EVALUATING A TWO-STAGE ROADSIDE DITCH DESIGN TO IMPROVE ENVIRONMENTAL PERFORMANCE

Final Report
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16. **Abstract**

Roadside ditches are integral components of watershed-scale hydrologic processes that are designed to rapidly convey surface runoff from roads to receiving streams. In this project, a two-stage roadside ditch was constructed during expansion of Highway 30 in east-central Iowa. Pre-construction monitoring and development of a preliminary design was conducted in 2020 and 2021, and between January to April 2021, the two-stage roadside ditch was graded, seeded and finalized. Post-construction monitoring was originally slated for 2021-2023, but monitoring efforts were compromised on several occasions and the monitoring period extended into 2024. Performance monitoring of the two-stage ditch site focused on vegetation conditions, hydraulic changes and water quality improvements. Native vegetation was established successfully and seeding densities increased while invasive species were reduced. Hydraulic modeling for design storms indicated the two-stage ditch reduced peak flow rates, total water volume and maximum velocities relative to a standard single stage configuration. Water quality monitoring conducted upstream and downstream of the two-stage ditch included stage, turbidity and dissolved constituents. Turbidity measurements revealed a statistically significant impact of the two-stage ditch on daily mean turbidity with the difference in turbidity between the upstream and downstream monitoring sites increasing following construction. Using siting criteria established for the project, 314 roadside ditches were identified across Iowa that could be converted to a two-stage design, potentially reducing particulate phosphorus and organic nitrogen loads. Overall, the construction and monitoring results of the two-stage roadside ditch were encouraging for reducing flood risks and improving water quality across the State of Iowa.

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EXECUTIVE SUMMARY

Conventional trapezoidal roadside ditches rapidly and efficiently deliver runoff, sediment and nutrients to downstream surface water systems. However, ditch sustainability is often threatened from erosional downcutting and excessive sedimentation, and many ditches require ongoing maintenance to ensure their long-term performance. In agricultural regions, some drainage ditches are being converted to a two-stage design whereby the conventional trapezoidal drainage ditch is modified to include floodplain benches constructed alongside the main stream channel. During storm events, the benches become inundated, allowing flood flows to spread out and slow down. There is reason to believe that two-stage ditches could be utilized along roadside environments to increase the long-term sustainability of ditches while reducing downstream flooding and water quality impacts.

The goals of this project were to: 1) evaluate the performance of two-stage roadside ditches for their ability to improve water quality by reducing sediment and nutrient concentrations; 2) quantify the effects of a two-stage roadside ditch on flow reductions occurring from the two-stage ditch design compared to the pre-construction ditch; 3) identify potential locations of other roadside ditches in Iowa for conversion to a two-stage design and quantify the potential impact of conversions on statewide nutrient export; and 4) discuss the challenges and opportunities associated with converting roadside ditches to a two-stage design.

A study site along Highway 30 was selected in consultation with the Iowa Department of Transportation (IDOT) because the section was being rebuilt as part of a major expansion project that converted the two-lane highway to a divided four-lane highway. The ditch site extended approximately 450 meters along the road right-of-way and receives drainage from a 194 ha watershed.

Pre-construction monitoring and development of a preliminary design was conducted in 2020 and 2021, and between January to April 2021, the two-stage roadside ditch was graded, seeded and finalized. Post-construction monitoring was originally slated for 2021-2023, but monitoring efforts were compromised on several occasions and the monitoring period extended into 2024. Roadway construction associated with Highway 30 expansion, flow losses to an unknown tile and unplanned post-construction excavation plagued the project. Eventually, an unplanned excavation of the two-stage channel on June 19-22, 2024, effectively ended the monitoring project.

Performance monitoring of the two-stage ditch site focused on vegetation conditions, hydraulic changes and water quality improvements. Native vegetation was established successfully and seeding densities increased while invasive species were reduced. Patterns of native species establishment in this two-stage ditch appeared to be very similar to establishing native species in roadsides.

A hydraulic model of the ditch site was constructed for four design storms (1-year, 2-year, 5-year, and 10-year) to compare single stage to a two-stage configuration. Peak flow rates were reduced by 22%, 21%, 7.5%, and 4.3%, respectively, while water volume reductions were near 6%.

Maximum velocities throughout the ditch corridor also decreased, with reductions spanning 32% (1-year) – 45% (10-year).

Water quality monitoring conducted upstream and downstream of the two-stage ditch included stage, turbidity and dissolved constituents. Turbidity measurements revealed a statistically significant impact of the two-stage ditch on daily mean turbidity with the difference in turbidity between the upstream and downstream monitoring sites increasing following construction. Upstream-downstream grab sampling for dissolved ions during four post-construction events showed similar patterns at upstream and downstream sites offset by a lag in travel time between the two sites, but no statistical differences were observed.

Using siting criteria established for the project, 185 potential sites along state highways and 129 sites along county roads where roadside ditches were identified that could be converted to a two-stage design. If all of these ditches were converted to a two-stage design, potential roadside ditch projects have the capacity to remove 4,290 kg/yr of particulate phosphorus and 31,700 kg/yr of organic nitrogen across Iowa.

Although the project was compromised by unforeseen challenges that limited the ability of monitoring to fully evaluate its efficacy of the two-stage design, the construction and monitoring results were sufficiently encouraging that the design should be reconsidered at a new site. The two-stage roadside joins other roadway innovations, such as on-road structures, low-grade weirs, and vegetation management, as new technologies available to IDOT for reducing flood risks and improving water quality across the State of Iowa.

1. INTRODUCTION

1.1 PROBLEM STATEMENT

Conventional trapezoidal roadside ditches rapidly and efficiently deliver runoff, sediment and nutrients to downstream surface water systems. However, ditch sustainability is often threatened from erosional downcutting and excessive sedimentation, and many ditches require ongoing maintenance to ensure their long-term performance. Excessive erosion in ditches contributes to road and shoulder instability whereas excessive sedimentation fills the ditches and limit their ability to drain water runoff in the long term.

In agricultural regions, roadside ditches receive drainage from cropped fields and transport nutrient-laden water from the fields to the receiving stream or river. The export of nutrients as nitrate-nitrogen (NO3-N) and phosphorus (P) continues to be a major problem in Iowa, contributing to degradation of streams, lakes and rivers at local and regional scales, including the Gulf of Mexico (Turner et al., 2008). Consequently, many Midwestern states are adopting nutrient reduction strategies to reduce nutrient export (Christianson et al., 2017). Strategies that enhance nutrient processing in agricultural regions while minimizing loss of crop production are highly desired (McLellen et al., 2015).

One nutrient reduction strategy used in other Midwestern states, including Indiana and Minnesota, is converting agricultural drainage ditches to a two-stage design. Ditches are modified by converting the conventional trapezoidal ditch into one that better replicates the features of a natural stream through the addition of adjacent benches. While this practice has been adopted for agricultural drainage ditches, it has not been adapted to a roadside environment. This project evaluating the efficacy of the two-stage design for a roadside ditch application serves to address two challenges posed above, increasing ditch sustainability and reducing nutrient export from agricultural watersheds.

1.2 LITERATURE REVIEW AND MOTIVATION FOR PROJECT

Roadside ditches located throughout urban and rural landscapes are integral components of watershed-scale hydrologic processes (Wemple et al., 2017; Buchanan et al., 2013; Forman and Alexander, 1998). As linear features, they cross topographic boundaries and serve to concentrate flow from roadways and the catchment areas that drain into them (Wemple et al., 2017), efficiently delivering runoff in downstream surface water systems. Roadside ditches lining more than 6.3 million km of public roads in the U.S. have the potential to significantly alter watershed-scale hydrology (Buchanon et al., 2012) and, inherently, play a significant role in downstream sediment and pollutant transport (Sheriden and Noske, 2007; Buchanan et al., 2013).

Current roadside ditches are designed to rapidly convey runoff from roads to receiving streams (Figure 1-1). Normal ditch depth for rural highways is five feet and the normal ditch width is 10 feet and they are typically designed to increase width with the direction of flow to reduce the risk of erosion (Iowa DOT Design Manual). However, many roadside ditches are threatened by excessive sedimentation or erosion. It is understood by roadside managers that when sedimentation levels in the ditch increase to a level where water flow is impeded, maintenance of the roadside ditch is required (Wendling 2019). This maintenance involves digging out the deposited soil sediments, transporting to nearby fields or hauling off-site, re-grading the ditch, and re-seeding the vegetation within the ditch, which can cost approximately $20 USD/m of ditch (Wendling 2019). When erosion occurs in the ditch, ditch sideslopes are impacted and the stability of the roadway may be threatened.

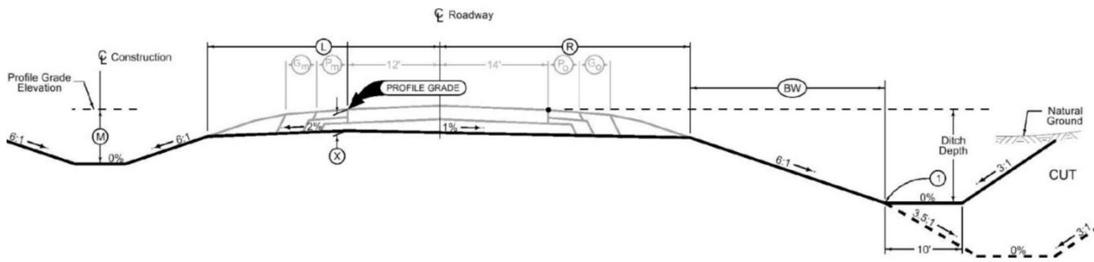

Figure 1-1. Typical cross section of a normal ditch (Iowa DOT Office of Design, Design Manual, Chapter 1, 3G-1).

Recent work in Iowa has highlighted the potential role that roadside ditches can play in nutrient reduction efforts. For example, in a study of roadside ditches in Lime Creek watershed located in Buchanan County, Schilling et al. (2018) reported that groundwater NO3-N concentrations were observed to decrease from upgradient (10.6) to downgradient (4.3 mg/l) locations (average 60% reduction). Streeter et al. (2019a) quantified sedimentation of silt-sized particles, TN and soil carbon in the same watershed estimating that 42 Mg/ha of TC and 5 Mg/ha of TN are being stored in agricultural ditch soils. Lastly, Streeter and Schilling (2019b) evaluated the relation of catchment soil erosion to ditch sedimentation in Lime Creek ditches and found that installation of catchment conservation practices could significantly reduce soil erosion and ditch sedimentation. Schilling et al. (2018) suggested that a good optimization path for increasing retention and infiltration capacity of ditches could be done through two-stage ditch designs.

In alternative two-stage ditch designs, the conventional trapezoidal drainage ditch is modified to include floodplain benches constructed alongside the main stream channel. During storm events, the benches become inundated, allowing flood flows to spread out and slow down (Roley et al., 2012). This reduces the sheer stress of the high flows and reduces erosion due to bank slumping and undercutting (Powell et al., 2007). In addition, the benches serve to reduce nutrient export by increasing water residence time and sedimentation during inundation, thereby enhancing vegetation assimilation of nutrients and increasing infiltration and denitrification (Roley et al., 2012; Davis et al., 2015; Hodaj et al., 2017; Mahl et al., 2015). For example, Davis et al. (2015) reported that turbidity, sediment, and total P were significantly reduced during floodplain inundation at four two-stage ditch sites in northern Indiana.

To date, two-stage ditches have been primarily installed in Midwestern agricultural settings along existing drainage channels. The two-stage ditch is an alternative ditch design applied to conventional trapezoidal ditches in agricultural regions whereby floodplain benches are constructed alongside the main stream channel (Figure 1-2). During storm events, the two-stage design mimics natural floodplain processes and the benches become inundated so the flood flows can spread out and slow down. This reduces the sheer stress of the high flows and reduces bank slumping and undercutting due to erosion (Powell et al., 2007).

In addition, the benches also serve to reduce nutrient export by increasing water residence time during inundation, allowing for increased sediment (and phosphorus) deposition, enhancing vegetation assimilation of nitrogen and phosphorus and increasing infiltration and denitrification. Two-stage designs have been successfully developed for agricultural drainage ditches in other US states (e.g., Hodaj et al., 2017; Mahl et al., 2015). The associated research illustrates their success in reducing nutrient export (Davis et al., 2015; Mahl et al., 2015) and increasing denitrification (Roley et al., 2012). For example, Davis et al. (2015) reported that turbidity, sediment and total phosphorus were significantly reduced during floodplain inundation. The widened channel is able to contain the greater discharge within the larger channel and make the entire waterway more stable (NEH, 2007).

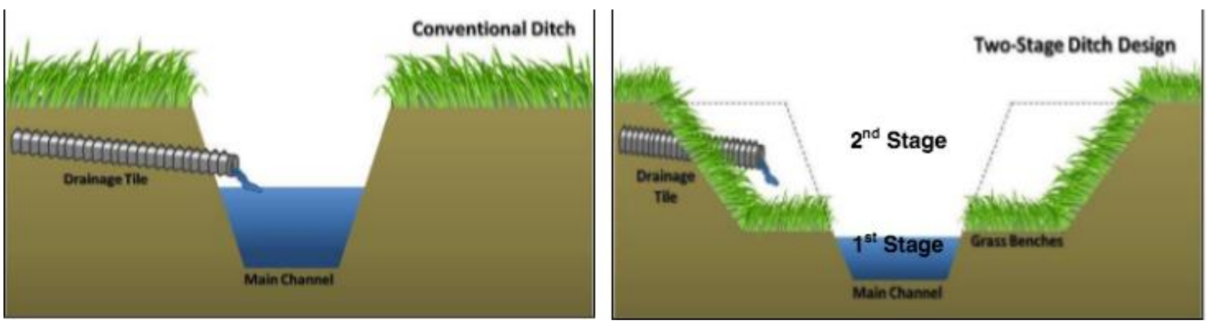

Figure 1-2. Conventional open channel agricultural ditch design (left) and a two-stage ditch (right) (NRCS 582).

To date, two-stage ditches have been primarily installed in Midwestern agricultural settings along existing drainage channels. However, there is reason to believe that two-stage ditches could be utilized along roadside environments to increase the long-term sustainability of ditches while reducing downstream water quality impacts. This project focused on implementing a two-stage design along a roadside right-of-way and investigating the efficacy of this alternative design in improving water transport capacity and sediment and nutrient processing in ditches while simultaneously improving ditch stability and reducing maintenance.

1.3 OBJECTIVES

The objectives of this project were to:

- Evaluate the performance of two-stage roadside ditches for their ability to improve water quality by reducing sediment and nutrient concentrations;

- Quantify the effects of a two-stage roadside ditch on flow reductions occurring from the two-stage ditch design compared to the pre-construction ditch
- Identify potential locations of other roadside ditches in Iowa for conversion to a two-stage design and quantify the potential impact of conversions on statewide nutrient export; and
- Discuss the challenges and opportunities associated with converting roadside ditches to a two-stage design.

1.4 ORGANIZATION OF THE REPORT

This report is divided into eight chapters that describe the steps taken to meet the defined research objectives and present the results of the research. Chapter two describes the background of the site selection process, preliminary construction design evaluations and a chronological site history of pre- and post-construction monitoring and ongoing logistical roadblocks and challenges. Chapter three describes the monitoring and modeling methodology along with statistical methods utilized to evaluate ditch performance. The chapter also includes the Geographic Information System (GIS) methodology used to identify potential ditch sites across Iowa. Chapter four provides the results of the vegetation assessment of the roadside ditch. Chapter five describes the hydraulic modeling results to quantify the effects of the ditch on water flow volumes and rates. Chapter six presents the results showing the effects of the two-stage ditch on sediment and nutrient export whereas Chapter seven showcases the locations where two-stage ditches can be constructed across Iowa and quantifies their potential effectiveness as a nutrient reduction strategy. Chapter eight summarizes major findings, discusses the challenges and opportunities associated with converting roadside ditches to a two-stage design, and describe the impact of the research efforts.

2 BACKGROUND AND SITE HISTORY

2.1 LOCATION AND SETTING

The two-stage roadside ditch site is located along the north side of Highway 30 in Benton County, Iowa (Figure 2-1). The study area is located in the Iowan Surface landform region of Iowa and is characterized by rolling, weathered till-plain hills and a well-integrated drainage network (Prior, 1991). Most of the soils are loams or sandy loams formed in loess and/or weathered and fractured pre-Illinoian glacial till. The ditch watershed drains to Prairie Creek to the west, a fourth-order tributary of the Cedar River (Figure 2-1).

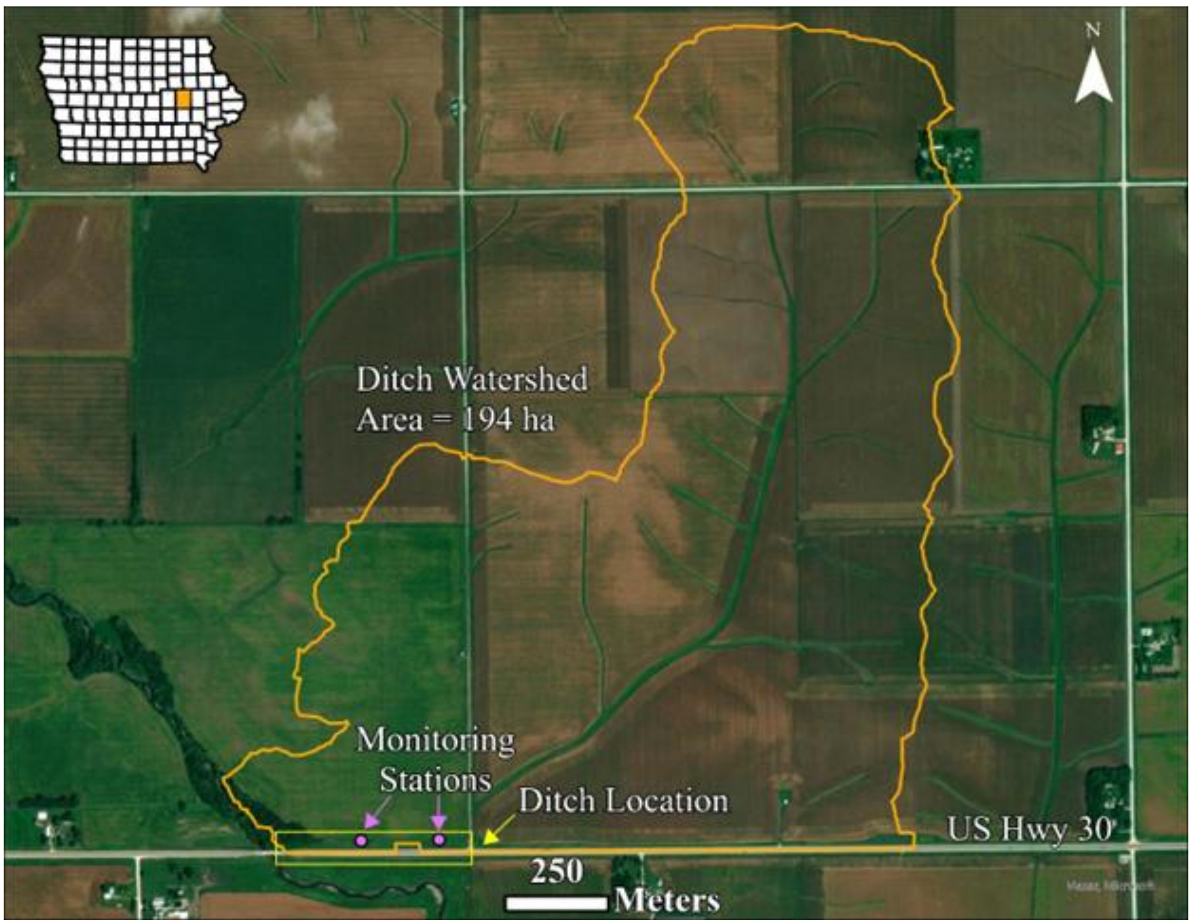

Figure 2-1. Location map of the two-stage ditch and its watershed.

The study site was selected in consultation with the Iowa Department of Transportation (IDOT) in conjunction with a major expansion project that converted the two-lane Highway 30 to a divided four-lane highway. The ditch extends approximately 450 meters along the road right-of-way and receives drainage from a 194 ha watershed that primarily consists of cropped fields of corn and soybeans. Surface water runoff generated by storm events entering the ditch from the watershed, and baseflow is largely sustained by discharge from subsurface tiles that drain the cropland east of the ditch. Tile drainage flow enters the ditch upstream of the two-stage construction area and provides sustainable flows from approximately March to July. When the tiles cease to flow, the ditch typically dries up in the late summer and fall unless fed by rainfall runoff events.

The natural ditch prior to the two-stage intervention was approximately 1-1.5 m wide and 1 m deep, and it meandered slightly within its confines. The slope of the ditch on the floodplain of Prairie Creek was 0.06%. The pre-construction ditch was visibly incised, displaying a migratory nick-point in the central area of the test channel. The upper part of the incised ditch was abundantly covered by mature, uniformly distributed grass density. Vegetation was dominated by smooth brome (*Bromus inermis*), bare ground/thatch, reed canary grass (*Phalaris arundinacea*), and stinging nettle (*Urtica dioica*) (Figure 2-2). This type of vegetation community is very common in disturbed roadside ditches throughout Iowa.

Figure 2-2. The roadside ditch prior to two-stage construction.

2.2 PRELIMINARY DESIGN

Following selection of the Highway 30 ditch for the research project, site characterization activities were needed to develop a preliminary design for the two-stage dimension. A topographic survey was conducted to develop cross-sections needed for final design (Figure 2-3). Elevations ranged from nearly 262 m to less than 255 m along the ditch profile and near-ditch riparian zone. Water flow from the contributing watershed entered the ditch from a collection pool upstream of the bridge on the Level B road access. Additional flow entered the ditch from the roadside ditch along the Level B road approximately 300 feet north of the ditch.

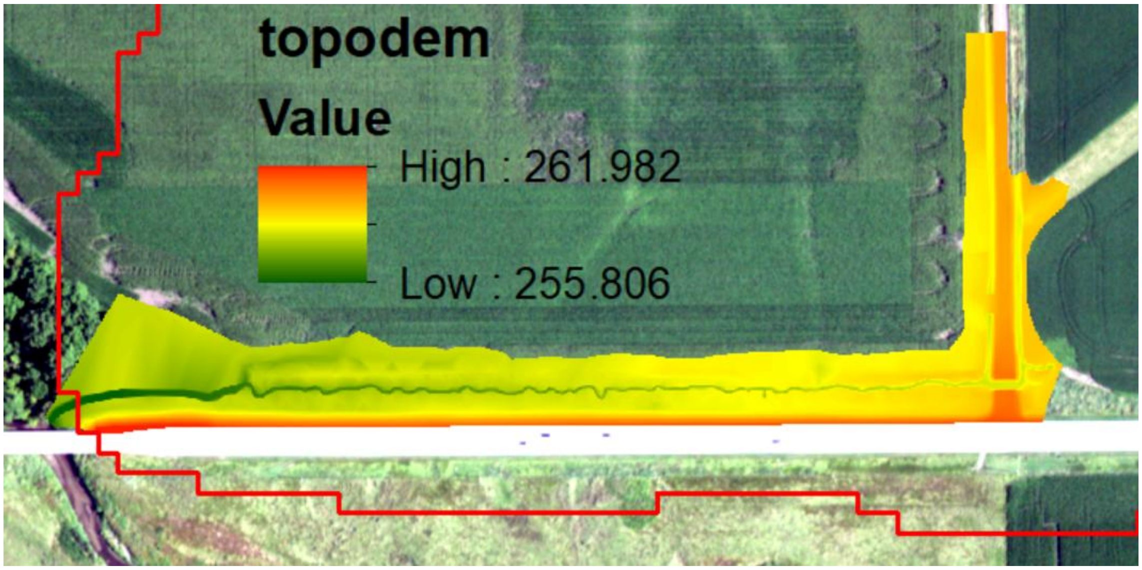

Figure 2-3. Topographic map of the roadside ditch prior to construction.

Surface flows in the ditch were needed to develop the preliminary design and appropriately size the channel bench dimensions but the ditch was ungauged. Although a USGS stream gage was available for Prairie Creek at Fairfax, it was measuring flow from a significantly larger basin (175 mi^2) than the 0.75 mi^2 ditch catchment and it was uncertain whether unit flows was scale to the much smaller size. Instead, peak flows were derived from a gauge located approximately four miles north of the ditch site near Van Horne, IA. The Prairie Creek Tributary near Van Horne, IA site (USGS 05464535) monitors peak annual stage in the small stream (drainage area 0.94 mi^2). Given the similar size of the tributary to the ditch catchment, peak flows were downloaded from the USGS web site (Figure 2-4) and plotted for a return period (Figure 2-4). From this plot, peak flows in the proposed two-stage ditch could be estimated by return period for flood of interest.

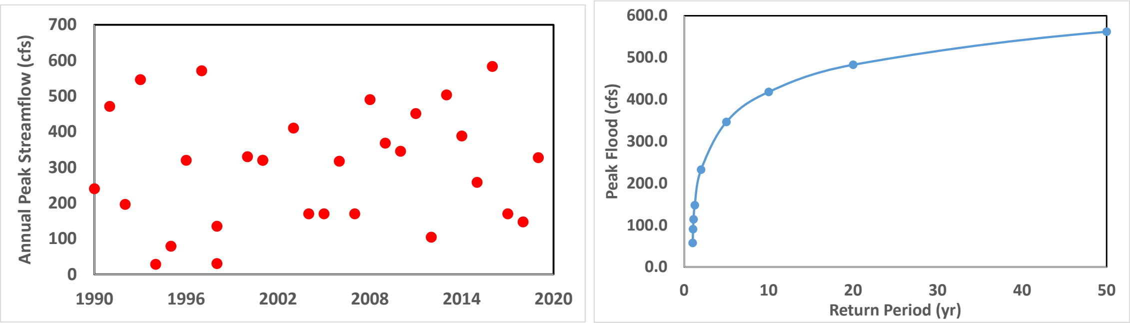

Figure 2-4. (left) Annual peak flows measured at The Prairie Creek Tributary near Van Horne, IA (USGS 05464535); (right) Annual return period for peak flows at the Prairie Creek Tributary site.

It is important to note that during this early reconnaissance period, in March 2020, a broken tile line was observed about mid-way along in the ditch from the Level B road to Prairie Creek. DOT reported fixing the tile line hole in March 2020.

On June 15, 2020, a pressure transducer was installed in the ditch at the approximate longitudinal midpoint to collect stage readings every 15 minutes (aka “stage sensor”). An initial small flow event (1-year return flow) was captured on June 18, 2020, but on June 25, 2020, the area experienced significant rainfall and a large flood event was observed (Figure 7). The ditch area was completely inundated and the surface flows brought in a massive amount of corn residue (Figure 2-5).

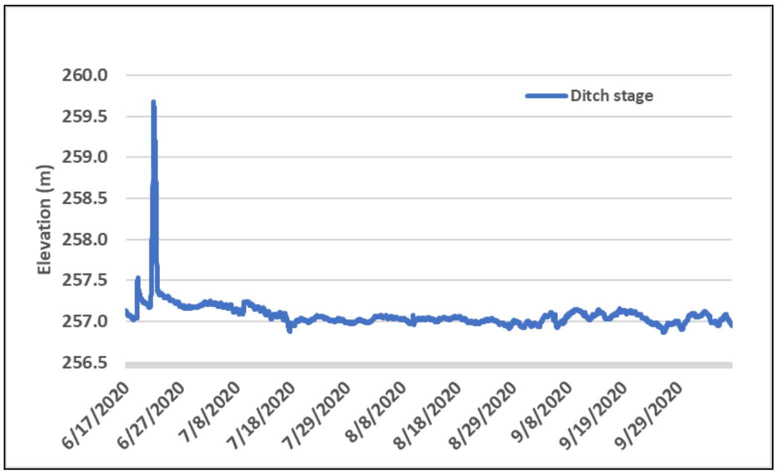

Figure 2-5 (top) Stream stage in the ditch in 2020. Note the small initial peak on June 18 followed by a much larger event on June 25. (bottom) Photograph taken on July 2 at the ditch following the June 25 event and the large amount of corn residue observed at the site.

Based on the ditch stream stage observed on June 18 and using the nearby information from the Prairie Creek Tributary, ditch flow for the 1-year event was estimated to be 25 cubic feet per second (cfs).

From the site topographic map, six channel cross-sections were obtained (Figure 2-6) and used to develop preliminary cross-sectional profiles of the existing ditch (Figure 2-7). From the cross-sectional profiles and return flow information, a preliminary design of the two-stage channel was proposed, expanding the top channel width to 20 feet, leaving the existing channel depth unchanged (2 feet deep) and constructing a bench approximately 1.3 feet below the top of the channel (Figure 2-9).

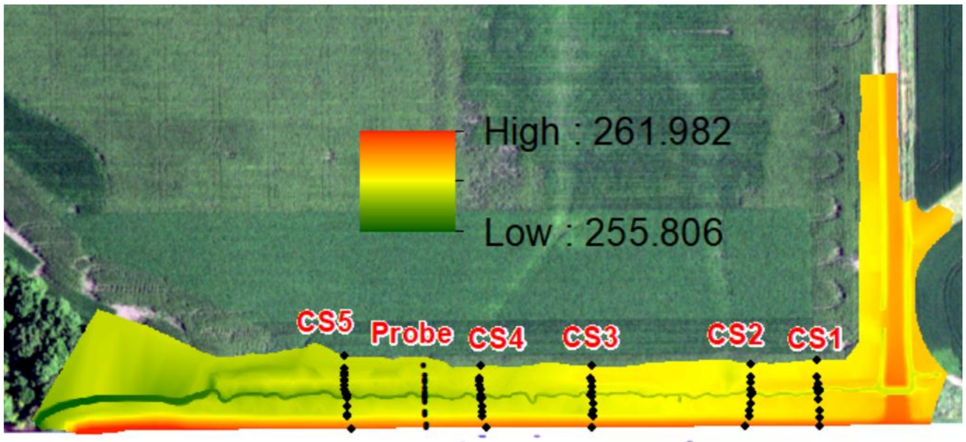

Figure 2-6. Location of cross-sections of the pre-existing ditch used to develop preliminary design.

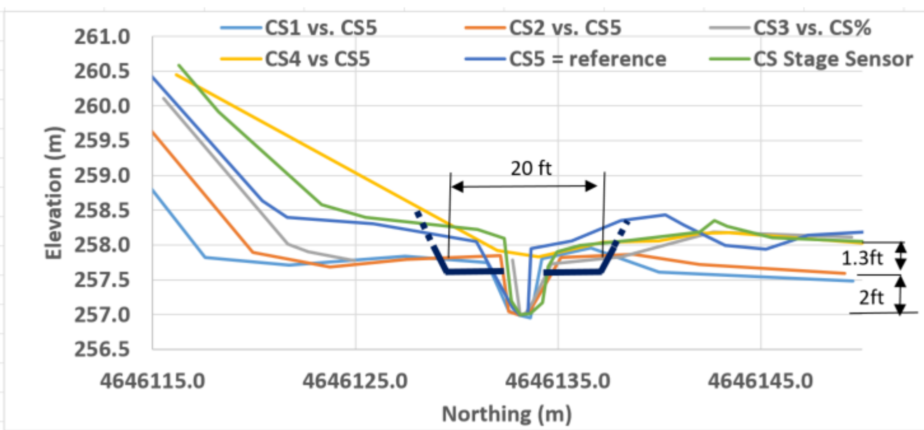

Figure 2-7. Co-located cross-sections of the ditch showing dimensions of the existing channel and proposed bench dimensions.

A summary of the preliminary analysis of the ditch geometry and flows is provided in Table 2-1. The approach used to estimate ditch properties was derived from a combination of site survey information, national guidelines for two-stage ditches (USDA, 2017) and calculated data using a rudimentary 1-D cross-sectional model. From the cross-sections, proposed channel dimensions and other design information gathered from the ditch site, a plan specification sheet was produced by DOT engineers and provided to the contractor. A portion of the final design plan is provided in Figure 2-8.

Table 2-1. Preliminary design characteristics for the two-stage ditch.

Characteristics		**Approach Used**	**Values Obtained**
1st Stage	Bed width	Surveyed	3.3 ft
	Bank slope (1:1)	Guidelines[1]	100%
	Stage depth	Estimated	2 ft
	Area	Calculated	10 ft^2
	Avg. Velocity	Calculated	2.4 ft/s
2nd Stage	Width	Guidelines	20 ft
	Bank slope (2:1)	Guidelines	200%
	Stage depth	Estimated	1.3 ft
	Area	Calculated	30 ft^2
Combined 1st and 2nd stages	Area	Calculated	40 ft^2
	Velocity	Calculated	3.6 ft/s
Discharge (Q) 1st stage (for 1-yr return flow = 25 cfs			
Q total (for >1 year return flow) = 148 cfs			

[1]Guidelines from USDA, 2017

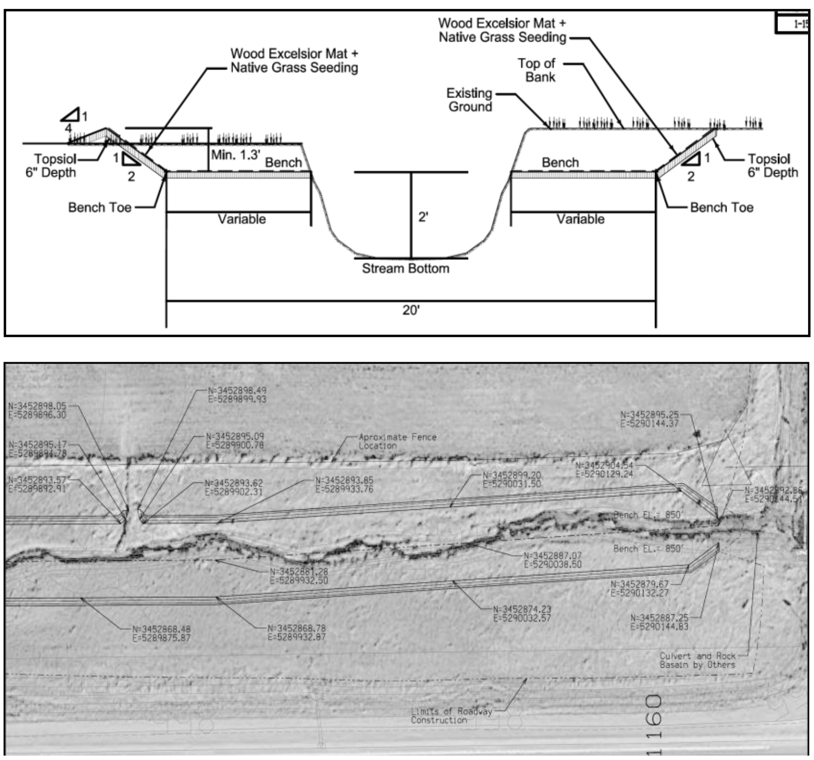

Figure 2-8. Portion of two-stage ditch construction drawings delivered by DOT. (top) cross-sectional dimensions for the two-stage ditch. (bottom) plan view of existing ditch and width of inset bench.

2.3 SITE CONSTRUCTION TIMELINE

The original project timeline of pre- and post-construction monitoring was adjusted several times during the project and the timeline below reflects what actually happened rather than what was initially scoped in the initial work plan.

Pre-construction monitoring was initially delayed in 2020 due to travel restrictions from COVID-19. Monitoring, consisting of upstream and downstream water quality sampling and installation of shallow monitoring wells, began on July 15, 2020 and procedures are provided in Chapter 3 and results are reported in Chapter 4. Pre-construction monitoring conducted in 2020 and 2021 is considered to be "pre-project", that is, monitoring conducted to characterize site conditions prior to the construction of the two-stage ditch. In the fall of 2021 and continuing through the spring and summer of 2022, the two-stage ditch was under construction and ongoing modification. Documentation of site construction activities was assisted greatly with a webcam installed at the site on May 4, 2021.

2.3.1 Two-Stage Ditch Construction

On January 17, 2022, 2-stage ditch construction was initiated at the site and the grading work was finalized on January 21, 2022 (Figure 2-9). On April 18, 2022, the two-stage ditch was seeded and finalized (Figure 2-10).

Figure 2-9. (Left) Excavation work initiated on January 17 and (Right) work finalized on January 21, 2022.

Figure 2-10. Seeding finalized at two-stage ditch site.

In the latter half of 2022 and all of 2023, demolition and rebuilding of Highway 30 was underway. Heavy equipment and limited access to the site prevented on-site monitoring. In addition, uncontrolled water runoff and sediment erosion entered the ditch to a limited degree that complicated routine monitoring. On April 3-4, 2023, instrumentation was deployed in the ditch for monitoring stage and turbidity (Figure 2-11). The upstream sensor was placed in water, but the downstream location was largely dry for most of the monitoring period. The planted vegetation was becoming established during this time.

Figure 2-11. Instrumentation deployed on April 3-4, 2023.

On June 12-15, 2023, a portion of the ditch near the repaired tile line was excavated. This was unplanned and unexpected and the excavation disrupted the vegetation growth and monitoring of the ditch site (Figure 2-12). In addition, for periods between July 10 and October 20, 2023, the webcam captured several periods of unplanned excavation and road grading in close proximity to the ditch (Figure 2-12). Shoulder expansion of Highway 30 encroached on the ditch and sediment runoff into the ditch was observed.

Figure 2-12. (left) Excavation of a portion of the ditch on June13, 2023; (right) finished road grading and shoulder repair in close proximity of the ditch as seen on October 20, 2023.

On March 1, 2024, instrumentation was deployed at the ditch, including upstream and downstream turbidity sensors. From April to mid-June, 2024, the two-stage ditch operated as planned. On site visits confirmed that the ditch was retaining sediment (phosphorus) with the widened channel by the floodplain vegetation, baseflow was observed for the entire length of the ditch and there were no backwater anomalies in flow along the length. The two-stage ditch captured several events in the spring of 2024 and appeared to work as planned (Figure 2-13).

Figure 2-13. (left) Baseflow in the two-stage ditch on May 7, 2024. (right) Stormflow captured in the ditch on May 21, 2024.

On June 19, 2024, the landowner of property upstream of the ditch contacted a local DOT representative complaining about drainage from his field into the ditch (it is important to note that the two-stage channel actually increases drainage efficiency). At the behest of the landowner, the DOT excavated the upstream portion of the two-stage ditch immediately upgradient of the upstream turbidity sensor and throughout the test section (Figure 2-14). This channel excavation completely changed the geometry of the two-stage ditch by increasing the size and width of the base channel. The landowner-requested excavation on June 19-22, 2024, effectively ended the monitoring project since the channel was changed from it's designed condition.

2.3.3 Timeline Summary

Figure 2-14. Excavation of the two-stage channel on June 19-22, 2024, that ended the monitoring project.

While the design of the two-stage ditch was sound, roadway construction associated with Highway 30 expansion, flow losses to an unknown tile and unplanned post-construction excavation plagued the project. The ditch was observed to function as planned on several occasions and monitoring data during these periods documented the performance (see Chapters 5 and 6). However, it was exceedingly difficult to maintain the integrity of the two-stage ditch during the monitoring period. Lesson learned from the project are presented in Chapter 8.

2.4 VEGETATION ESTABLISHMENT

Vegetation planting and monitoring activities during the project were provided by the Tallgrass Prairie Center (TPC) at the University of Northern Iowa in Cedar Falls, IA. Following ditch construction, using the planting seed mix recommended by TPC, DOT used a native seed mix designed for wet-mesic conditions to revegetate the bench areas (Table 2-2). This seed mix was comprised of 50 native species and was seeded at a rate of 1194 seeds/m^2 during the spring of 2022. No other areas of the right of way were seeded or disturbed by the construction.

Table 2-2. Seed mix planted on the constructed two-stage ditch.

Functional Group	*Common Name*	*Scientific Name*	*Seeds/m²*
warm-season	big bluestem	*Andropogon gerardii*	32.28
warm-season	switchgrass	*Panicum virgatum*	21.52
warm-season	Indiangrass	*Sorghastrum nutans*	21.52
warm-season	prairie cordgrass	*Spartina pectinata*	5.38
cool-season	yellowfruit sedge	*Carex annectens*	21.52
cool-season	heavy sedge	*Carex gravida*	0.54
cool-season	troublesome sedge	*Carex molesta*	10.76
cool-season	awlfruit sedge	*Carex stipata*	10.76
cool-season	fox sedge	*Carex vulpinoidea*	75.32
cool-season	Canada wildrye	*Elymus canadensis*	21.52
cool-season	Virginia wildrye	*Elymus virginicus*	32.28
cool-season	fowl mannagrass	*Glyceria striata*	53.80
cool-season	Dudley's rush	*Juncus dudleyi*	215.20
cool-season	rice cutgrass	*Leersia oryzoides*	21.52
cool-season	green bulrush	*Scirpus atrovirens*	215.20
annual/biennial	nodding beggartick	*Bidens cernua*	5.38
legume	showy ticktrefoil	*Desmodium canadense*	2.15
spring forb	Canadian anemone	*Anemone canadensis*	0.54
spring forb	Virginia iris	*Iris virginica*	0.22
spring forb	foxglove beardtongue	*Penstemon digitalis*	32.28
spring forb	purple meadow-rue	*Thalictrum dasycarpum*	1.08
spring forb	bluejacket	*Tradescantia ohiensis*	1.08
spring forb	golden zizia	*Zizia aurea*	5.38
summer forb	swamp milkweed	*Asclepias incarnata*	2.69
summer forb	common milkweed	*Asclepias syriaca*	1.08
summer forb	tall tickseed	*Coreopsis tripteris*	1.08
summer forb	button eryngo	*Eryngium yuccifolium*	3.23
summer forb	spotted joe pye weed	*Eutrochium maculatum*	10.76
summer forb	smooth oxeye	*Heliopsis helianthoides*	2.15
summer forb	great St. Johnswort	*Hypericum ascyron*	32.28
summer forb	prairie blazing star	*Liatris pycnostachya*	4.30
summer forb	winged lythrum	*Lythrum alatum*	10.76
summer forb	wild bergamot	*Monarda fistulosa*	10.76
summer forb	obedient plant	*Physostegia virginiana*	5.38
summer forb	narrowleaf mountainmint	*Pycnanthemum tenuifolium*	21.52
summer forb	Virginia mountainmint	*Pycnanthemum virginianum*	21.52
summer forb	blackeyed Susan	*Rudbeckia hirta*	10.76
summer forb	sweet coneflower	*Rudbeckia subtomentosa*	21.52
summer forb	browneyed Susan	*Rudbeckia triloba*	10.76
summer forb	swamp verbena	*Verbena hastata*	21.52
summer forb	Culver's root	*Veronicastrum virginicum*	32.28
fall forb	common boneset	*Eupatorium perfoliatum*	21.52
fall forb	flat-top goldentop	*Euthamia graminifolia*	10.76
fall forb	common sneezeweed	*Helenium autumnale*	43.04
fall forb	sawtooth sunflower	*Helianthus grosseserratus*	1.08
fall forb	cardinalflower	*Lobelia cardinalis*	21.52
fall forb	great blue lobelia	*Lobelia siphilitica*	43.04
fall forb	smooth blue aster	*Symphyotrichum laeve*	5.38
fall forb	New England aster	*Symphyotrichum novae-angliae*	10.76
fall forb	prairie ironweed	*Vernonia fasciculata*	5.38

3 INVESTIGATION METHODS AND MODELING

The two-stage ditch project included a variety of field monitoring activities along with statistical and flow modeling. This chapter outlines the procedures used to collect and analyze data for the project.

3.1 FIELD MONITORING METHODS

3.1.1 Groundwater Monitoring

For pre-construction monitoring, groundwater wells were installed using a 4 in-diameter hand auger. Well depths were approximately 3 m below land surface. A 1.5-m long factory-slotted PVC well screen and a solid PVC riser were installed in the borehole. A silica sand filter pack was poured around the screen, bentonite chips were added to provide a seal and drill cuttings were backfilled in the rest of the borehole. Monitoring wells were installed in the ditch at two locations (Figure 3-1). At each location, one well was located near the stream and a second well was located near the road. The wells were sampled on seven occasions in 2020 and eight occasions in 2021. More samples were collected from the wells than surface water at this time because water was present in the wells even when the ditch was dry. Water levels in wells were measured to the nearest 0.01 foot (0.3 cm) at the time of sampling and samples were collected using a peristaltic pump. The wells were removed for construction and not installed thereafter.

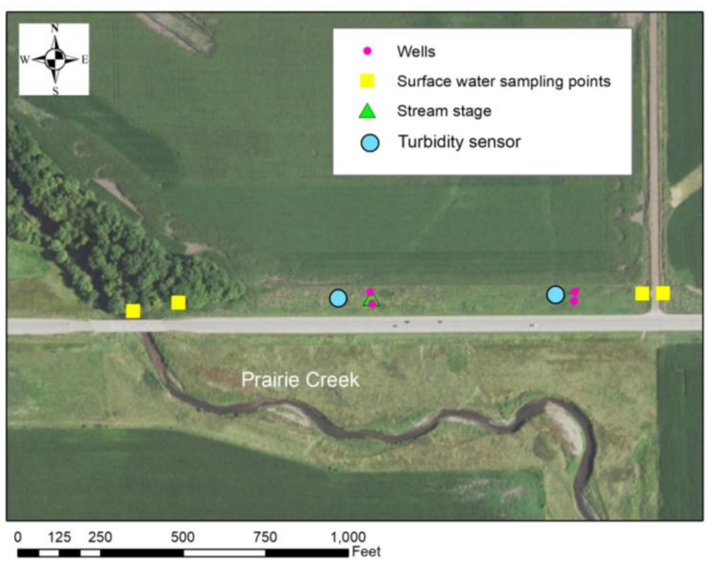

Figure 3-1. Monitoring locations at two-stage ditch site.

3.1.2 Stream Stage

Surface water stage was measured every five minutes using a pressure transducer placed in the bottom of the ditch near the mid-point of the ditch between the level B road and Prairie Creek. Stream stage measurements began on June 17, 2020 and continued through December 21, 2020 and commenced again from May 3 to December 9, 2021. Following ditch construction, stream stage was monitored at approximately the same location from April 3, 2023 to July 14, 2024.

3.1.3 Turbidity Sensors

Turbidity monitoring was conducted both before and after construction to evaluate the effectiveness of the two-stage roadside ditch in reducing sediment and nutrient export. A pressure transducer was installed in the ditch at the midpoint of the monitoring length to measure stream stage at a five-minute frequency. In-situ turbidimeters were installed at upstream and downstream locations along the ditch (Figure 3-1). These devices were installed both pre-construction and post-construction to evaluate the influence of the two-stage ditch on turbidity compared to the original roadside ditch. Apart from the winter months, when the equipment was retrieved to avoid damage related to freezing conditions, the turbidimeters remained active throughout the entirety of the water year.

Turbidity was monitored every 5-15 minutes at each sensor with FTS DTS-12 turbidimeters (Forest Technology Systems, Langford, BC, Canada) using nephelometric turbidity units (NTU). Occasionally (<5% of days), sensor fouling resulted in missing turbidity values. Furthermore, it was common for the ditch to dry out in August and September due to lack of flow from tile lines, resulting in fewer turbidity datapoints in these two months. Upon collection, turbidity values were compiled as daily averages and log-transformed for analysis.

3.1.4 Grab Sampling

Grab samples of surface water in the ditch were collected from upstream and downstream locations at an approximate monthly to bi-monthly frequency. The frequency was expanded or reduced at times due to hydrologic conditions. Prior to construction, surface and groundwater quality were monitored in the ditch and receiving stream (Prairie Creek) to verify that the site was representative of local and regional conditions. Grab samples of surface water were collected from the ditch at upstream and downstream locations at an approximate monthly to bi-monthly frequency. The frequency was expanded or reduced at times due to hydrologic conditions. In 2020, seven surface water samples were collected, whereas in 2021, six bi-monthly samples were collected from April to July (n=13). Surface and groundwater samples were analyzed in the field for temperature, specific conductance (SC), pH, dissolved oxygen (DO), and oxidation-reduction potential (ORP) using a YSI ProDSS water quality meter.

Samples to be analyzed for NO3-N, chloride (Cl), and sulfate (SO4) were collected in polyethylene bottles and submitted to the Coe College water quality laboratory. Samples analyzed for dissolved reactive phosphorus (DRP) were filtered in the field immediately upon collection through a 0.45 µm filter into a 60 mL acid-washed brown glass bottle. Concentrations of NO3-N, Cl, and SO4 were measured using a Dionex ICS-1000 ion chromatograph equipped with an AS-14A 5µm ion exchange column, an AS-14A guard column, an AMMS-III or AERS 500 suppressor, and Na2CO3/NaHCO3 eluent. A Dionex autosampler (AS40) was utilized with autosampler vials fitted with 20 µm filter caps. Dissolved reactive orthophosphate (DRP) was analyzed using a Lachat QuikChem 8500 Series 2 flow injection analyzer running Lachat method 10-115-01-1-P.7

During spring 2024 (post-construction), grab samples were collected during four separate runoff events using automated Teledyne ISCO samplers (6712 Full-size Portable Sampler; Teledyne Labs, Lincoln, NE, USA). Samplers were placed in close proximity to the turbidity sensors and programmed to collect a ditch water sample every 10 minutes once activated. Approximately 24 samples were collected per event (full carousel).

Samples to be analyzed for NO3-N, chloride (Cl), and sulfate (SO4) were collected in polyethylene bottles and analyzed at the IGS laboratory. Samples for dissolved reactive phosphorus (DRP) were filtered in the field immediately upon collection through a 0.45 µm filter into a 60 mL acid-washed brown glass bottle. All water samples collected using the ISCO were analyzed by ion chromatography at the Iowa Geological Survey laboratory for dissolved constituents, including NO3-N, orthophosphate (OP), Cl, and sulfate. All samples were collected using methods approved by the US Environmental Protection Agency and stored at 4°C while transported to the lab on the day of collection.

3.2 VEGETATION ASSESSMENT

The vegetation of the right-of-way and the two-stage ditch were assessed before and after construction and revegetation. Changes in plant functional groups and species richness were documented to better understand the potential for two-stage ditches to serve as biodiverse, multifunctional habitat. Seedling establishment was measured in the two-stage ditch to assess potential for native species planted to persist.

Two areas were sampled that corresponded to 1) the overall right-of-way and 2) the two-stage ditch. The approach was similar to Schilling and others (2018) who conducted a comparable survey. For the overall right-of-way, the QGIS (QGIS Development Tam 2022) was used to delineate a sample area polygon that encompassed the entire area of interest (right-of-way bounded by roads, adjacent fields, and forest) then randomly generated 25 sampling points within the area (Fig. 2). The overall area prior to construction was sampled in September 2020 and the year after construction and revegetation in September 2022. To define the sampling area for the two-stage ditch, the distances from roads and property lines in the DOT construction plans was used to delineate the area in QGIS (QGIS Development Team 2022) and randomly generated 24 sampling points within (Figure 3-2).

In the overall right-of-way survey, a handheld GPS unit was used to locate each sampling point. At each point, the vegetation was sampled within a $1m^2$ square quadrat. All species present, excluding seedlings, and assessed canopy cover were assessed for each species using Daubenmire cover classes. The same method was used to survey the two-stage ditch area, though in 2022 native seedlings (ramets) present in the southwest $0.125m^2$ of the $1m^2$ quadrat was also counted. Any sampling point that intersected with the main channel was repositioned to ensure the entire quadrat was on level ground. The main channel vegetation was not assessed.

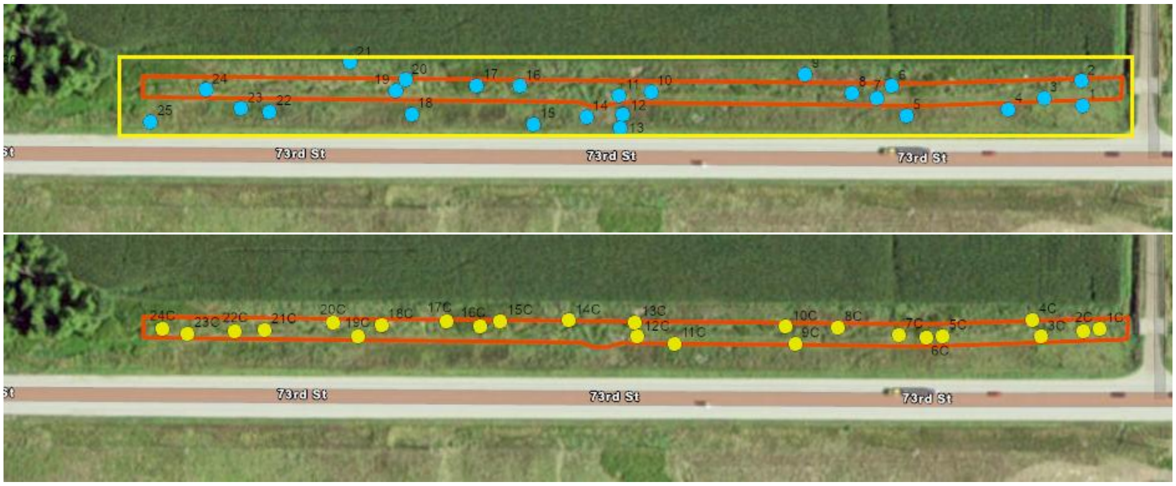

Figure 3-2. (top) Overall right-of-way sampling area (yellow outline), n=25 sample points. Red outlined area shows two-stage ditch extent. (bottom) Two-stage ditch sampling area (red outline), n=24 sample points.

3.3 STATISTICAL CHANGES IN TURBIDITY

Because of the intermittent record of data collection that corresponded with ditch construction, tile repair and unplanned excavation, only limited statistical tests could be conducted. Turbidity had the longest and most complete record of data collection available for the project and for that reason, A statistical assessment was used to quantify the impact of the two-stage ditch on turbidity. In both the 2021 and 2024 water years, we calculated the turbidity gradient (difference between upstream and downstream locations) by subtracting the downstream observations from their concurrent upstream counterparts. This provided a large sample (~30,000 in each year) of the spatial turbidity differences observed along the ditch in the pre- and post-construction conditions. Turbidity in surface waters often exhibits strong positive skewness, so it is a common practice to transform the data prior to analysis. The natural logarithm of the turbidity measurements was used to construct a dataset of the log-transformed turbidity gradients. Furthermore, we also aggregated high-resolution turbidity values to daily means by taking the arithmetic mean of the high-resolution observations within each day. These daily means were used to calculate untransformed and log-transformed turbidity gradients. For the 2021 water year, there were 168 days when turbidity measurements were available at both sites, whereas the 2024 water year contained 242 paired measurements.

To evaluate differences between the pre- and post-construction gradients, the Mann-Whitney U test (McKnight & Najab, 2010) was applied to each of the four gradient datasets. In this formulation, the test explored whether the turbidity differences observed between the upstream and downstream monitoring sites were similar in 2021 and 2024. A low p-value indicates that we reject the null hypothesis that the 2021 and 2024 turbidity gradients originate from the same underlying distribution. The Mann-Whitney U test is a nonparametric test that does not rely on assumptions of normality within the datasets. To visualize the differences between 2021 and 2024, we created histograms of the log-transformed high-resolution and daily mean gradients for each year, along with their corresponding cumulative distribution functions.

Finally, the ditch's turbidity gradient was investigated related to the overall level of turbidity within the channel to ensure that the reported pre- and post-construction differences did not result from hydrologic differences between the 2021 and 2024 water years but rather reflected the influence of the two-stage ditch on sediment transport. This concept was explored by plotting turbidity gradient values against the average turbidity within the ditch (i.e., the arithmetic mean of upstream and downstream observations). A smoothing line was then applied to document any potential bias of the turbidity gradients.

3.4 HYDRAULIC MODELING

3.4.1 Modeling Framework

The HEC-RAS (Hydrologic Engineering Center River Analysis System; UASCE, 2010) modeling platform was used to quantify water transport throughout the ditch in response to wet weather (runoff) events. A hydrologic and hydraulic model was constructed following the typical procedure for simulating two-dimensional open channel flow in HEC-RAS. This model utilized a computational mesh to represent the terrain of the original single-stage ditch (i.e., the existing condition prior to the two-stage intervention) and its upstream watershed. The mesh was constructed to capture land use, vegetative density, slope, and soil characteristics of the watershed, along with their hydrologic connectivity. Landscape elevations for the upstream watershed were determined using a digital elevation model constructed from local LiDAR measurements (Sampath & Irwin, 2025). Elevations for the ditch corridor were obtained through a topographic survey conducted in conjunction with the roadway construction project. A higher-density mesh was used throughout the ditch corridor, where accurately documenting flow behavior was critical. Vegetation and land use details were obtained from the National Land Cover Database (Dewitz, 2021).

Key hydrologic parameters (e.g., roughness values, infiltration rates, etc.) across the mesh were estimated using a standard calibration process, in which water elevations at the ditch outlet were compared with those from a historical wet weather event. Initial estimates of these parameters were made using IDOT design manual guidance pertinent to the vegetation and soil types found in our study watershed. Water stage and rainfall were monitored during the fall of 2020—before any construction activities took place—and recorded a significant storm event (~68 mm over 26 hours) similar to the 24-hour 1-year design storm (66.2 mm). The rainfall event in the HEC-RAS model for this event was simulated and the model's hydrologic parameters were calibrated to increase the agreement between the model's stage elevations and the observed stage elevations near the ditch outlet. Water elevations in Prairie Creek monitored during this event were used as the tailwater boundary conditions during calibration.

Following calibration, an alternative model was constructed where the two-stage ditch design was incorporated into the computational mesh. Here, the ditch corridor mesh was replaced with the terrain of the constructed two-stage ditch, and the roughness throughout the ditch footprint was replaced with values more consistent with the native vegetation planted after ditch construction. The upstream and downstream watershed characteristics (i.e., the areas outside the ditch border) were kept consistent. This setup thus allowed us to explore hydrologic and hydraulic differences primarily driven by the change in channel geometry associated with converting a typical single-stage ditch to a two-stage.

Once the HEC-RAS models were completed, four design storms were simulated across the single-stage and two-stage meshes. These synthetic wet weather events spanned 24 hours, with rainfall totals corresponding to the 1-year, 2-year, 5-year, and 10-year return periods. Total precipitation for these events was 66.2, 76.9, 95.9, and 113 mm, respectively (Table 3-1), and rainfall intensities throughout the storms were determined using Huff curves developed for eastern Iowa (Bonta, 2004). The methods for selecting and quantifying the design storms used in this study align with the technical recommendations provided by the IDOT for drainage design along Iowa roadways.

Table 3-1. Summary of the four events simulated in this study and the resulting peak flows and total water volumes at the ditch outlet. Rainfall spanned a 24-hour duration for each event.

Return Period	Rainfall (mm)	Peak Flow (cms)		Total Volume (1000 m^3)	
		Single-Stage	Two-Stage	Single-Stage	Two-Stage
1-year	66.2	0.51	0.40	18.5	17.4
2-year	76.9	0.79	0.63	26.9	25.4
5-year	95.9	1.32	1.22	45.0	42.2
10-year	113	1.96	1.87	62.8	59.5

3.4.2 Flood Reduction Analysis

To determine the two-stage ditch's capacity to reduce flooding, simulated flow rates between the single-stage and two-stage scenarios were compared. Specifically, a location near the downstream end of the ditch was selected that resided within its typical cross-sectional geometry and captured nearly all the water discharged by the ditch into Prairie Creek. The location was also chosen because its elevation was above the expected water surface levels in Prairie Creek for each of the design storms. Therefore, the hydraulics at this location were solely influenced by upstream hydrology, not by downstream tailwaters. Focusing on this location allowed the amount of water discharged by an entire two-stage ditch to be estimated, while removing the influence of the local receiving waterbody. Consequently, no downstream boundary conditions were used in any of our simulations, and the flow rates reported herein correspond to normal depth values at the ditch outlet.

Discharge values at this outlet location were extracted for the eight simulated events (i.e., the single-stage and two-stage scenarios for each of the four design storms) Figure 3-3 displays the simulated hydrographs for each design storm, along with the events' hyetographs. These reported flow values completely encompass each event, which spanned 0 to 50 hours. Here, the 0 timestep corresponded to the start of the rainfall, and within 50 hours, flow rates at the ditch outlet had returned to 0 cms (i.e., the ditch had become dry).

For each event, two key hydrologic parameters were examined with implications for flooding: 1) peak flow and 2) total volume. Peak flows were determined by simply identifying the maximum flow rate at the outlet at any point during the event. Total volumes were determined by integrating the hydrographs, thereby generating the cumulative water volume that passed through the ditch over the entire event. We used the %Reduction metric to compare outputs from two-stage and single-stage models. It was defined as follows

%Reduction= (Single Stage-Two Stage)/(Single Stage)

where Single Stage and Two Stage refer to the peak flows and total volumes for a given storm event. %Reduction thus provides the percent change observed in these hydrologic parameters when comparing two-stage ditch values to those of the corresponding single-stage simulation.

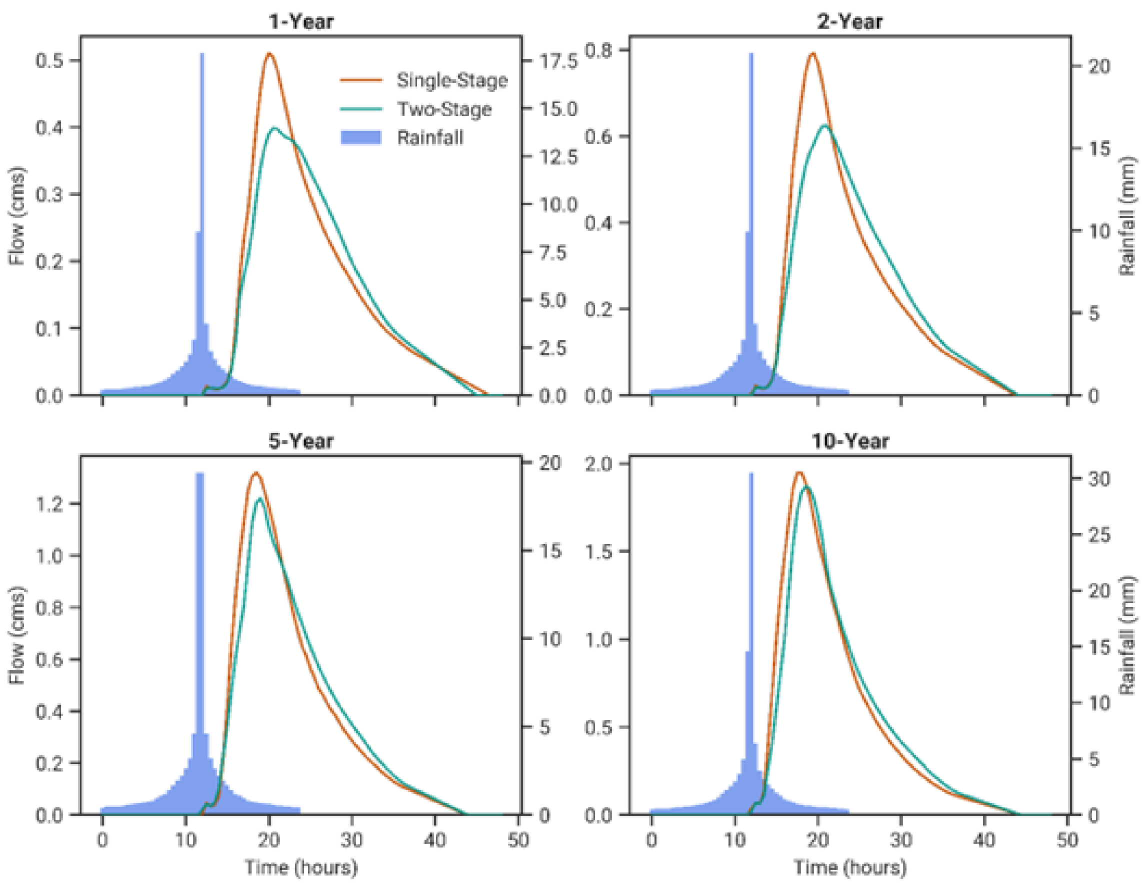

Figure 3-3. Rainfall and hydrographs at the ditch outlet for each simulated storm event.

3.4.3 Erosion Reduction Analysis

The potential of the two-stage ditch to reduce erosion rates across its profile was explored. The erosion risk can be highly influenced by the velocity of water passing through it during a wet weather event, so changes to the ditch geometry that reduce velocity at high flows can also reduce its erosive potential (Wilkin & Hebel, 1982). Whereas flooding concerns are almost always most prominent at a ditch's outfall, erosion risks can abound throughout the length of a ditch channel.

To quantify water velocities throughout the ditch, 25 cross-sections (roughly evenly spaced) were identified that spanned the ditch's corridor. The 1st cross-section was placed at the very upstream end of the ditch, and the 25th corresponded to the ditch outlet. The maximum water velocity observed at each segment was extracted during each event. These maximum velocity values are cross-sectional averages of the two-dimensional flow rates and thus reflect the complete velocity profile for each ditch location. The %Reduction values were also calculated at each segment to compare the single-stage and two-stage conditions.

4 VEGETATION MONITORING RESULTS

4.1 PRE-CONSTRUCTION VEGETATION

Overall vegetation of the right-of-way was entirely dominated by perennial weed species (Table 4-1). Smooth brome (*Bromus inermis*) was most common, though reed canary grass (*Phalaris arundinacea*) was dominant in a handful of areas. While perennial weeds made up 64% of the cover on site, 3% was comprised of ruderal native perennials like common milkweed (*Asclepias syriaca*) and Pennsylvania smartweed (*Persicaria pensylvanica*). Species richness was 6. Unusually, there was high cover (34% cover) of thatch (corn stover) derived from extensive flooding the previous year.

Pre-construction vegetation of the two-stage ditch area was generally similar to the overall right-of-way (Table 4-1). Species richness was 7. Perennial weeds were very dominant (87% relative cover) while the remaining vegetation was ruderal native perennials (5% relative cover). Reed canary grass (P. arundinacea) was about twice as abundant compared to the overall right-of-way area, likely due to the proximity to the main stream channel. Otherwise most species and species' abundances were similar to the overall area. However, thatch/bare ground was not as prevalent (7% relative cover).

4.2 POST-CONSTRUCTION VEGETATION

After construction, overall vegetation of the right-of-way generally resembled the pre-construction vegetation (Table 4-2). While I observed some small decreases smooth brome (B. inermis) and reed canary grass (P. arundinacea), the overall area contained considerable abundance of perennial weeds. Species richness increased from 6 to 27.

In the two-stage ditch, abundance of functional groups after construction/revegetation was more even and species richness increased. Perennial weeds were reduced from 87% to 31% relative cover, while native perennials and annual/biennial weeds increased from 0 to 10% and 0 to 19% relative cover, respectively. Unvegetated areas (bare ground in this case) made up 39% relative cover. Within the perennial weed group, smooth brome (*B. inermis*) and reed canary grass (*P. arundinacea*) decreased considerably, while Canada thistle (*Cirsium arvense*) increased. The most abundant native perennials were black-eyed Susan (*Rudbeckia hirta*) and Virginia wildrye (*Elymus virginicus*), though most native perennials were quite similar in abundance. Annual/biennial weeds were mostly dominated by oats (*Avena sativa*), tall water hemp (*Amaranthus tuberculatus*) and lamb's quarters (*Chenopodium album*). Abundance of ruderal native perennials remained essentially the same as before construction. Overall species richness increased from 7 species to 36 species after revegetation. Of the total species richness, native perennial species richness was 11 and annual/biennial weed richness was 12.

Main channel areas (Stage 1) of the two-stage ditch were dominated by invasive species. While we did not formally survey vegetation in Stage 1 areas of the ditch, we consistently observed reed canary grass (P. arundinacea) to be dominant in the bottoms of the constructed ditch (Fig. 3). Other common wetland ruderals (e.g. smartweeds (*Persicaria spp.*), barnyard grass (*Echinocloa crus-gallii*) were sporadically present.

Table 4-1. Composition of vegetation in the overall right-of-way before (2021) and after (2022).

Common Name	*Scientific Name*	*Relative Cover (%)*	
		2021	*2022*
smooth brome	*Bromus inermis*	49.7%	44.4%
thatch/bare ground		33.8%	24.4%
reed canary grass	*Phalaris arundinacea*	9.1%	6.7%
stinging nettle	*Urtica dioica*	4.0%	0.2%
Pennsylvania smartweed	*Persicaria pensylvanica*	1.7%	1.2%
hedge bindweed	*Calystegia sepium*	1.0%	0.7%
Canada thistle	*Cirsium arvense*	0.7%	3.0%
tall water hemp	*Amaranthus tuberculatus*	0.0%	4.2%
oats	*Avena sativa*	0.0%	3.9%
Virginia ground cherry	*Physalis virginiana*	0.0%	1.9%
prickly lettuce	*Lactuca serriola*	0.0%	1.6%
black eyed Susan	*Rudbeckia hirta*	0.0%	1.6%
Virginia wild rye	*Elymus virginicus*	0.0%	1.2%
lambs quarters	*Chenopodium album*	0.0%	0.8%
giant foxtail	*Setaria faberi*	0.0%	0.8%
hairy cupgrass	*Eriochloa villosa*	0.0%	0.6%
dotted smartweed	*Persicaria punctata*	0.0%	0.6%
Indian grass	*Sorghastrum nutans*	0.0%	0.4%
velvetleaf	*Abutilon theophrasti*	0.0%	0.2%
big bluestem	*Andropogon gerardii*	0.0%	0.2%
false sunflower	*Heliopsis helianthoides*	0.0%	0.2%
common dandelion	*Taraxacum officinale*	0.0%	0.2%
ironweed	*Vernonia fasciculata*	0.0%	0.2%
Showy tick trefoil	*Desmodium canadense*	0.0%	0.1%
Canada wild rye	*Elymus canadensis*	0.0%	0.1%
Fall panicum	*Panicum dichotomiflorum*	0.0%	0.1%
switchgrass	*Panicum virgatum*	0.0%	0.1%
yellow coneflower	*Ratibida pinnata*	0.0%	0.1%

Native species established in the seeded bench (Stage 2) areas of the constructed ditch. Eight native species in the bench areas were found established as seedings, with four grasses and four forbs. Establishment rates of sown species were quite low, with an overall establishment rate of 1.1%. Though establishment rates were low, the density of seedlings was found to be more moderate, at 13.67 ramets/m2. The most common seedlings were Viginia wildrye (*E. virginicus*), Indian grass (*Sorghastrum nutans*), black-eyed susan (*R.hirta*), and ox-eye (*Heliopsis helianthoides*), all species typical of early successional tallgrass prairie reconstruction.

4.3 VEGETATION ASSESSMENT SUMMARY

Overall, the prototype two-stage ditch using native vegetation was established successfully. Seedling densities in the first growing season were over the threshold some authors set for long-term expectations of stand success (11 stems/m² (Smith et al. 2010)). Additionally, invasive species were reduced below 20% of total cover, providing future potential for native seedlings to mature without excessive competition. Ultimately, patterns of native species establishment in this two-stage ditch appeared to be very similar to establishing native species in roadsides generally.

An abundance of annual/biennial weeds and bare ground with a considerable presence of sown native species is typical of prairie reconstructions in roadsides and former crop fields (Meissen et al. 2020). Lessons learned across decades of using native vegetation in roadside rights-of-way should be readily applicable to this new and promising practice of roadside two-stage ditch construction.

Table 4-2. Composition of vegetation in the two-stage ditch before and after construction and revegetation. Seedling density is reported post-revegetation (2022).

Common Name	*Scientific Name*	*Relative Cover (%)*		*Seedlings /m²*
		2021	*2022*	
smooth brome	*Bromus inermis*	57.5%	8.4%	
reed canary grass	*Phalaris arundinacea*	22.7%	10.8%	
thatch/bare ground		7.3%	39.4%	
stinging nettle	*Urtica dioica*	4.8%	1.8%	
Penn.smartweed	*Persicaria pensylvanica*	3.4%	0.1%	
Canada thistle	*Cirsium arvense*	2.3%	8.2%	
common milkweed	*Asclepias syriaca*	1.5%	0.1%	
hedge bindweed	*Calystegia sepium*	0.3%	0.5%	
oats	*Avena sativa*	0.0%	9.5%	
tall water hemp	*Amaranthus tuberculatus*	0.0%	3.4%	
black eyed Susan	*Rudbeckia hirta*	0.0%	3.4%	2
lambs quarters	*Chenopodium album*	0.0%	2.6%	
Virginia wild rye	*Elymus virginicus*	0.0%	2.8%	3.67
false sunflower	*Heliopsis helianthoides*	0.0%	0.9%	1.67
giant foxtail	*Setaria faberi*	0.0%	0.9%	
common dandelion	*Taraxacum officinale*	0.0%	0.9%	
Indian grass	*Sorghastrum nutans*	0.0%	0.8%	3.67
ironweed	*Vernonia fasciculata*	0.0%	0.8%	1
hairy cupgrass	*Eriochloa villosa*	0.0%	0.7%	
velvetleaf	*Abutilon theophrasti*	0.0%	0.4%	
three seed mercury	*Acalypha rhomboidea*	0.0%	0.4%	
big bluestem	*Andropogon gerardii*	0.0%	0.2%	1
bull thistle	*Cirsium vulgare*	0.0%	0.2%	
Vir. ground cherry	*Physalis virginiana*	0.0%	0.2%	
Canada wild rye	*Elymus canadensis*	0.0%	0.2%	
yellow coneflower	*Ratibida pinnata*	0.0%	0.2%	
barnyard grass	*Echinochloa crus-galli*	0.0%	0.1%	
prickly lettuce	*Lactuca serriola*	0.0%	0.1%	
rice cut grass	*Leersia oryzoides*	0.0%	0.1%	
white mulberry	*Morus alba*	0.0%	0.1%	
yellow wood sorrel	*Oxalis stricta*	0.0%	0.1%	
common plantain	*Plantago major*	0.0%	0.1%	
little bluestem	*Schizachyrium scoparium*	0.0%	0.1%	0.33
New England aster	*Symphyotrichum novae-angliae*	0.0%	0.1%	0.33
wheat	*Triticum aestivum*	0.0%	0.1%	
golden Alexanders	*Zizia aurea*	0.0%	0.1%	

The two-stage ditch prototype represented a large ecological improvement from the previous conventional ditch (Figure 4-1). Where the conventional ditch was dominated by a handful of invasive species, implementing a two-stage ditch with native vegetation increased species richness nearly sixfold. Further study is needed to understand if these gains in biodiversity are typical or lasting. Since invasive species were still common in the overall right of way, it is unclear whether plant species richness will be maintained over long timeframes. Follow up vegetation surveys should occur on new two stage ditches, especially when vegetation is mature. Surveys conducted five or more years post-construction will provide better evidence about the longer-term nature of two-stage ditch vegetation.

Figure 4-1. View of typical main channel vegetation post-construction (September 2022).

5 HYDRAULIC MODELING

5.1 MODEL CALIBRATION

The single-stage HEC-RAS model was successfully calibrated using the historical October 2020 wet weather event. The peak stage of this observed event was 257.73 m, while the peak stage of the simulated model was 257.82 m. The lag between these peaks was approximately 1.5 hours. Comparing these two timeseries yielded a Kling-Gupta efficiency of 0.88 and a Nash-Sutcliffe efficiency of 0.55, which suggests that model calibration was satisfactory (Moriasi et al., 2015).

5.2 PEAK FLOWS AND WATER VOLUMES

Peak flow rates and total water volumes at the ditch outlet were successfully calculated for each design storm (Table 3-1). Flows for all simulated events stayed within the ditch channel, i.e., no overtopping of the roadway or field occurred. As expected, flows increased for more extreme return periods associated with greater rainfall (Figure 5-1).

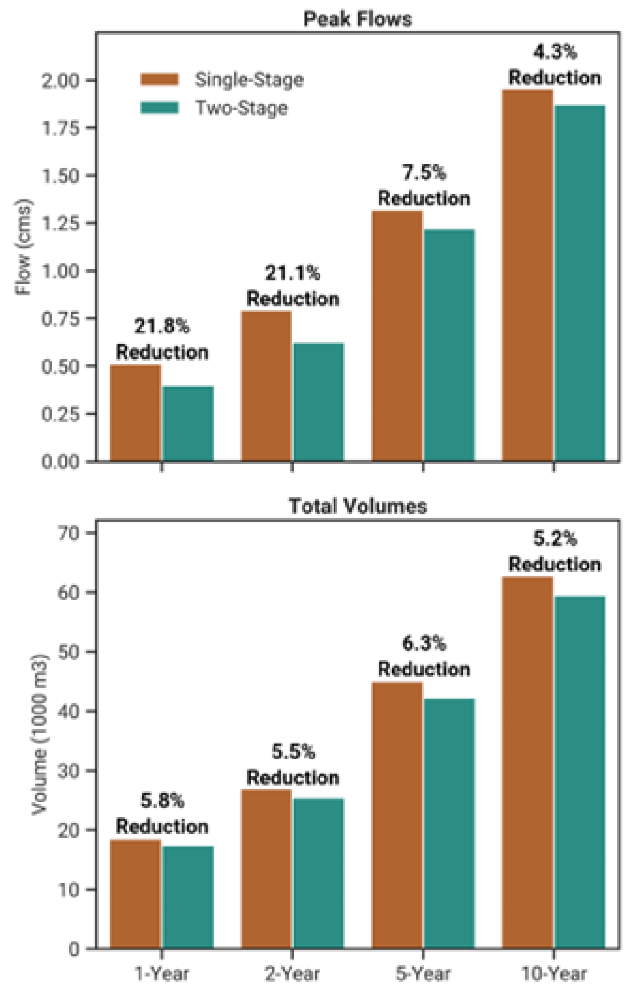

Figure 3-1. Peak flows (top) and total water volumes (bottom) for each simulated event. The corresponding %Reduction values are labeled.

For the 1-year event, peak flows decreased from 0.51 cms in the single-stage scenario to 0.40 cms in its two-stage counterpart. The remaining events exhibited similar behavior—producing peak flow declines of 0.79 to 0.63 cms (2-year), 1.32 to 1.22 cms (5-year), and 1.96 to 1.87 cms (10-year). The %Reductions corresponding to each of these decreases were 21.8%, 21.1%, 7.5%, and 4.3%, respectively (Figure 5-1, top). Notably, these %Reduction values monotonically decreased with larger precipitation events.

5.3 WATER VELOCITIES

As with the peak flows and total water volumes, maximum water velocities declined consistently between the single-stage and two-stage scenarios. Figure 5-2 provides an example of maximum velocities for the 10-year event across 25 cross-sections.

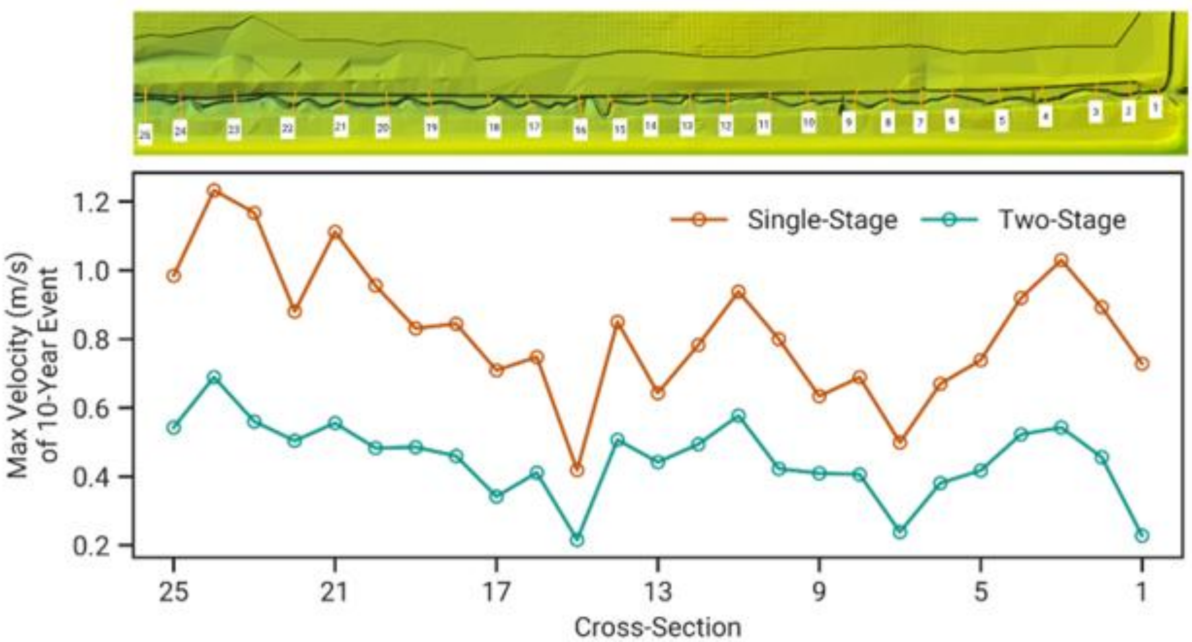

Figure 5-2. Maximum velocity at each cross-section for the 10-year event. Locations of cross-sections are shown in the top inset; cross-section 25 corresponds to the ditch outlet.

For the 1-year event, maximum velocities throughout the ditch corridor ranged from 0.37 – 0.91 m/s (mean of 0.66) in the single-stage scenario and from 0.20 – 0.64 m/s (mean of 0.45) in the two-stage (Figure 5-3). The remaining single-stage maximum velocity ranges were 0.42 – 1.03 m/s (mean of 0.73), 0.42 – 1.15 m/s (mean of 0.80), and 0.42 – 1.23 m/s (mean of 0.83) for the 2-year, 5-year, and 10-year events, respectively. Maximum velocities in the two-stage model were more consistent across design storms, with ranges of 0.22 – 0.70 m/s and average values of approximately 0.45 m/s.

The %Reduction values were also calculated at each segment to compare the single-stage and two-stage conditions (Figure 5-4). For the 1-year event, maximum velocities throughout the ditch corridor ranged from 0.37 – 0.91 m/s (mean of 0.66) in the single-stage scenario and from 0.20 –

0.64 m/s (mean of 0.45) in the two-stage. The remaining single-stage maximum velocity ranges were 0.42 – 1.03 m/s (mean of 0.73), 0.42 – 1.15 m/s (mean of 0.80), and 0.42 – 1.23 m/s (mean of 0.83) for the 2-year, 5-year, and 10-year events, respectively. Maximum velocities in the two-stage model were more consistent across design storms, with ranges of 0.22 – 0.70 m/s and average values of approximately 0.45 m/s.

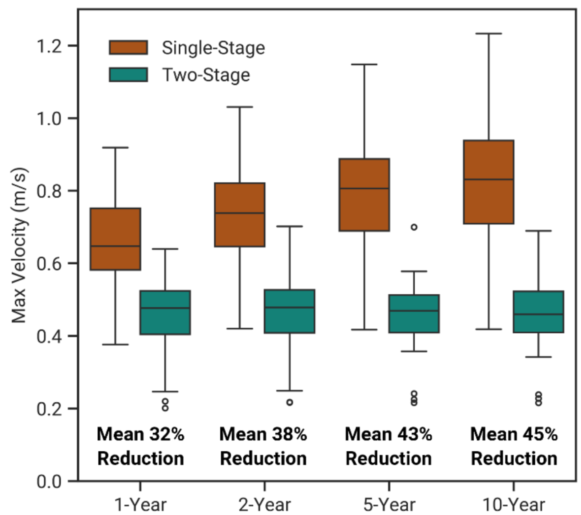

Figure 5-3. Boxplots of maximum velocities across the ditch cross-sections for each event. The average %Reduction values for each event are labeled.

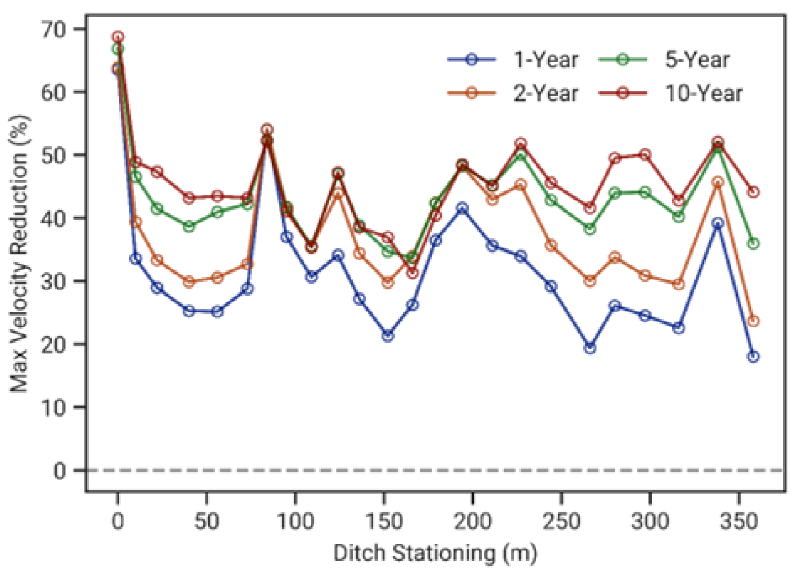

Figure 5-4. %Reduction in maximum velocity along the ditch profile. Ditch stationing refers to the distance from the most upstream cross-section.

5.4 IMPACTS OF ROADSIDE TWO-STAGE DESIGN ON DITCH HYDRAULICS

Modeling results from this study suggest that converting a roadside ditch from a single, trapezoidal shape to a two-stage design has hydrologic impacts. At smaller 1- and 2-year storm events, peak flows in the roadside ditch can decrease by more than 20% compared to a traditional ditch shape. Our design was specifically configured to ensure that during smaller events, the ditch's second stage becomes activated when water levels rise to inundate the floodplain bench. When this occurs, the flood peak encounters additional surface roughness provided by the dense plant growth on the bench, and the flood wave is slowed, resulting in attenuation of the maximum flow rate (Liu et al., 2004; Sholtes & Doyle, 2011).

During larger 5- and 10-year flood events, a greater proportion of discharge in the ditch does not encounter the increased surface roughness in the second stage. Therefore, there is less overall impact on flood peaks, which resulted in smaller %Reductions for the 5- (7.5%) and 10-year (4.3%) events, and it is likely that at more extreme events, the difference in peak flows between that single- and two-stage ditches would become even less pronounced. It should be noted, however, that the second stage accommodates a greater volume of discharge for every wet weather event, and water levels in the ditch would always be lower with the same amount of flow (Vastila et al., 2021). Lower water levels in a roadside ditch would reduce the potential for local roadway overtopping by better containing floodwaters during larger events. It is clear that increasing the attenuation of upstream flood peaks benefits downstream river reaches and reduces flood risks, and these benefits are likely most pronounced for less extreme flood events (Asselman et al., 2022; Lane, 2017; Dixon et al., 2016). Although not the focus of this paper, the inundation of the second stage of the two-stage ditch also results in increased water treatment, and reductions in turbidity, sediment, and nutrients have been measured during these conditions (Roley et al., 2012; Davis et al., 2015; Hodaj et al., 2017; Mahl et al., 2015).

In addition to flood peak attenuation, the roadside two-stage ditch was found to provide benefits by reducing total water volumes. Whereas peak flow reductions decreased during larger events, reductions in water volume remained relatively consistent (5.5 – 6.3%) across our suite of simulated design storms (Figure 5). These steady volume reductions are likely due to enhanced infiltration and evapotranspiration taking place within the two-stage design. The additional interaction with vegetation and soils along the ditch's second stage, coupled with the greater surface area of water in contact with the atmosphere, decreases the volume of water reaching the ditch outlet (Ahmed et al., 2015). Since these processes take place throughout the storm event, their effects are most evident in hydrologic metrics that describe an event's entire duration (e.g., total water volume). Indeed, the aforementioned attenuation of the flood wave taking place in the two-stage design prolongs the hydrograph (Sholtes & Doyle, 2010). This results in a lengthening of water's travel time through the ditch, allowing for more infiltration and evapotranspiration (Shanafield & Cook, 2014). The water volume removed by the ditch appears to scale linearly with the runoff volume produced by the storm event, resulting in consistent %Reduction values across the four design storms. Volume reductions would likely remain the same for greater events, provided that the water remains confined in the ditch channel.

The hydrologic impacts of the two-stage ditch were particularly evident for smaller 1- to 2-year events. This flood frequency coincides with a traditional definition of "bankfull discharge" with a recurrence interval near 1.5 years when stream flows are most effective at changing channel shape and characteristics (Wolman & Miller, 1960; Dunne & Leopold, 1978). In a natural channel, reducing bankfull discharge would result in a stream adjusting to a new channel-forming discharge condition and developing more stable width and depth dimensions (Edwards et al., 2019). In the two-stage roadside ditch, baseflows in the original channel are unchanged, but smaller events inundate the floodplain bench. Channels with floodplain benches have a more self-sustainable morphology and dissipate fluvial energy (Krider et al., 2017; Powell & Bouchard, 2010).

Evidence for decreased fluvial energy in the two-stage roadside ditch is shown by the decrease in maximum flow velocities relative to a single stage ditch. Reducing maximum velocities in the ditch reduces shear stress along the toe of the ditch bank and reduces the risk of mass wasting and sloughing (Magner et al., 2012; Krider et al., 2017). Indeed, in Iowa and across much of the glaciated Midwest, due to many factors such as land cover change, channelization, and removal of riparian vegetation (Schilling et al., 2004), many stream channels are incised and suffer from widespread and severe streambank erosion (Schilling et al., 2023; Wolter et al., 2021; Kessler et al., 2013). Roadside ditches receiving runoff from contributing watersheds and paved roadways can be vulnerable to the same pressures as incised stream channels and become unstable and erosive. Reducing stream velocity in the two-stage roadside ditch will reduce the risk of streambank and bed erosion and lessen the need for maintenance and repair by transportation officials (Schneider et al., 2019).

Modeling indicated that the two-stage configuration would serve to reduce peak flows, total water volumes, and maximum water velocities in the channel. Together with on-road structures, low-grade weirs, and vegetation management, two-stage ditches should be added to the portfolio of new innovations and best management practices for transportation infrastructure, with the potential to help mitigate downstream flood impacts.

6 WATER QUALITY MONITORING RESULTS

Water quality monitoring at two-stage ditch site included pre-construction monitoring and post-construction monitoring with a focus on turbidity and nutrient runoff events.

6.1 PRE-CONSTRUCTION MONITORING

Stream stage in the ditch was often very low during the 2020 and 2021 monitoring periods (Figure 3). A peak stage of approximately 259 m was measured in 2020 but stage did not exceed 257.5 in 2021. During both monitored years, the ditch was completely dry beginning in early to mid-July, with flow resuming in fall in 2020 (resuming on October 22 in 2020), but staying dry in 2021.

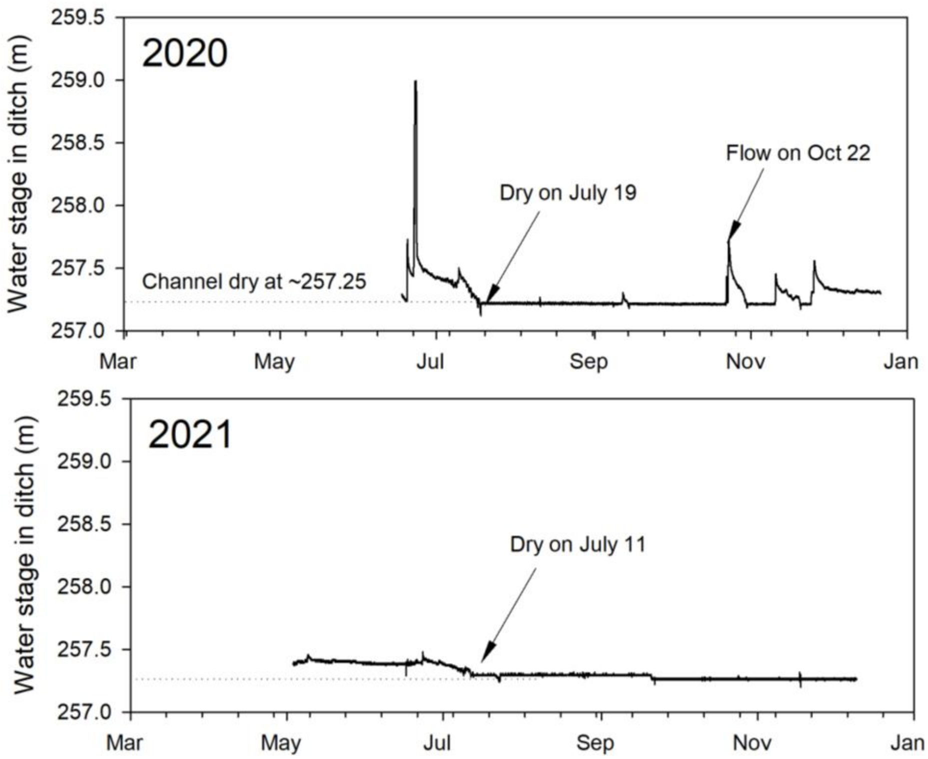

Figure 6-1. Streat stage in the two-stage ditch in 2020 and 2021.

Hourly turbidity measurements collected in 2020 and 2021 showed variations across several orders of magnitude (Figure 6-2). However, average turbidity values were often very low, with mean values of approximately 10-11 NTU in 2020 and 4-5 NTU in 2021 at both upstream and downstream sites. Overall, average turbidity was slightly higher in the upstream location compared to the downstream location but the difference was not statistically significant ($p>0.1$).

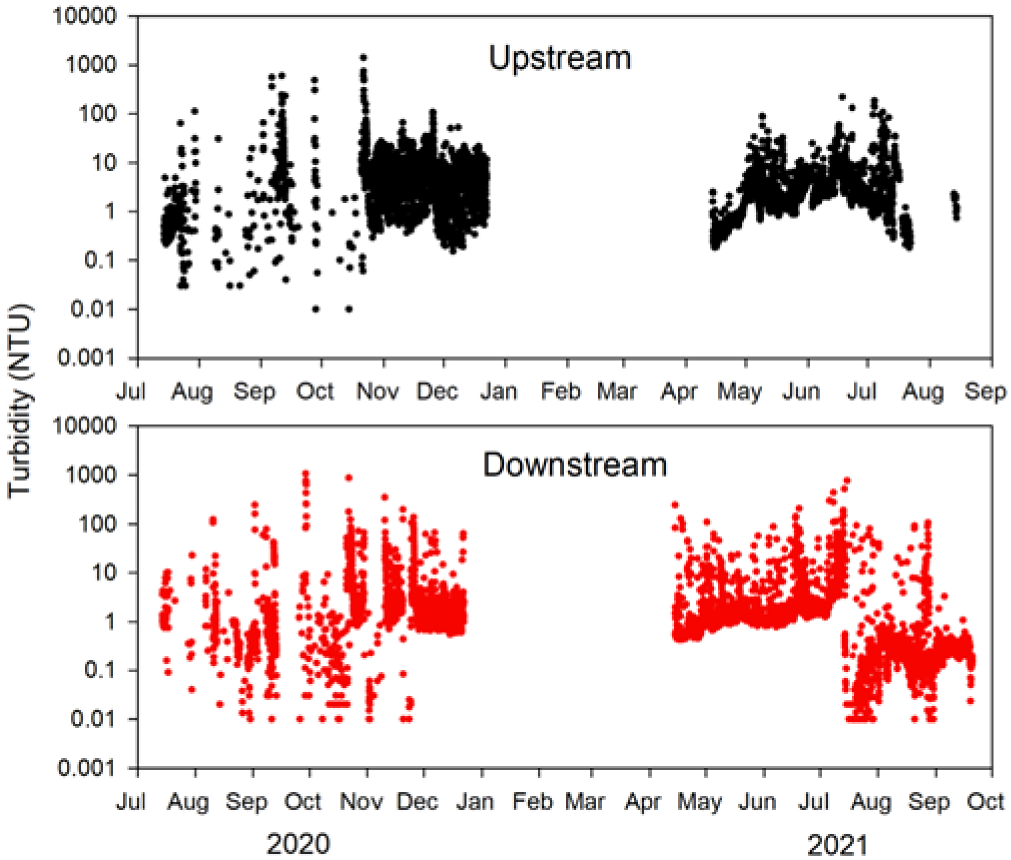

Figure 6-2. Upstream and downstream turbidity measurements collected at the two-stage ditch site.

Surface water sampling results from upstream and downstream locations in the ditch, monitoring wells and Prairie Creek were compiled for both 2020 and 2021 years and summarized in box plots (Figure 6-3). Among the measured parameters, dissolved oxygen (DO) and NO3-N concentrations varied most systematically among the four population groups. Similar DO concentrations were observed in surface water samples (mean 7.8 to 9.7 mg/l) but were lower in the ditch wells (mean 5.8 mg/l). Mean NO3-N concentrations were highest in the ditch upstream (11.7 mg/l) and downstream samples (8.4 mg/l) and lower in the wells and Prairie Creek (4.4 and 5.7 mg/l, respectively). Specific conductance and chloride concentrations were observed to occasionally spike in the downstream ditch samples and in the wells due to road salt impacts. Mean DRP concentrations ranged between 0.08 to 0.1 mg/l which is consistent with values measured in shallow Iowa groundwater (Schilling et al., 2019).

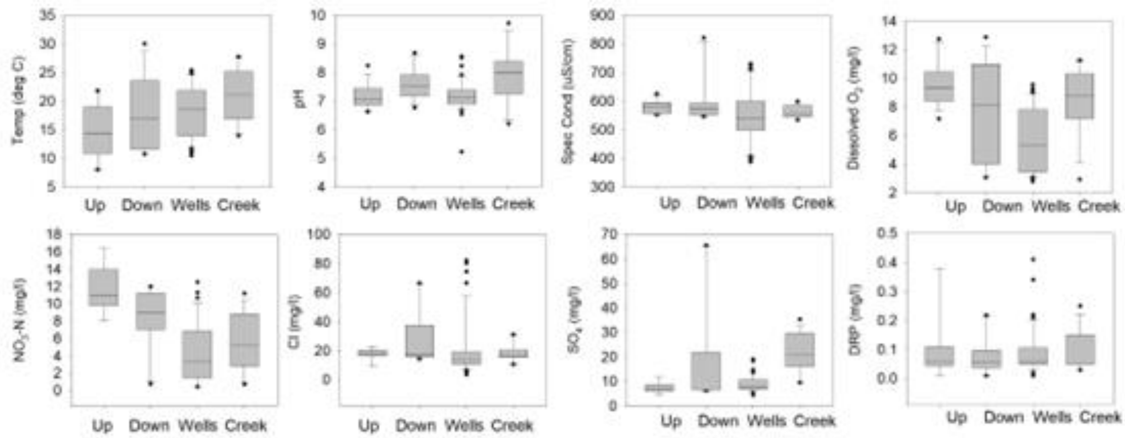

Figure 6-3. Box plots of water quality parameters measured at the two-stage ditch site, including upstream and downstream ditch locations, monitoring wells and Prairie Creek in 2020 and 2021.

6.2 TURBIDITY REDUCTIONS

High-resolution and daily mean turbidity gradients were evaluated for the 2021 (pre-construction) and 2024 (post-construction) water years (Figure 6-4). Note that a water year spans October to September; however, no monitoring data were available during the winter months in either period. Total precipitation was estimated for the 2021 (704 mm) and 2024 (923 mm) water years using a nearby rainfall gauge (~25 km northeast in Vinton, IA). Turbidity differences were only evaluated when turbidity data were available for both upstream and downstream sites.

For the 2021 water year, there were ~30,000 instances where turbidity measurements were available at both sites, whereas in the 2024 water year, there were ~33,600 paired measurements. Aggregating the daily values yielded 168 (in 2021) and 242 days (in 2024) with paired measurements available at both locations. Overall, turbidity in the ditch stream was very low for the majority of days, with upstream and downstream median values of 2.18 and 0.96 NTU in 2021 and 1.68 and 0.31 NTU in 2024, respectively (Table 6-1). Mean turbidity values were larger at both the upstream and downstream locations in 2024. Maximum daily mean turbidity values exceeded 1000 NTU at the sites in both years following rainfall-runoff events. Because the upstream location was near the point where watershed flow from the agricultural catchment entered the roadside ditch, turbidity was consistently higher at the upstream location than at the downstream location.

The results of the Mann-Whitney U test revealed statistically significant differences ($p<1E-5$) between the pre- and post-construction turbidity gradients for both the untransformed and log-transformed high-resolution values (Table 6-1). We thus rejected the null hypothesis that the turbidity gradient originated from the same statistical distribution. From pre- to post-construction, the median gradients increased by 0.35 NTU (untransformed) and 1.04 NTU (log-transformed). The log-transformed daily mean gradients also demonstrated a statistically significant ($p<1E-5$)

increase, rising from 0.35 to 1.03 NTU. The untransformed daily means were the only datasets that did not demonstrate a statistically significant difference (p=0.56), although their median values rose from 0.60 NTU to 0.82 NTU.

Table 6-1. Statistical summary of turbidity data collected at the two-stage ditch (units are NTU). The "Turb Gradient" columns refer to differences between the upstream and downstream observations.

Stat	2021 Water Year			2024 Water Year		
	Up Turb	**Down Turb**	**Turb Gradient**	**Up Turb**	**Down Turb**	**Turb Gradient**
count	32,622	47,139	29,948	57,147	34,416	33,622
mean	5.73	4.15	0.87	26.1	34.7	5.11
std	26.6	27.5	37.9	131	170	120
min	0.01	0.01	-1460	0.01	0.01	-1590
0.25	1.08	0.32	-0.18	0.94	0.17	0.34
0.50	2.18	0.96	0.42	1.68	0.31	0.77
0.75	4.44	1.57	2.13	3.37	2.04	1.51
0.90	9.95	4.08	6.52	16.8	11.7	7.24
0.99	58.6	69.3	48.7	728	1060	456
max	1600	1590	1490	1600	1600	1510

The histograms of the turbidity gradients (log-transformed) during the pre- and post-construction periods help to visualize the effect of the two-stage ditch on turbidity (Figure 6-5, top), with the 2024 distributions displaying notably higher values than in 2021. The cumulative distribution functions (Figure 5, bottom) further demonstrated that the increases observed from pre- to post-construction spanned almost the entirety of the distribution, i.e., the exceedance thresholds for the 2024 gradients were consistently larger than the 2021 gradients. Analysis of the turbidity gradient as a function of overall turbidity within the ditch also revealed no relationship between these parameters, indicating that the turbidity gradient was not steeper during periods of higher turbidity in 2024. This analysis suggested that the observed changes in turbidity between 2024 and 2021 were not a byproduct of more turbid conditions in 2024.

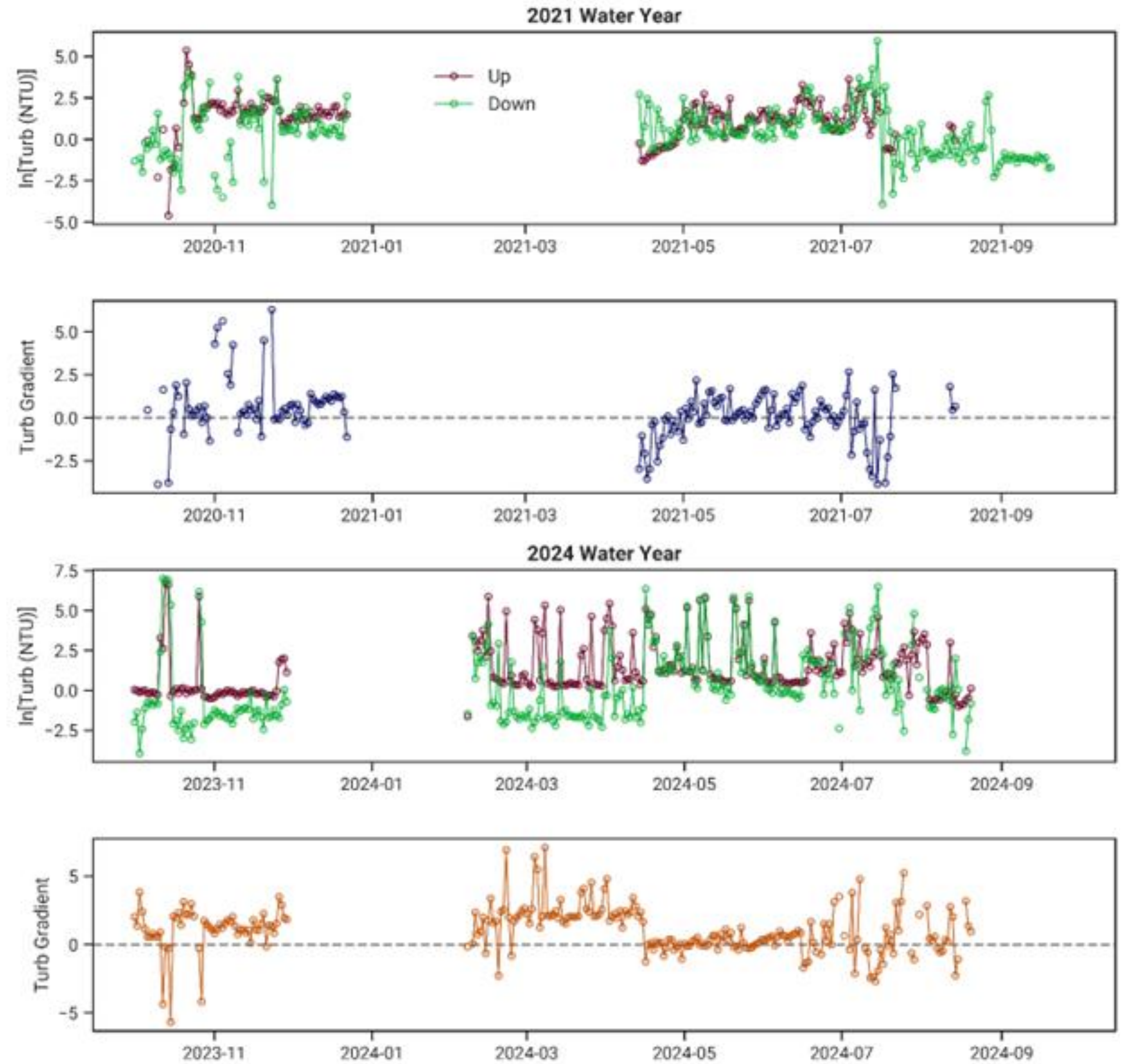

Figure 6-4. Log-transformed mean daily turbidity values measured during the 2021(pre-construction) and 2024 (post-construction) water years. The second and fourth subplots contain the turbidity gradient (i.e., the difference between upstream and downstream turbidity values) in the 2021 and 2024 water years, respectively.

Table 6-2. Results of the Mann-Whitney U test comparing the turbidity gradient (i.e., upstream – downstream) between the 2021 and 2024 water years.

Data Type	Transformation Type	Median Turbidity Gradient [Up - Down]		Mann-Whitney U Test	
		2021 WY	2024 WY	2024 Median - 2021 Median	p-value
high-resolution	untransformed	0.42	0.77	0.35	<1E-5
	log-transformed	0.27	1.31	1.04	<1E-5
daily means	untransformed	0.60	0.82	0.21	0.56
	log-transformed	0.35	1.03	0.68	<1E-5

A pre- vs. post-construction comparison of upstream and downstream turbidity was used to demonstrate that the roadside two-stage ditch increased the turbidity gradient (Figure 6-5). The quantitative results presented in the previous section illustrate the mitigation efficiency for turbidity reduction, despite the limited 450-m length of the 2-stage ditch retrofitted reach. A change in turbidity following two-stage ditch construction is consistent with other monitoring studies that reported that two-stage ditches reduced water column turbidity during bench inundation (Mahl et al., 2015; Davis et al., 2015). However, these studies did not include a pre-construction monitoring period to document conditions prior to construction, as was done in our study. Prior to construction, pre-BMP monitoring indicated that downstream turbidity was already lower than the upstream values. With the construction of the two-stage ditch, the downstream difference in turbidity increased, indicating that the two-stage ditch was reducing turbidity more than observed prior to construction.

In this project, in-situ turbidimeters were used that collected high-frequency observations to assess performance during pre- and post-construction water years that captured both baseflow and stormflow events. In other studies, two-stage ditches were reported to have negligible impacts during baseflow when conditions are dry (Mahl et al., 2015). This analysis of high-temporal-resolution turbidity data indicated that the roadside two-stage construction reduced turbidity across the spectrum of flows and background turbidity conditions. Maximum turbidity was capped at 1600 NTU in our project, and it is likely that maximum turbidity differences would have been greatest during periods of high flows and floodplain bench inundation—similar to other studies.

Given the recentness of the construction relative to our monitoring, we attribute water quality changes, specifically turbidity, to the modified channel shape and the interception of flow by bench vegetation. Floodplain benches in two-stage designs have been shown to enhance local plant diversity in agricultural landscapes (DeZiel et al., 2019; Vastila et al., 2021; Huttunen et al., 2024). At our roadside location, plant diversity was increased following planting, resulting in reduced perennial weed cover and increased native perennials and overall species richness. Increased plant diversity, including stiff native prairie plants, is understood to increase surface roughness, slow runoff, and increase infiltration during runoff events (Schilling and Drobney, 2014; Gerla, 2007). We suspect that one of the lasting impacts of the roadside ditch construction will be the conversion of ditch vegetation from a mix of weeds and invasive cool-season grass to a diverse mix of warm- and cool-season perennials.

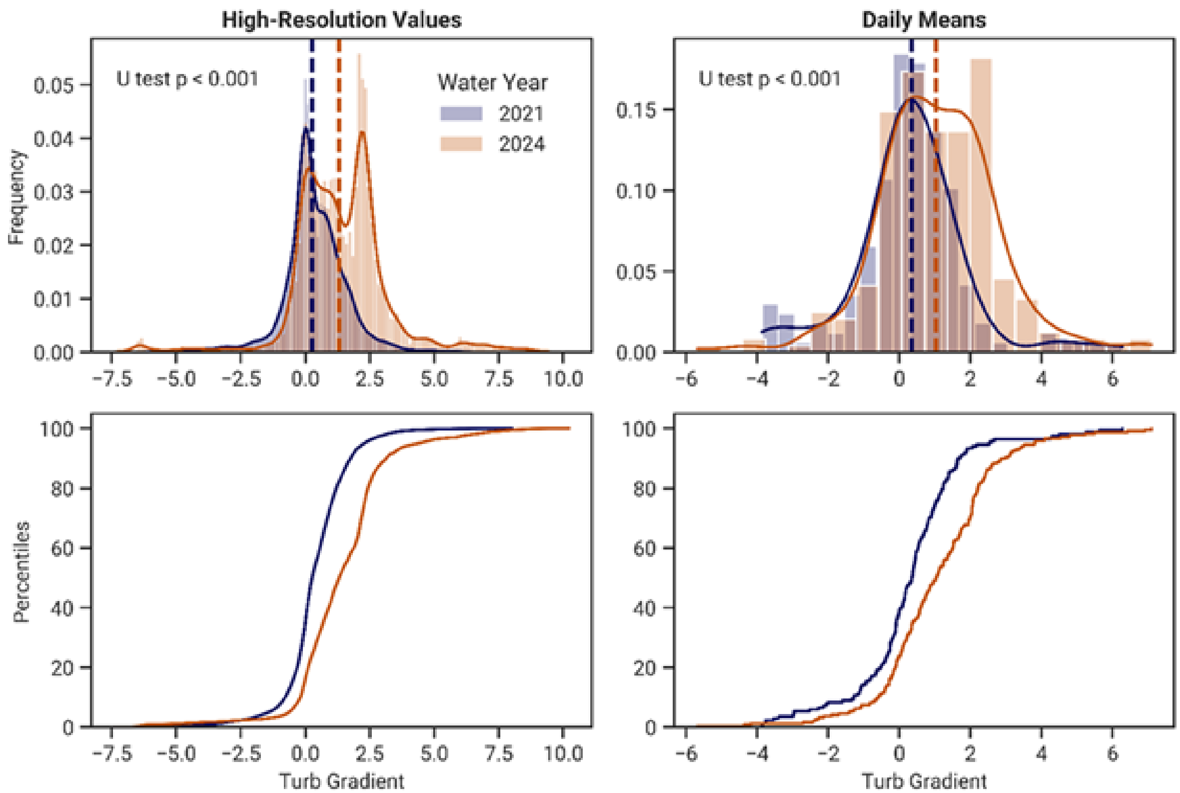

Figure 6-5. Histograms (top) and empirical cumulative distribution functions (bottom) of the high-resolution (left) and daily mean (right) log-transformed turbidity gradients in the 2021 (pre-construction, in blue) and 2024 (post-construction, in orange) water years. Vertical lines represent median values for each water year

In Iowa, turbidity is strongly linked to particulate nutrients (Anderson et al., 2024; Schilling et al., 2017). Hence, a reduction in turbidity associated with the roadside two-stage ditch would translate to a reduction in PartP and ON exported from the contributing agricultural field. We used the relationship between turbidity and particulate nutrients to assess the impact of turbidity reductions on nutrient concentrations. To quantify nutrient levels at our study site, we constructed a surrogacy relationship using water quality data collected from Wolf Creek in La Porte City, IA. The Wolf Creek watershed is located ~40 km north of our study site; it also lies within the Iowan Surface landform region and contains very similar land use, geologic, and hydrologic characteristics compared to our study site. Substantial water quality sampling (n=298) has been conducted at Wolf Creek, and we utilized these water quality data to relate turbidity to PartP and ON (Figure 6-6).

With the surrogacy equations, we estimated corresponding PartP and ON concentrations for each paired turbidity observation at the two-stage ditch site. Table 6-3 summarizes the mean

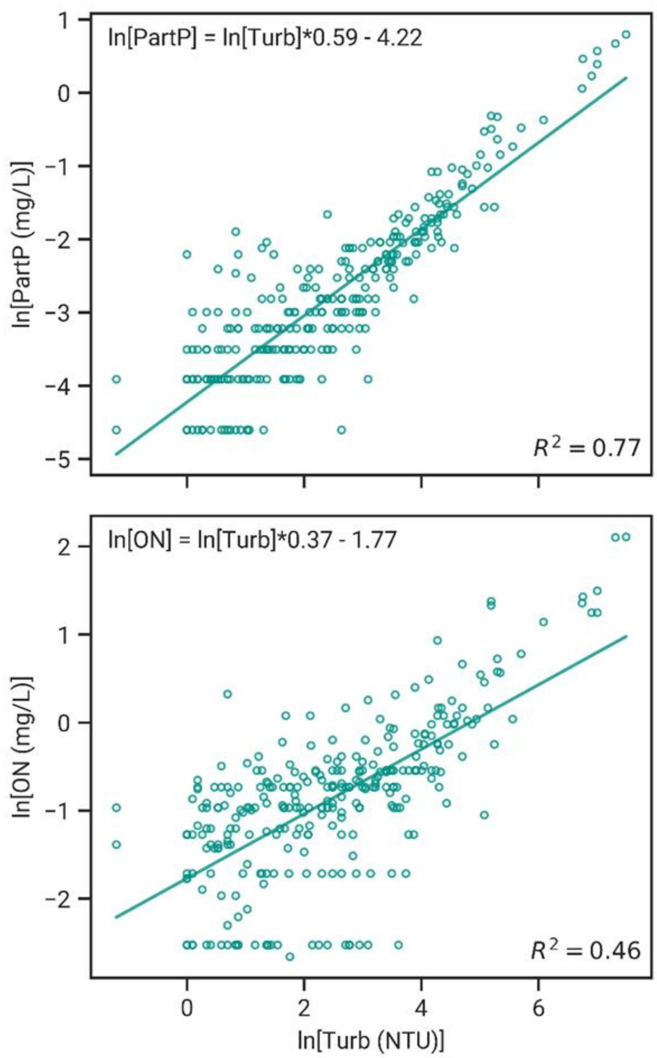

Figure 6-6. Surrogacy model relating turbidity observations to particulate P (top) and organic N (bottom) in Wolf Creek near La Porte City, IA.

concentrations for each nutrient form, monitoring location, and water year. In each case, the concentration difference increased from 2021 to 2024—rising from 0.005 to 0.014 mg/L for PartP and 0.030 to 0.097 mg/L for ON. These reductions in nutrient levels were primarily due to lower concentrations at the downstream portion of the ditch. Indeed, upstream concentrations were similar pre- and post-construction (0.024 and 0.026 mg/L for PartP; 0.230 and 0.242 mg/L for ON), but downstream concentrations were noticeably lower (0.019 and 0.011 mg/L for PartP and

0.200 and 0.145 mg/L for ON). These results highlight the effectiveness of the two-stage ditch in reducing export of particulate nutrients.

Given the recentness of the construction relative to our monitoring, we attribute the observed turbidity reduction changes to the modified channel shape and to the interception of flow by bench vegetation. Floodplain benches in two-stage designs have been shown to enhance local plant diversity in agricultural landscapes (DeZiel et al., 2019; Vastila et al., 2021; Huttunen et al., 2024).

Table 6-3. Estimated mean concentrations of particulate nutrient forms along the two-stage ditch. Units are mg/L as P for PartP and mg/L as N for ON.

Particulate Nutrient Form	2021 Water Year			2024 Water Year		
	Up Conc	Down Conc	Conc Gradient	Up Conc	Down Conc	Conc Gradient
PartP	0.024	0.019	0.005	0.026	0.011	0.014
ON	0.230	0.200	0.030	0.242	0.145	0.097

At our roadside location, plant diversity was increased following planting, resulting in reduced perennial weed cover and increased native perennials and overall species richness. Increased plant diversity, including stiff native prairie plants, is understood to increase surface roughness, slow runoff, and increase infiltration during runoff events (Schilling and Drobney, 2014; Gerla, 2007). We suspect that one of the lasting impacts of the roadside ditch construction will be the conversion of ditch vegetation from a mix of weeds and invasive cool-season grass to a diverse mix of warm- and cool-season perennials.

6.3 DISSOLVED CONSTITUENTS

In spring 2024 (post-construction), four high-flow events were sampled for dissolved constituents, and NO3-N and Cl patterns showed similar variations (Figures 6-7 and 6-8, respectively). Plots of OP and sulfate concentrations are provided in Figures 6-9 and 6-10. During the April 18 and May 21 events, sampling commenced after the flood peak had passed, whereas during the May 2 and June 5 events, sampling captured the rising and falling limbs of the hydrograph. Changes in water stage during the sampled events varied from approximately <0.1 m during the April 18 and June 5 events to nearly 0.3 m during the two May events. NO3-N concentrations ranged from approximately 4 to nearly 12 mg/L during the four events, which was consistent with concentrations measured pre-BMP grab sampling in 2020 and 2021. Cl concentrations exhibited more variability than NO3-N, with values ranging from ~12 mg/L to 58 mg/L. The much lower Cl concentrations observed during the recession of the large May 21 event indicate dilution of ditch surface water. Likewise, sulfate concentrations were much lower during the May 21 event than during the other time periods (Figure 6-9). On the other hand, OP concentrations measured during the May 21 event were much higher (0.4 to 0.6 mg/L) than the other three events (<0.01 to 0.16 mg/L; Figure 6-10).

For all dissolved constituents, concentration patterns were often very similar at upstream and downstream sites but offset by a lag in travel time between the two sites. For example, a plot of sulfate concentrations during the June 5 event shows this pattern quite distinctly (Figure 6-10). The upstream concentration peak coincided closely with the hydrograph peak, whereas the downstream concentration peaked approximately 40 min later. For other hydrograph and chemograph comparisons, the offset lags ranged from <10 to >40 min. For NO3-N, during the two complete hydrograph events capturing rising and falling limbs (May 2 and June 5), early event concentrations were much higher at the upstream site than at the downstream site (Figure 6). Near the hydrograph peak, upstream and downstream concentrations became similar (with an offset)

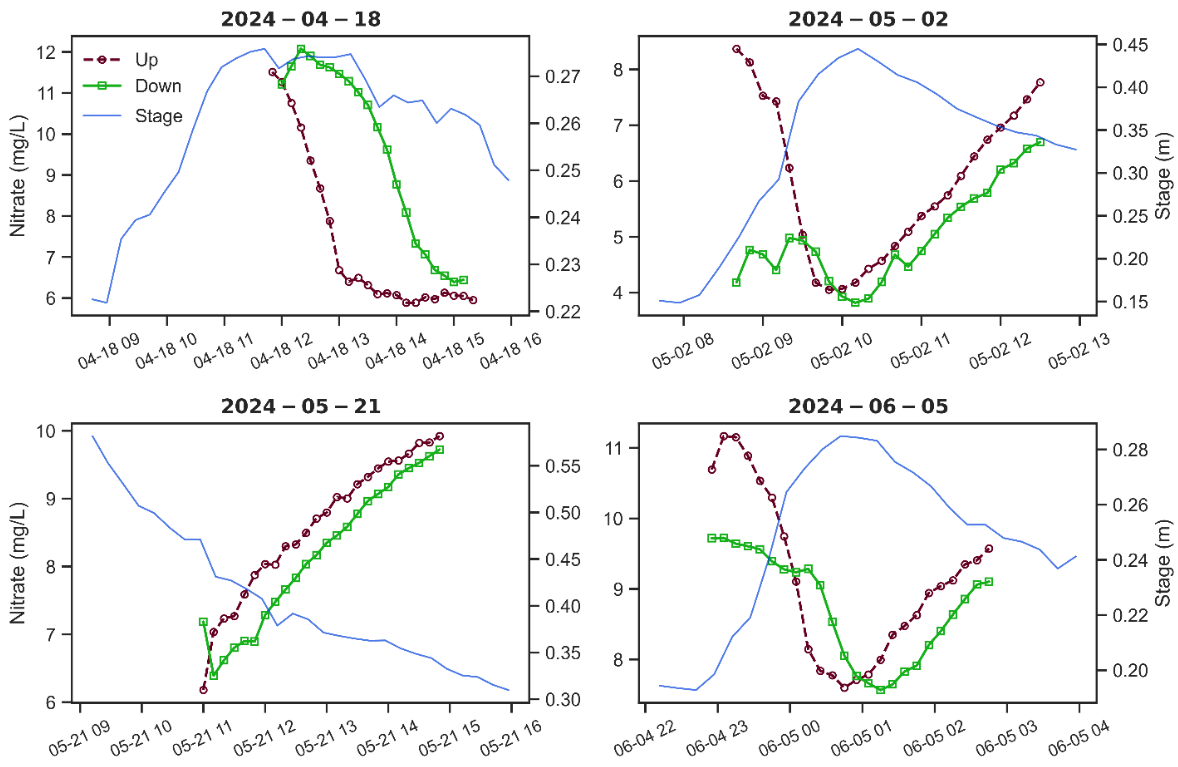

Figure 4-7. Sampled NO_3-N concentrations during high-flow events.

and largely mimicked patterns during the falling limb. Similar rising and falling patterns were observed for Cl and sulfate, but early hydrograph OP concentrations were often higher at the downstream than at the upstream site. Still, it was evident that automated sampling did not necessarily capture the entirety of each event, due to variable hydrologic responses following these four storms. Overall, the variable lag times and different early hydrograph behavior prevented detailed statistical analyses of the dissolved ion differences between upstream and changes in NO3-N or other dissolved constituents following the roadside ditch construction. During four

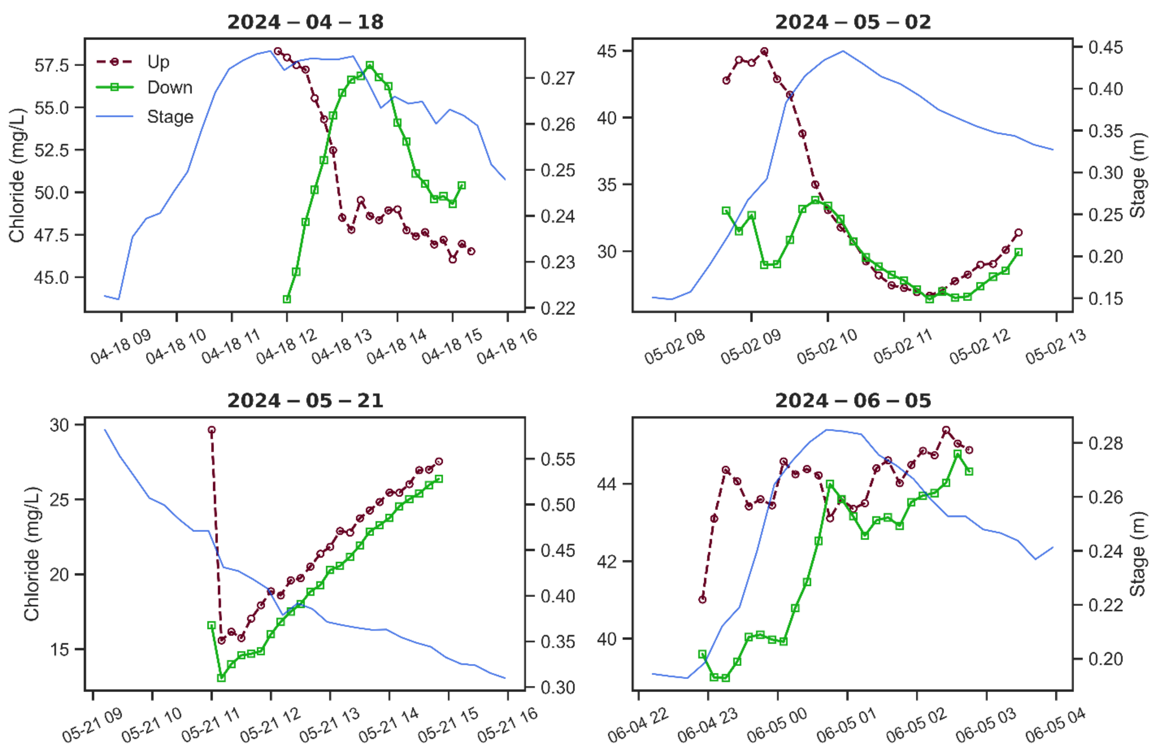

Figure 6-8. Sampled Cl concentrations during high-flow events

inundation events in 2024, we observed a close lagged relation between upstream and downstream monitoring sites but were unable to statistically quantify any changes associated with ditch construction (Figures 6-8). Documenting the success of two-stage construction on NO_3-N reductions is challenging, and some researchers use the accumulation of organic matter (OM) in two-stage reaches as a measure of success (Speir et al., 2020; Dee and Tank, 2020). An accumulation of organic matter combined with high rates of in-situ denitrification measured in the laboratory has been used to suggest that the NO_3-N loss is possible in two-stage ditches if they are sufficiently long and water is retained in them (Arango et al., 2007; Roley et al., 2012; Mahl et al., 2015; Davis et al., 2015; Hanrahan et al., 2015; Han et al., 2025).

At our roadside ditch, the relatively short ditch length (450 m) and flashy behavior of storm flow would limit the potential for significant NO_3-N reduction on both accounts. However, Speir et al. (2020) report that NO_3-N removal on two-stage ditch benches can increase once denitrification-driven NO_3-N removal recovers following construction. In unaltered Iowa ditches, Schilling et al. (2018) observed that subsurface conditions are amenable to subsurface NO_3-N processing via denitrification, reporting that concentrations were reduced by 60% from upgradient to downgradient ditch locations.

Cl concentrations measured in excess of 20 mg/L during the spring high-flow events suggest transport of roadside salt to the two-stage ditch. Road salt (i.e., NaCl) is the most widely used deicer in the US (Gardner and Royer, 2010), and many studies have shown high Cl concentrations in urbanized areas due to road salt contamination (e.g., Williams et al., 2000; Jackson and Jobbagy, 2005; Perera et al., 2013; Schilling et al., 2018). Pre-BMP monitoring of groundwater at the ditch site showed Cl concentrations averaging 44 mg/L in shallow groundwater, and event monitoring showed surface water flow with concentrations exceeding 40-50 mg/L. The similar concentrations of surface water in the ditch suggest possible subsurface conveyance of road salt to the roadside two-stage ditch.

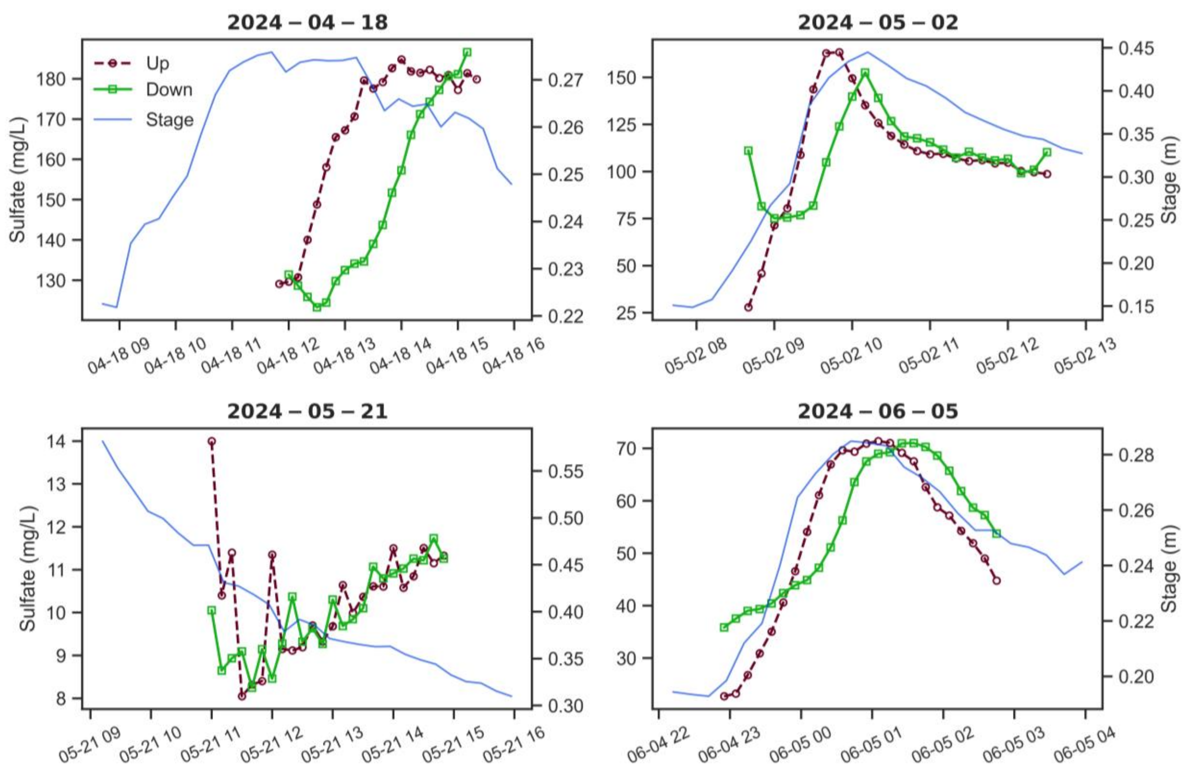

Figure 6-9. Sampled SO4 concentrations during high-flow events

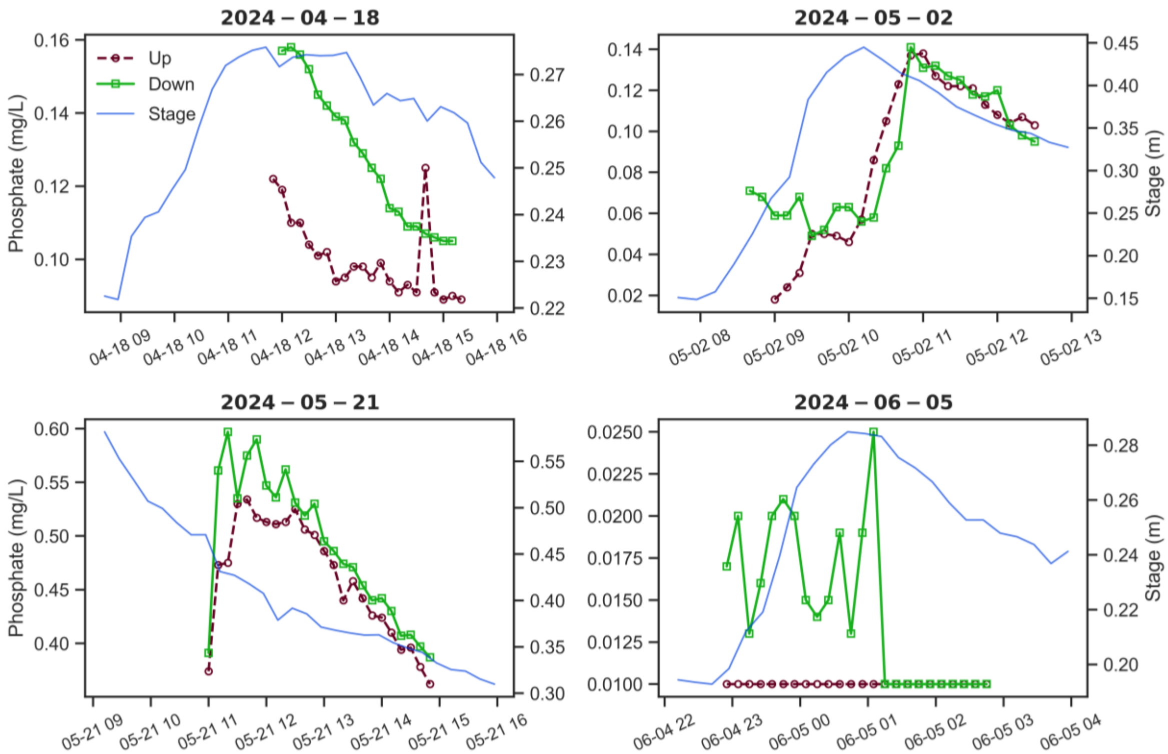

Figure 6-10. Sampled PO_4 concentrations during high-flow events

7 OPPORTUNITIES FOR ROADSIDE TWO STAGE DITCHES IN IOWA

Converting the conventional one-stage roadside ditch to a two-stage design is a novel application of a BMP that has traditionally been applied only to agricultural drainage ditches in the US Midwest. While the application of the technique to roadside ditches was unique, a question arises whether there are additional locations in Iowa where this could be done.

7.1 POTENTIAL LOCATIONS OF TWO-STAGE DITCHES

High-resolution topographic data in Iowa was used to identify where catchments up to 25.9 km^2 (10 mi^2) in size drained into a roadside ditch before discharging into a receiving stream. From this population of suitable catchment sizes, sites with a ditch length of 300 m and a slope of 1% or less were selected. This criteria was consistent with the current project and consistent with guidelines for two-stage agricultural ditches (USDA, 2017). From this analysis, 185 potential sites along state highways and 129 sites along county roads where roadside ditches were identified that could be converted to a two-stage design (Figure 7-1). This screening analysis suggests that there is a considerable potential for two-stage ditches to be utilized in Iowa roadway ditches. A particular benefit of installation in roadside ditches is that the location does not require land to be taken out of production (McLellan et al., 2015).

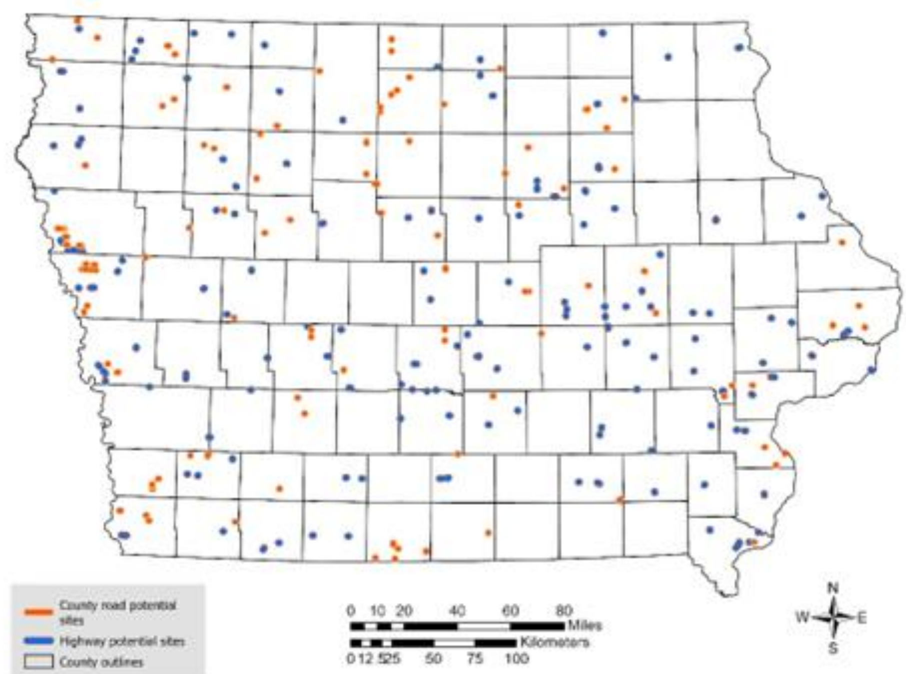

Figure 7-1. Location of potential two-stage ditch sites along roadsides in Iowa.

Among the 314 possible two-stage ditch locations across Iowa, the average length was 515 m and lengths ranged from 300 to 1,743 m (Table 7-1). The two-stage ditch length constructed as part of this project (450 m) was equivalent to the median of potential locations in the state.

Table 7-1. Spatial statistics of 314 potential locations for future two-stage ditches along Iowa roadways.

Statistic	Slope (%)	Sinuosity	Length (m)
mean	0.403	1.10	515
std	0.276	0.18	230
min	0.004	1.00	300
25th	0.148	1.00	363
median	0.374	1.04	446
75th	0.596	1.11	586
max	0.992	2.56	1,743

However, the universe of potential sites would not be considered particularly large compared to other nutrient reduction practices. For example, assuming all potential sites were converted to two-stage ditches (n=314) and all sites were treating a maximum area of 25.9 km2, the ditch practice could conceivably treat approximately 8132 km^2 of crop lands in Iowa. Considering that there are approximately 123,833 km^2 of row crops in Iowa, the two-stage treatment capacity would address 0.07% of Iowa's cropped landscape. Although roadside ditch opportunities are limited in Iowa, the two-stage ditch concept is an established BMP, and the roadside environment can join a mix of other locations where it can be applied, including agricultural drainage ditches (Roley et al., 2012; Mahl et al., 2015; Davis et al., 2015; Hodaj et al., 2017) and urban streams (McMillan and Noe, 2017).

7.2 EFFECTS OF FUTURE TWO-STAGE DITCHES ON REDUCING STATEWIDE NUTRIENT LOADS

Water monitoring during the project showed a reduction in turbidity that would suggest that the ditch is reducing particulate P and organic nitrogen concentrations. The average annual export load of particulate phosphorus (PartP) and organic nitrogen (ON) from Iowa was recently estimated to be approximately 12,600,000 and 46,900,000 kg/yr, respectively (Anderson and Schilling, 2024).

Using surrogacy equations produced from historical water quality data collected in a nearby stream (Wolf Cr near La Porte City, IA, USGS station 05464250), the decreases in particulate nutrients (i.e., particulate P (PartP) and organic N (ON)) were estimated that corresponded to the observed turbidity reductions that followed the two-stage ditch construction. The two-stage ditch was found to reduce PartP and ON concentrations by an average of 0.009 and 0.067 mg/L, respectively, which equates to an annual load reduction of 5.3 kg/yr (PartP) and 39.1 kg/yr (ON), given the typical streamflow rates observed in the region (average streamflow yield of ~300 mm/yr). The two-stage ditch thus removed particulate nutrients at a rate of 0.027 kg per meter of ditch per year (kg/m/yr) for PartP and 0.196 kg/m/yr for ON. By extrapolating these reduction rates over the total length of potential two-stage ditches in Iowa (~162,000 m), we calculated that potential two-stage ditch projects have the capacity to remove 4,290 kg/yr of PartP and 31,700 kg/yr of ON across Iowa. export. This equates to a statewide reduction in nutrient export of approximately 0.034% (PartP) and 0.068% (ON). However, it is important to note that nutrient export varies across the state and reductions in PartP and ON from two-stage ditch implementation may have greater impact at local scales. For example, many small lakes and impoundments are impacted by excessive nutrient enrichment, so constructing a two-stage roadside ditch upstream of the smaller waterbodies could have measurable impacts on improving lake water quality.

8 CONCLUSIONS AND RECOMMENDATIONS

Converting the conventional roadside ditch to a two-stage design is a novel application of a BMP that has traditionally been applied only to agricultural drainage ditches in the US Midwest. This chapter summarizes the outcome of the two-stage monitoring project in Benton County, discusses some lesson learned and offers recommendations for future work on the topic.

8.1 SUMMARY AND CONCLUSIONS

Two-stage ditches are a recognized nutrient reduction practice for drainage ditches in agricultural regions, and in this project, a novel two-stage ditch was constructed and monitored in unique roadside environment. The 450-m-long two-stage ditch, which included an intermittent stream and 194-ha tributary catchment, was constructed as part of the Highway 30 roadway expansion project in Benton County, Iowa. While pre-construction design and monitoring were straightforwardly implemented, post-construction monitoring activities were compromised by the active road building along Highway 30 (limiting access and introducing sediment erosion and deposition to the ditch), along with flow diversion into an unknown tile and unauthorized excavation of the ditch on at least two occasions, the latter of which effectively ended the monitoring project (see Chapter 2 timeline). Given the challenges faced by the project team, it was an achievement that monitoring data could be collected and analyzed to produce meaningful results.

A vegetation survey conducted after two-stage construction showed a marked improvement in vegetation composition and an increase in plant diversity. Hydraulic modeling results indicated that at smaller 1- and 2-year storm events, peak flows in the roadside ditch could decrease more than 20% compared to a traditional ditch shape. Total water volumes declined more consistently (~6%) between the single- and two-stage scenarios, and reductions in maximum velocities ranged from 32% (1-year) to 45% (10-year). Upstream-downstream monitoring during both the pre- and post-construction periods revealed a statistically significant impact of the two-stage ditch on daily mean turbidity. The difference in turbidity between the upstream and downstream monitoring sites significantly increased following construction, implying a reduction in particulate P and nitrogen (organic nitrogen). Upstream-downstream, high-resolution grab sampling for dissolved ions, including NO3-N, OP, Cl, and sulfate, during four post-construction events showed similar patterns at upstream and downstream sites offset by a lag in travel time between the two sites, but no statistical differences were observed.

While building two-stage channels in roadside ditches is limited in Iowa to only a select number of possible locations and treat only 0.07% of Iowa's cropped areas, demonstrating this practice in a unique roadside setting expands the availability of locations for potential deployment sites to other landscape locations.

8.2 CONSIDERATIONS AND LESSONS LEARNED

For roadside two-stage ditches, there are additional challenges to be considered. For this project, the two-stage ditch was constructed as part of a larger road expansion of a major US highway.

While this was initially thought to be an advantage in terms of design, cost, and ease of construction, converting a two-lane highway to a four-lane highway involved substantial regrading and construction of new road surfaces, rights-of-way, and medians. During the two-year construction period, it was difficult to prevent water runoff and sediment from entering the ditch, and monitoring activities were severely limited or compromised during the construction period. Hence, in this case, the monitoring activity was consolidated to focus on a pre- and post-construction monitoring program, with the post-construction period occurring after the road was completely finished. Because of these challenges, for others considering roadside two-stage ditch applications, careful consideration should be given to building the ditch independent of any roadway construction, so that outside variables can be better managed and controlled, and monitoring can be focused exclusively on the performance of the ditch. Furthermore, unlike two-stage construction within agricultural fields where channel dimensions may be flexible, the widths of roadside two-stage ditches would be constrained by right-of-way easements. Ditch widths would be dependent upon flows from the contributing watershed and design considerations. Applicable highway design and drainage criteria would also have to be met in order to satisfy permitting requirements for storm water control.

A final challenge for roadside two-stage ditches would be ongoing ditch vegetation management, as well as potential impacts from road salt or deicers. Road departments often manage roadside vegetation for safety and weedy plant removal, often desiring shorter vegetation near intersections, driveways, and structures, and are sometimes required by law to remove noxious weeds (Nemec et al., 2022). Revegetation of two-stage ditches along roadways will need require careful selection of vegetation consistent with local and regional ordinances. For example, roadside vegetation management may need to consider mowing and spraying practices, prescribed burns, or modifying habitat to reduce wildlife-vehicle collisions (Nemec et al., 2022). Furthermore, roadside environments are prone to contamination from salt and de-icing fluids (Cl and Ca) as well as heavy metals accumulating from vehicle emissions and contributions from fuels, engine oils, and tire and brake wear (DeSilv et al., 2019; Trombulak and Frissell, 2000). The impacts of contamination on roadside plantings should be considered when selecting suitable vegetation. Overall, the unique application of two-stage ditches along roadsides may require additional attention to match vegetation to specific needs and threats.

8.3 RECOMMENDATIONS FOR IMPLEMENTATION AND EXPECTED BENEFITS

Based on the results of the two-stage ditch project, it is recommended that the IDOT construct a new roadside two-stage ditch to conduct additional performance testing. The current project was compromised by unforeseen challenges that limited the degree to monitoring needed to fully evaluate its efficacy of the two-stage design. However, the construction and monitoring results were sufficiently encouraging that the design should be reconsidered at a new site. The project identified 314 potential locations across the state where the two-stage design could be implemented and it is recommended that additional evaluation of potential testing sites be conducted in more detail to select a new site for construction and testing. Recommendations for future research are provided in Section 8.4 below.

The vegetation planting of the two-stage ditch with a native seed mix introduced much-needed variety and resilience to the plant community. The reduction in turbidity, and the implied reductions of particulate P and organic nitrogen, were partly due to the flow resistance provided by the native vegetation. The benefits of planning native vegetation are well understood by the roadside community and study results provided additional evidence that native vegetation is appropriate for other non-traditional ditch designs as well. It is recommended that future non-traditional designs continue to utilize native seed mixes in their design and implementation.

Adopting the recommendation to construct a new roadside two-stage ditch would encourage the IDOT to develop new strategies that integrate roadside ditches into statewide nutrient reduction efforts. Previous work established that currently utilized designs reduce nitrate concentrations and loads (Schilling et al., 2017) but earlier work did not examine reductions in P. In this study, the two-stage design produced a reduction in P and ON that will contribute to a reduction in nutrient export from the state.

8.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the project results, there are additional avenues of research needed to establish two-stage channels as a viable alternative for roadway ditches. Given the challenges faced by the implementation of the two-stage ditch along with major roadbuilding, it is recommended that a new roadside location be identified and retrofitted with a two-stage configuration so testing can be done in isolation from unplanned complications.

More work is needed to document the hydrologic and hydraulic effects at multiple field sites. Attention should be given to developing a better understanding of underlying hydrologic processes. For example, establishing a relationship between ditch length and flood reductions would be useful for scaling up the potential flood mitigation effects to larger watersheds. In addition, the specific hydrologic processes should be investigated, including the role of vegetation type and management, and the effects of evapotranspiration, infiltration, and increased residence time on reductions in flow volume. Interestingly, urban environments may be ideal locations for designing, monitoring, and evaluating roadside ditch improvements like two-stage designs. Excessive runoff and channel incision are common in many urban settings (Booth, 1990; Bledsoe & Watson, 2001; Hardison et al., 2009; Solins & Cardenasso, 2022), and a two-stage roadside ditch design may help mitigate their impacts and support more sustainable development.

Site monitoring should be conducted to quantify ditch performance and nutrient reduction effectiveness and include pre- and post-construction monitoring and upstream and downstream monitoring sites. Water level stage and discharge should be emphasized to quantify changes in hydrology associated with the two-stage design. Turbidity sensors, like those used in the present study, are highly recommended, showing great utility in their ability to capture rapid changes in turbidity and their clear link to particulate nutrients (Anderson et al., 2021). If possible, nitrate sensors could be deployed along with turbidity sensors to collect high resolution upstream and downstream nitrate concentration data. Overall, the monitoring design planned for the current study was appropriate, but on-site circumstances and other complications, made the collection and interpretation of project data very difficult. Project results show that the two-stage roadside ditches hold promise for ditch design, but more sites and data are needed to quantify the performance and suggest design modifications. Isolating new testing sites away from planned roadbuilding and with full cooperation of upstream neighbors will be critical for future success.

Although not a focus of the current study, the two-stage design of roadside ditches should be investigated for potential highway safety improvements. Many ditches along primary and secondary roads in Iowa trapezoidal in shape with rather steep sides that present a roll-over risk for vehicles. The two-stage design, as conceived and built along Highway 30, showed that the first stage of the ditch (the original channel) conveyed baseflow drainage from the contributing catchment. The first-stage channel would also allow an outlet for subdrainage beneath the road and shoulder to drain to the low elevation. If a second stage could be designed for the roadside ditch, the second stage would be higher in elevation and closer in elevation to the road pavement, which could serve to lessen the risk for rollovers if vehicles entered the ditch. The second stage could also help dampen vehicle velocity before it reached the full depth of the first stage (existing ditch elevation). It is recommended that engineering designs be developed to alter the shape of roadsides to a two-stage design and assess these configurations on roadside safety. Design considerations would have to account for the limited right-of-way opportunities and other site-specific issues, but this project reporting the first-ever two-stage road ditch construction project, raises an interesting question about their potential enhancement for roadside safety.

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