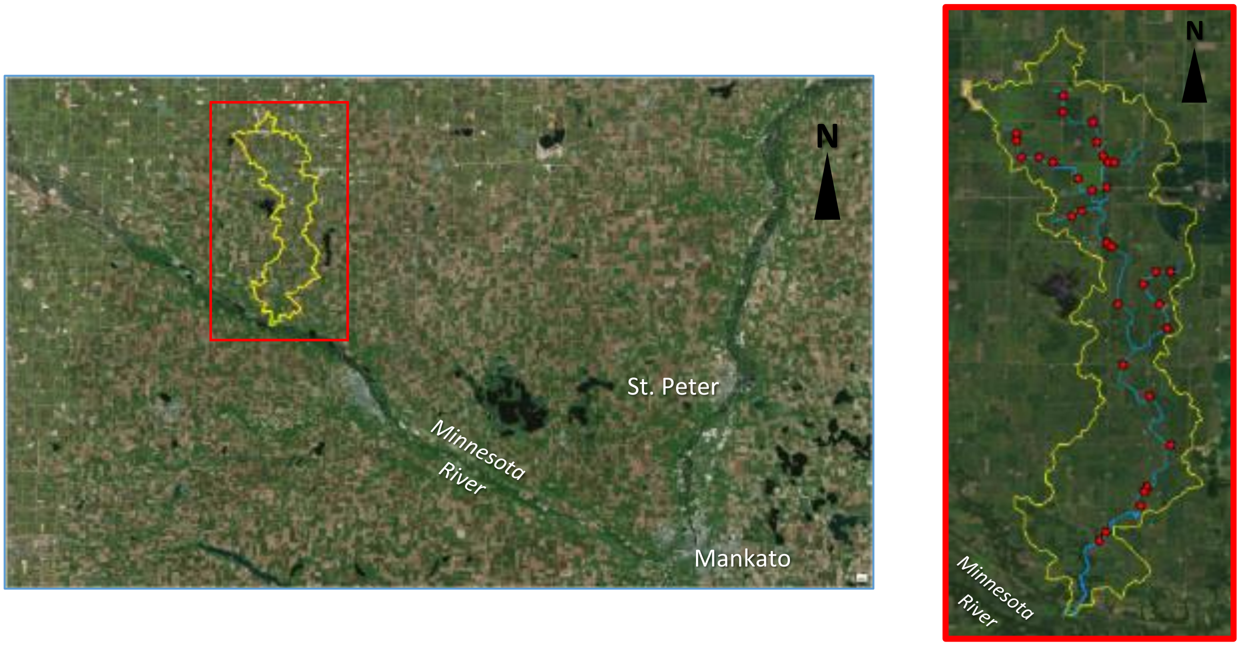

Figure 4. Map of the study area of Eight Mile Creek. The bottom half of the watershed is in Nicollet County and the north half is in Sibley County. The 33 culverts are displayed as red dots and the ditch system is in blue.

METHODS

The HEC-RAS (Hydrologic Engineering Center-River Analysis System) software system available online form the Army Corps of Engineers, coupled with the HEC-GeoRAS toolbar in ArcMap, was the hydrologic model chosen for this study. HEC-RAS was the model of choice due to multiple reasons: it is free and available online to the public, it has the capabilities to run surface water scenarios, and it is requires no coding experience unlike other hydrologic models.

Before the model could be run, geometry data for the Eight Mile Creek watershed needed to be completed so the model would know how water should flow through the watershed.

The methods in a HEC-RAS tutorial by Venkatesh Merwade (2016) were followed for the preprocessing of the geometry data. This included digitizing the stream lines, flow lines, banks, culvert locations, and cross sections into respective feature classes at regular intervals along the whole ditch system based on the digital elevation model (DEM) data and aerial images. The DEM was provided by Eric Miller of the Soil and Water Conservation District and the aerial imaging was provided in ArcMap under the ‘Basemap’ options. This information was then exported from ArcMap and uploaded into the HEC-RAS program.

Once in the HEC-RAS program, the culvert material, shape, height, and length measurements were added. The culvert measurements were taken both in the field using a measuring tape and from Nicollet County records provided by Eric Miller. Manning’s n and entrance coefficient values were also added to the model and were determined using the HEC-RAS manual provided online from the Army Corps of Engineers. See **Appendix A** for the culvert information. The process for running the HEC-RAS program was conducted, again, by following the tutorial by Venkatesh Merwade (2016). The measurements, shape, and material of the culverts within the ditch system were also used to simulate the effect of increased water flow from more intense rainstorms.

Three flow profiles were calculated for the Eight Mile Creek watershed. These profiles included flow measurements for each reach of the Eight Mile ditch system (***Figure 5***) at average flow, 2-year flood discharge, and 20-year flood discharge. The values for these flows were determined based on the Department of Natural Resources (DNR) hydrograph based on flow measurements in nearby Seven Mile Creek, which is a similar watershed on the east side of the county. Seven Mile Creek and Eight Mile Creek are similar in size (to within 1,000 acres). Also, both watersheds have most of their area on the low-slope glacial till plain, then the trunk stream drains steeply down to the Minnesota River (***Figure 6***). The ditch systems are fully channelized, and only meander once they exit the farm fields on the uplands. And, both have similar ditches in terms of size, shape, and vegetation.

The similarities between the two watersheds allows for an appropriate use of the flow measurements from Seven Mile Creek in this study for Eight Mile Creek. Higher flow values were assigned to reaches that are being fed by other reaches compared to flow values for reaches being fed by farmland runoff and tile drains. The flow measurement for each reach was a ratio between the reach's watershed to the whole upstream watershed (***Table 1***). After HEC-RAS ran the model the results were imported back into ArcMap and used to created inundation maps using the HEc-GeoRAS toolbar.

Figure 5. The layout of the Eight Mile Creek ditch system in HEC-RAS. Each section of the system is labeled as a reach.

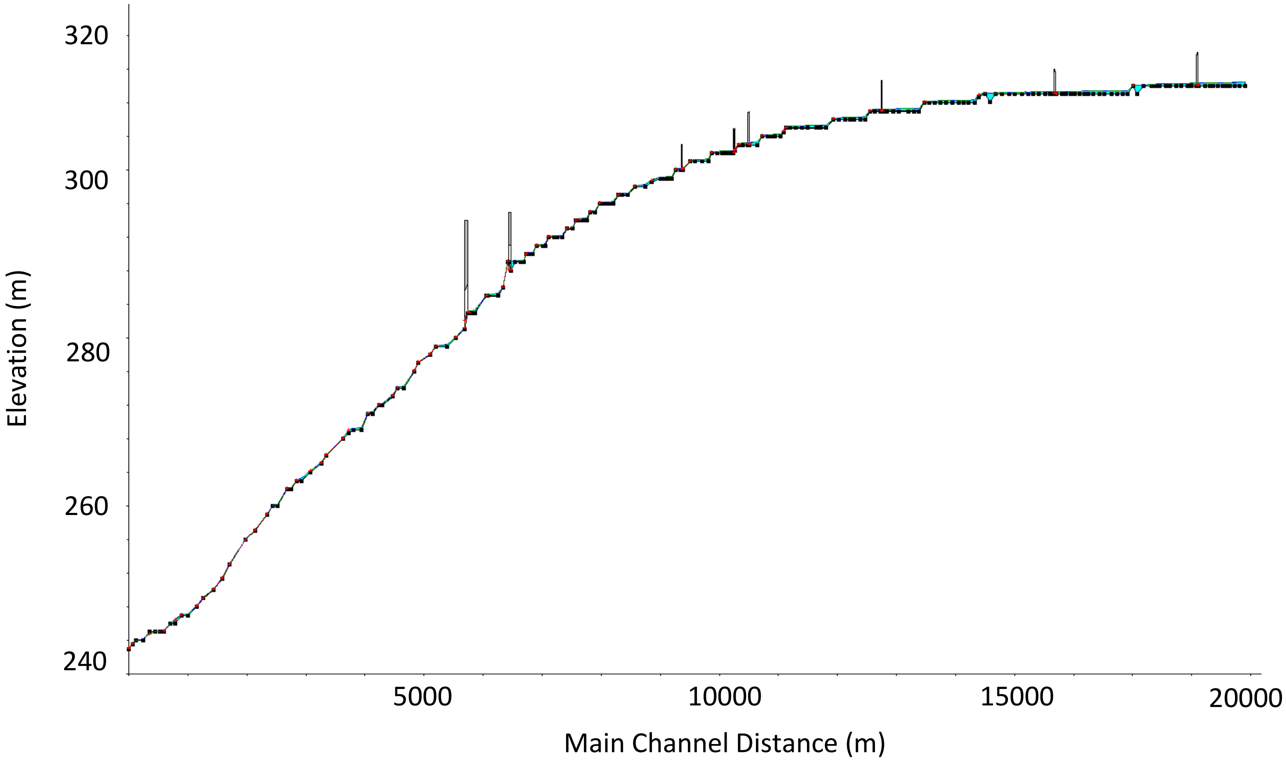

Figure 6. The elevation profile of Reach 11 with the left side of the graph representing downstream. The vertical lines represent culverts located along the channel. The upstream section of the Eight Mile ditch system is very flat, whereas the downstream section of Reach 11 shows significant elevation decline.

Table 1. The discharge values in cubic feet per second (cfs) for each reach for each scenario run through the model.

		Scenario			
		Average (cfs)	*2-year Flood (cfs)*	*20-year Flood (cfs)*	*1000 cfs*
Reach	*1*	5.9	74.3	110.7	148.7
	2	6.0	75.3	112.2	150.5
	3	1.8	22.5	33.6	45.0
	4	7.8	97.8	145.7	195.6
	5	2.6	32.7	48.8	65.5
	6	10.4	130.5	194.5	261.1
	7	16.4	204.9	305.3	409.7
	8	1.2	14.4	21.4	28.8
	9	17.5	219.3	326.7	438.5
	10	2.5	30.7	45.8	61.5
	11	20	250	372.5	500

RESULTS

After the HEC-RAS model ran the three scenarios, the data were processed in ArcMap in order to create flood inundation maps. The flood inundation maps showed that two culverts were flooded during the average discharge scenario, three were flooded during the 2-year flood discharge, and the same three flooded during the 20-year flood discharge scenario (***Figure 7***, ***Figure 8***, and ***Figure 9****)*. All of the culverts that flooded were located within reaches that did not have water flowing in from an upstream reach. This means that all of the water flowing through them is from surface runoff or tile drains.

None of the larger culverts beneath county roads flooded, so a fourth scenario was run through the model to determine at what point the larger culverts would fail. This scenario was chosen to consist of 1000 cfs discharge, which is higher than any record on the Seven Mile Creek flow measurement dataset that extends back to 2002. There was not enough data in the Seven Mile Creek dataset to determine a 100-year flood volume so it is unknown whether 1000 cfs is close to a 100-year flood volume or not. After running this scenario two more culverts were flooded; however, these two were still small culverts in the middle of fields and were not beneath county roads.

During the 2-year flood, 20-year flood, and 1000 cfs scenarios there was a buildup of water behind County Road 5 at the location of Culvert 1 in Reach 11. The water built up behind the culvert did not technically flood the culvert and overtop the road, but it does highlight an area of flood potential (***Figure 10***).

DISCUSSION

The HEC-RAS model output depicted three culverts being affected by the flow discharge scenarios. These were culverts number 14, 29, and 33, none of which are beneath county roads. Culvert 14 is located in Reach 10, Culvert 29 is located in Reach 1 and Culvert 33 is located in Reach 8 (***Figure 5***). Culvert 14 and Culvert 33 were interestingly flooded for all three scenarios (***Figure 8*** and ***Figure 9***). The reason behind this could be a geometry issue within the HEC-RAS model possibly due to the LiDAR picking up vegetation as the bottom of the ditch. In this way, the ditch channel would appear shallower and thus easier to flood. The other possible reason behind this could be that these particular culverts may be in serious need of replacement. Given that Culvert 33 is placed beneath a driveway to a farm it is more likely that there is a geometry issue in the model rather than the driveway to someone’s farm being continually flooded.

On the other hand, Culvert 29 was only flooded in the 2-year and 20-year flood scenarios (***Figure 7***). This culvert is a corrugated metal pipe that is 6 feet in diameter. These are common types of culverts used for moving smaller amounts of water compared to the larger concrete box and ellipse shaped culverts underneath most of the county roads in the watershed. From the result of this culvert being flooded during the 2-year and 20-year flood scenarios it can be assumed that the size of this culvert may be too small for the amount of water that needs to flow through it during heavy rainstorms.

None of the larger concrete culverts were flooded during the three scenarios, which means that they are most likely not undersized and can handle the amount of water flowing through them. For further studies it would be important to determine the point at which some of these culverts failed. Another flood discharge scenario could be run through the model to provide important information to the county in terms of when they should be concerned with increasing the sizes of the culverts. It would also be interesting to see which type of culverts were the most effective. The two counties have different styles of culverts; Nicollet County using box culverts and Sibley County using ellipse and circular culverts.

More detailed observations in the field would be helpful for making this model more accurate in order to portray the actual behavior of the ditch system. For example, the flow values for the scenarios were taken from flow data collected from the Seven Mile Creek watershed instead of Eight Mile Creek since there is no water monitoring station on the mainstem of the Eight Mile Creek. The values may not be significantly different; however, the watersheds may react differently to sudden surges of increased precipitation in ways unknown to us. For example, differences in data could stem from the fact that Seven Mile has two main tributaries whereas Eight Mile only has one. This could impact the way increased precipitation influences the water monitoring station downstream because there may be a quicker response in Seven Mile versus Eight Mile. The Eight Mile ditch system may be longer than the Seven Mile ditch system since the two tributaries into Seven Mile Creek make the watershed shorter and wider than the Eight Mile Creek watershed; however, the watersheds are extremely similar in area. It would also be more accurate to include where the tile drainage pipes are and how much flow they are contributing to the ditch they are entering. In this way the addition of water flow in the ditches in the model runs would be more like the real-life situation, providing more detailed and accurate results. Despite this, it would not be possible to model every watershed in Minnesota with the correct data, which means that for the purpose of this particular study it was reasonable to use data from a very similar watershed.

Another way to make the model used for this study more accurate would be to couple it with a groundwater model and potentially a model that can simulate sediment movement. These two factors are important in this study because they could have a large impact on the failure of culverts. The HEC-RAS model that was used only factors in the surface water and cannot account for the amount of sediment build up behind a culvert and it does not factor in the effect that groundwater plays in the stability beneath the road bed. If these two ideas were applied to the HEC-RAS model the situation of water build up behind County Road 5 and Culvert 1 in Reach 11 the road may actually prove to fail (***Figure 10***). The reason that the larger county culverts do not flood in the model results may ultimately be due to these reasons and could explain why the county culverts did not seem to have trouble draining the excess water flowing through the ditch system.

CONCLUSION

Following 30 years of observations and numerous climate models, climate scientists have predicted an increase in rainstorm intensity in the Midwest region in the coming years. This could be problematic for agricultural areas such as south-central Minnesota due to the reliance on open drainage ditches. Based on the results of the HEC-RAS model it was determined that the small culverts beneath field access roads were most at risk of failure while the larger county culverts beneath county roads were less at risk. However, this does not mean that counties in south-central Minnesota should not be prepared for culvert failures as bigger, more intense storms begin to develop in this region. To fully understand the situation it is suggested that further modeling is done by coupling HEC-RAS with groundwater and sediment models to understand the effect on the stabilization of County Road 5 above the box culvert in Nicollet County specifically, as this area may be a point of weakness.

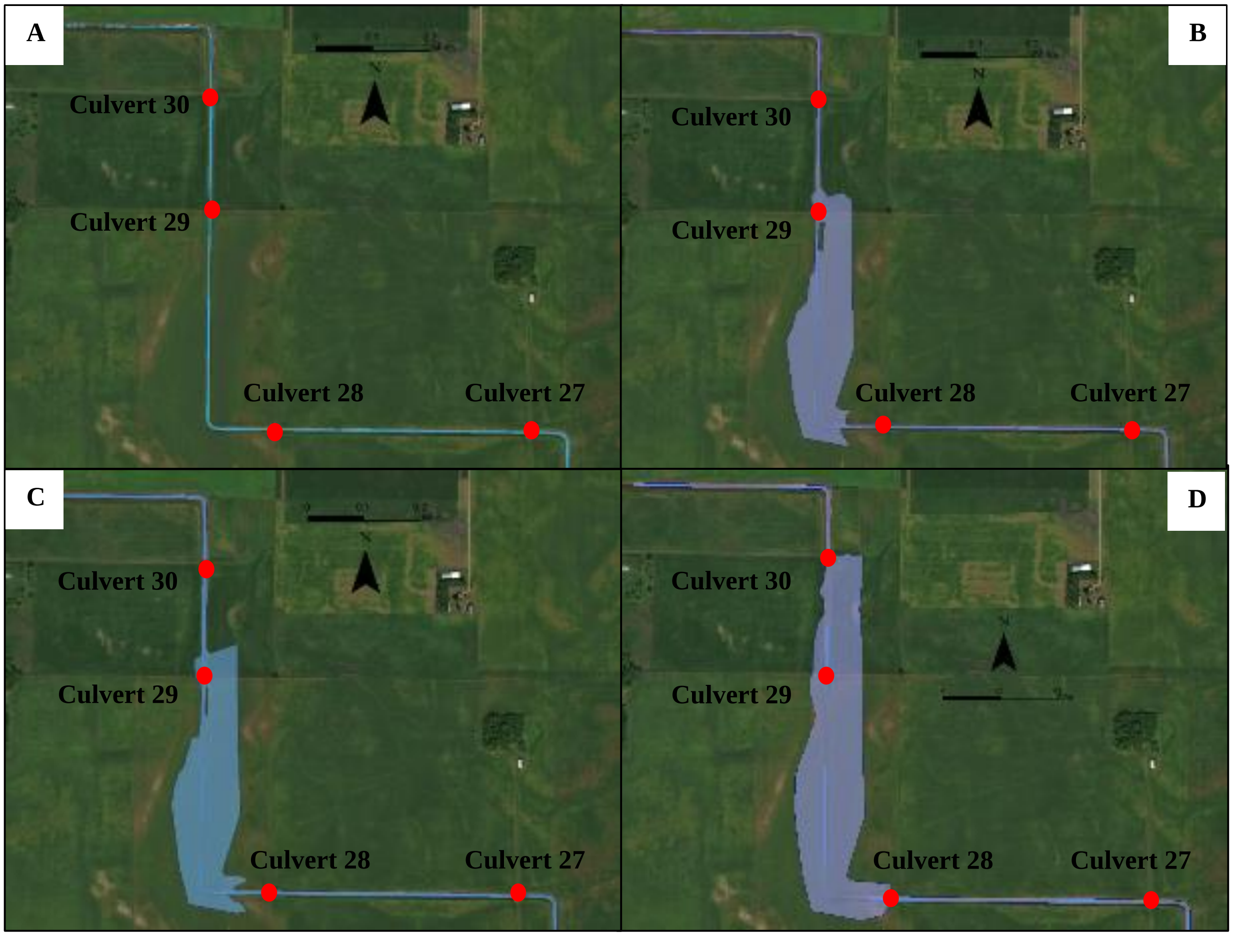

Figure 7. All three of these photos are aerial views of a portion of Reach 1 with the culverts symbolized by red dots. **A**. Depicts the average flow impact. **B**. Depicts the 2-year flood flow impact. **C**. Depicts the 20-year flood flow impact. **D**. Depicts the 1000 cfs flow impact, which included another flooded culvert (Culvert 30). As is seen in the photos, Culvert 29 was flooded by the 2-year and 20-year flood and the 1000 cfs flow scenarios.

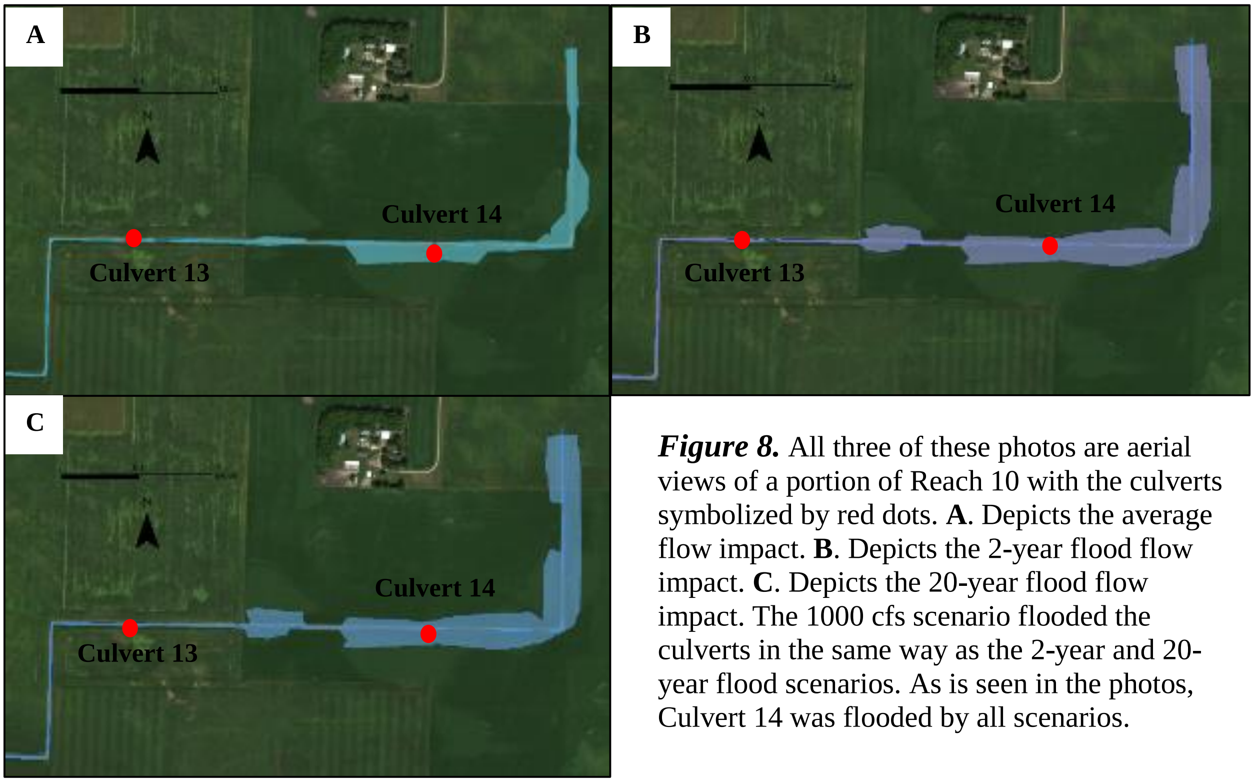

Figure 8. All three of these photos are aerial views of a portion of Reach 10 with the culverts symbolized by red dots. **A**. Depicts the average flow impact. **B**. Depicts the 2-year flood flow impact. **C**. Depicts the 20-year flood flow impact. The 1000 cfs scenario flooded the culverts in the same way as the 2-year and 20-year flood scenarios. As is seen in the photos, Culvert 14 was flooded by all scenarios.

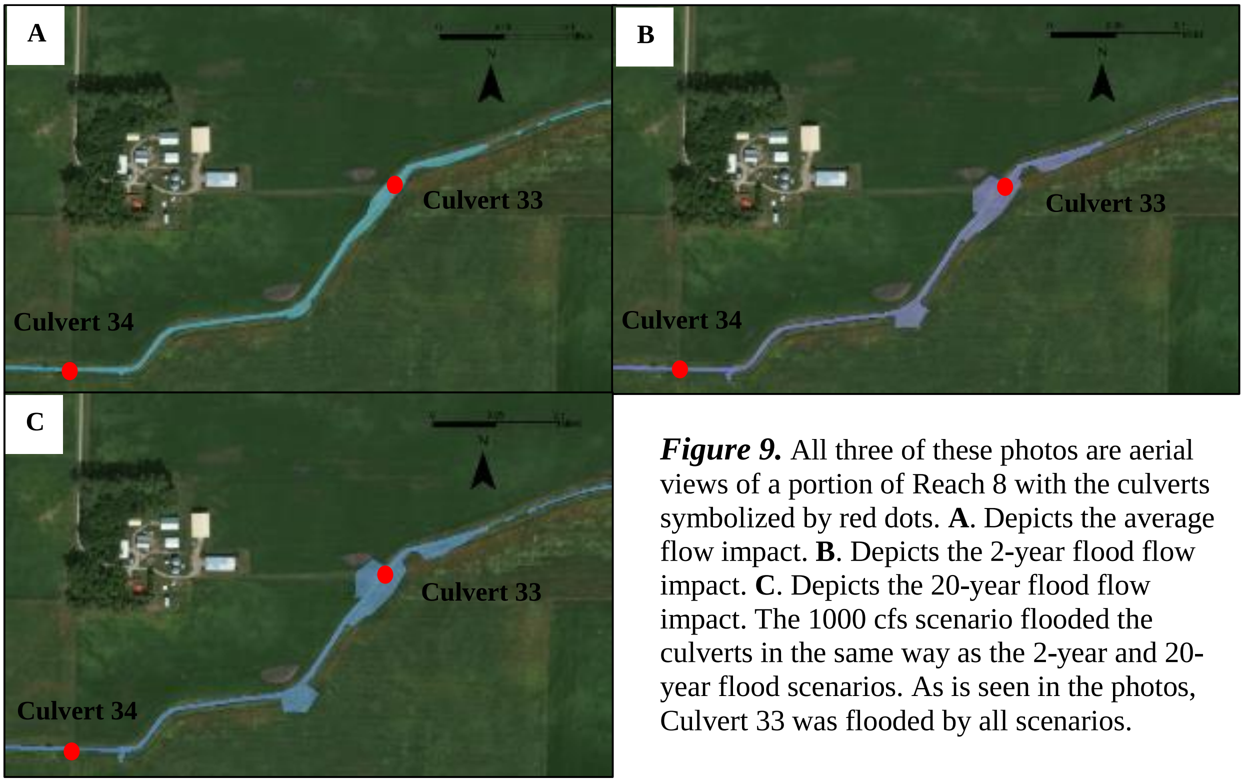

Figure 9. All three of these photos are aerial views of a portion of Reach 8 with the culverts symbolized by red dots. **A**. Depicts the average flow impact. **B**. Depicts the 2-year flood flow impact. **C**. Depicts the 20-year flood flow impact. The 1000 cfs scenario flooded the culverts in the same way as the 2-year and 20-year flood scenarios. As is seen in the photos, Culvert 33 was flooded by all scenarios.

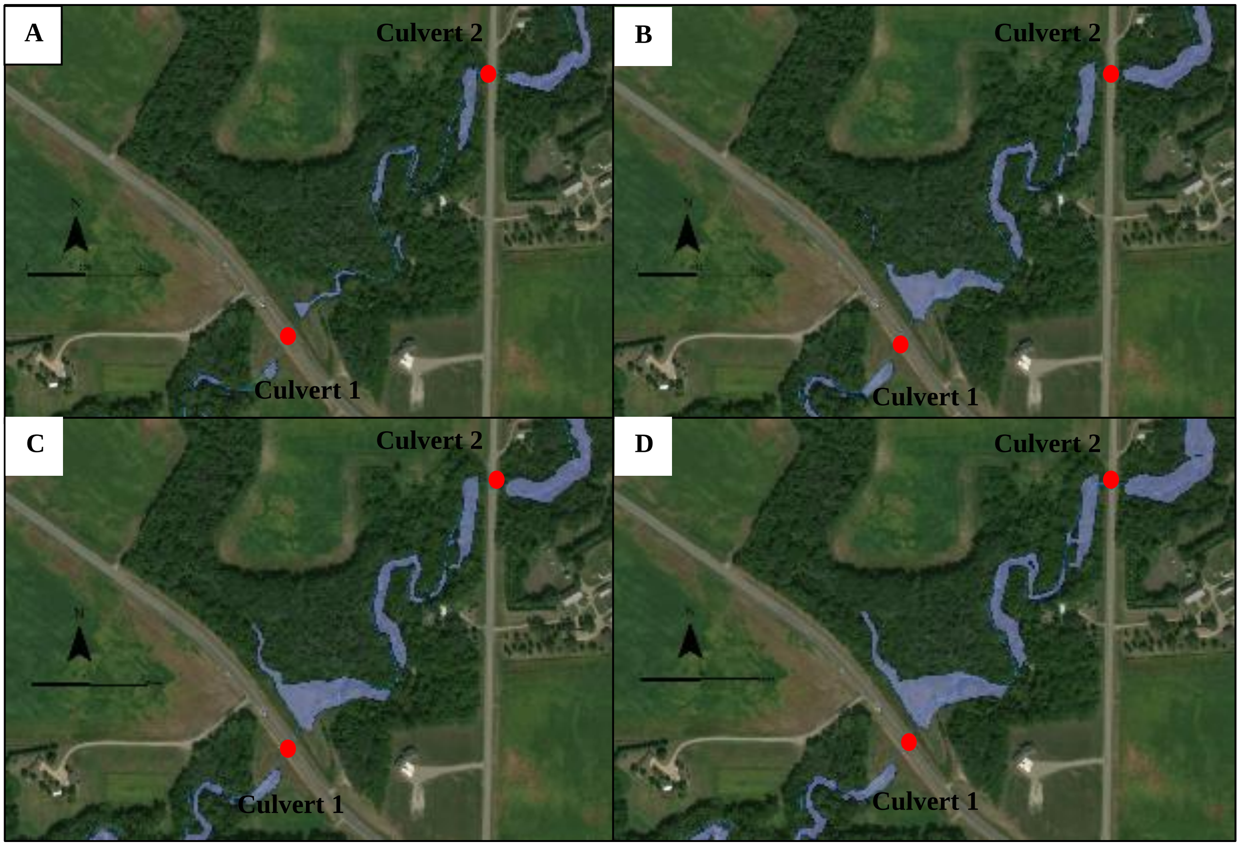

Figure 10. All three of these photos are aerial views of a portion of Reach 11 with the culverts symbolized by red dots. **A**. Depicts the average flow impact. **B**. Depicts the 2-year flood flow impact. **C**. Depicts the 20-year flood flow impact. **D**. Depicts the 1000 cfs flow scenario impact. The road that Culvert 1 runs beneath is County Road 5 which may be subject to stability issues.

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APPENDIX A: Culvert Information

Culvert	Shape	Single or Double	Material	Span (ft)	Rise (ft)	Length	Manning's n	Entrance coefficient
1	Box	Single	Concrete	11.5	11.5	204	0.011	0.5
2	Box	Single	Concrete	10	10	145	0.011	0.5
3	Box	**Double (3 ft between)**	Concrete	10	10	48	0.011	0.5
4	Box	**Double (3 ft between)**	Concrete	9	9	47	0.011	0.5
5	Box	Single	Concrete	13	13	82	0.011	0.5
6	Not Culvert							
7	Box	**Double (5 ft between)**	Concrete	12	12	50	0.011	0.5
8	Oval	**Double (6 ft between)**	Concrete	12.5	9 (4.5)	70	0.011	0.7
9	Box	**Double (2 ft between)**	Concrete	12	12	100	0.011	0.5
10	Oval	**Double (5 ft between)**	Concrete	12	10	62	0.011	0.7
11	Circular	Single	Corrugated Pipe	6	6	80	0.024	0.9
12	Circular	Single	Corrugated Pipe	6	6	61	0.024	0.9
13	Circular	Single	Corrugated Pipe	6	6	45	0.024	0.9
14	Circular	Single	Corrugated Pipe	6	6	43	0.024	0.9
15	Circular	Single	Corrugated Pipe	6	6	53	0.024	0.9
16	Box	**Double (4 ft between)**	Concrete	12	12	109	0.011	0.5
17	Box	**Double (4 ft between)**	Concrete	12	12	100	0.011	0.5
18	Circular	Single	Concrete	12	12	167	0.011	0.7
19	Circular	Single	Corrugated Pipe	6	6	81	0.024	0.9
20	Circular	Single	Corrugated Pipe	6	6	86	0.024	0.9
21	Oval	Single	Concrete	12	4	93	0.011	0.7
22	Circular	Single	Corrugated Pipe	6	6	113	0.024	0.9
23	Circular	Single	Corrugated Pipe	6	6	73	0.024	0.9
24	Circular	Single	Corrugated Pipe	6	6	90	0.024	0.9
25	Circular	Single	Corrugated Pipe	6	6	60	0.024	0.9
26	Circular	Single	Concrete	6	6	73	0.011	0.5
27	Circular	Single	Concrete	6	6	73	0.011	0.5
28	Circular	Single	Concrete	6	6	54	0.011	0.5
29	Oval	Single	Concrete	8	4	63	0.011	0.7
30	Oval	Single	Concrete	8	4	63	0.011	0.7
31	Circular	Single	Concrete	6	6	55	0.011	0.5
32	Circular	Single	Concrete	10	10	184	0.011	0.5
33	Circular	Single	Corrugated Pipe	6	6	40	0.024	0.9
34	Circular	Single	Corrugated Pipe	6	6	35	0.024	0.9