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Modeling the Potential of a Roadside Two-Stage Ditch to Reduce Flooding and Erosion Risks

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Abstract

Recent efforts to address flooding have explored incorporating flow-reduction capabilities into existing infrastructure. Roadside ditches have historically been viewed as an underutilized component of flood reduction, and a two-stage design has been proposed that modifies a conventional trapezoidal ditch by incorporating bench insets along the main channel. While it is expected that this second stage becomes inundated during storm events, resulting in flow attenuation, the exact impacts of this design are unknown. This study quantified the impact of the two-stage design by modeling a roadside ditch corridor in eastern Iowa. An existing single-stage ditch was converted to a two-stage design, and a HEC-RAS model was constructed to investigate the ditch's impacts for four design storms (1-year, 2-year, 5-year, and 10-year). In the modeled results, 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). These results indicate that increased travel times and infiltration associated with the two-stage design provide hydrologic and hydraulic benefits by lessening flood and erosion risk. While further study is needed to verify this behavior through monitoring and modeling at other locations, our findings suggest that two-stage ditches can be a useful best management practice for the transportation community.

Keywords: two-stage ditch; ditch; flooding; erosion; road; HEC-RAS

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1. Introduction

Flooding is one of the most pressing societal challenges faced in the central United States (US) [1]. In Iowa, for example, Federal Emergency Management Agency records indicate that 80% of federally declared disasters were related to flooding, with economic losses to property and crops nearing $20 billion [2]. Improving resilience to flooding will require innovative landscape solutions that are scalable across large geographic areas. Some of the most promising strategies for flood mitigation aim to incorporate flow reduction capabilities into existing landscape infrastructure [3].

Roadside ditches are underutilized landscape features that line nearly all roadways and cross topographic boundaries, serving to concentrate water flow from roads and catchment areas and convey runoff, sediment, and pollutants to downstream surface water systems [4–6]. Roadside ditches have been shown to intercept the runoff from up to

one-third of a watershed's tributary area in agricultural regions [6,7]. Hence, modifying the hydrology of transportation infrastructure and roadside ditches has the potential to help mitigate downstream flood impacts. For example, on-road structures (ORSs) offer a viable alternative to traditional culvert design by utilizing the roadway embankment as a dam to provide temporary flood storage for significant flow events (e.g., up to the 50- or 100-year return period) [8]. Low-grade weirs are also being used to increase temporary water storage, promote infiltration, and reduce discharge in ditches [9,10]. Likewise, improving roadside vegetation management can increase water retention and infiltration [11–14]. Consequently, roadside ditches may provide an opportunity to bolster flood resilience through the installation of new flow mitigation practices within their footprint.

One potential mitigation strategy for roadsides that has not been previously investigated is modifying the shape of a ditch to a two-stage design. In a two-stage design, a conventional trapezoidal ditch is altered to include floodplain benches constructed alongside the mainstream channel. During storm events, the benches become inundated, allowing flood flows to spread out and slow down [15]. The practice has been primarily used in agricultural drainage ditches in the Midwestern states of Indiana, Ohio, Michigan, and Minnesota, where most research has been focused on quantifying nutrient reductions [15–18]. Less attention has been given to quantifying hydraulic benefits associated with the two-stage design. The floodplain benches are often assumed to increase fluvial stability by increasing the wetted channel width, slowing water velocity, and decreasing shear stress during floodplain inundation [19,20]. While most natural channels in the US Midwest are prone to increased streambank erosion risk [21], geomorphic assessments have found that two-stage ditch channels are highly stable with a low risk of bank erosion [19].

Hydrologic and hydraulic modeling of agricultural drainage ditches have shown that a two-stage design decreases flood peaks and increases flow conveyance capacity [22]. Other modeling efforts have evaluated how changes in ditch geometry and water flow rate affected water depths in existing ditches [23]. However, it is unknown whether the potential benefits of agricultural two-stage ditches on water flow, volume, and erosion risk apply to a unique roadside ditch environment and whether the two-stage design can serve as a reliable best management practice for road managers.

In this study, we report on a roadside two-stage ditch constructed in eastern Iowa and quantify the effects of transitioning from a trapezoidal single-stage to a two-stage design on local hydrology and hydraulics. This study is novel in that the flow and velocity reductions associated with converting an existing single-stage condition to a two-stage ditch were modeled in a roadside application. Specifically, our objectives were to: (1) briefly describe the conversion of an existing roadside ditch from single-stage to two-stage; (2) develop a hydrologic and hydraulic model of the ditch; and (3) use this model to quantify potential reductions in flood and erosion risk brought about by the two-stage design. It is important to document the capacity of roadside ditches to reduce flood and erosion risks for federal, state, and local agencies tasked with managing roadside infrastructure for environmental sustainability.

2. Materials and Methods

2.1. Location and Project Construction

This study centered on a roadside ditch located in Benton County, Iowa (IA) (Figure 1, 41°57′50″ N, 92°08′45″ W). This ditch spans approximately 450 m and runs along the northern side of US Highway 30. It is the primary mechanism for removing water from the northern half of the roadway but also drains a substantial amount of nearby farmland. The tributary area draining to the ditch is 194 ha, with corn and soybean row cropping comprising the vast majority (>90%) of its land use. The ditch's watershed lies within the Iowan

Surface, a landform region characterized by gentle, rolling terrain with well-established drainage networks, and the region's soils are generally loams formed in glacial tills or loess. Our study area also lies within the humid continental climate region, experiencing strong seasonal variations in rainfall and streamflow with an average annual precipitation of ~900 mm. While snowmelt can contribute significantly to streamflow volumes, nearly all peak flows in eastern Iowa result from storm events in the Spring, Summer, and Fall. Therefore, regional guidelines for drainage systems do not recommend incorporating snowmelt in design storm modeling.

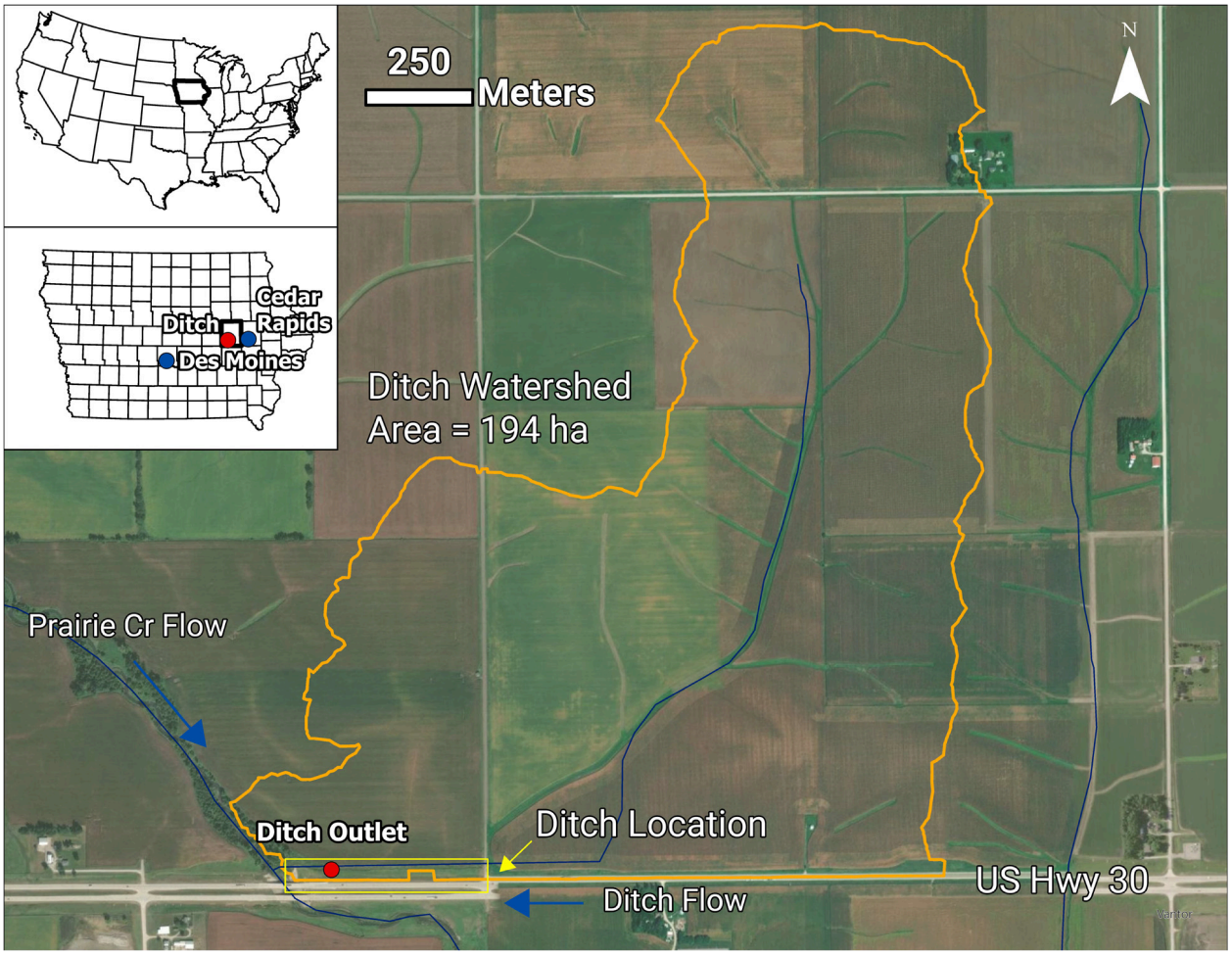


Figure 1. Location map of the study's ditch and its watershed. The locations of Iowa and Benton County are shown in the insets.

Water in the ditch flows from east to west until outfalling into Prairie Creek, a much larger perennial tributary of the Cedar River. Flows are greatest following wet weather events, where heavy rainfall causes large amounts of runoff to drain from the nearby landscape into the ditch channel. Baseflow is also delivered to the ditch via tile lines that drain the adjacent farmland. These tile lines generally discharge water during the spring and summer, but the ditch often dries out in the absence of rainfall throughout the rest of the year.

This particular site was chosen after consultation with the Iowa Department of Transportation (IDOT), which owns the right-of-way containing the ditch. This ditch's topographic and hydrologic characteristics are representative of many agricultural catchments in the Midwest, and a planned expansion of US Highway 30 provided an opportunity to convert the existing single-stage ditch into a two-stage condition. These factors, coupled

with the cooperation of local landowners, made the site a suitable candidate for this study. While analyzing a longer ditch corridor (>500 m) would have been ideal, local constraints, such as the extent of easements and locations of tile drainage lines, limited the ditch profile to 450 m. Regional technical guidance suggests that two-stage installations are most suitable in a roadside ditch with a catchment area between 0.5–26 km^2, length > 300 m, slope < 1%, and width > 3 m.

Figure 2 displays the typical cross-section of both the existing single-stage roadside ditch and the constructed two-stage condition. The existing ditch consisted of a standard single-stage design, with a slope of 0.006 and channel width spanning 1–1.5 m. This single-stage design is typical of many roadside ditches in Iowa and is commonly referred to as a trapezoidal channel in regional drainage nomenclature. The ditch was notably incised and demonstrated some slight meandering of its main channel (sinuosity of 1.04). Existing vegetation was dominated by a plant community common to many of Iowa's ditches, mostly comprising segments of thatch, reed canary grass, smooth brome, and bare ground.

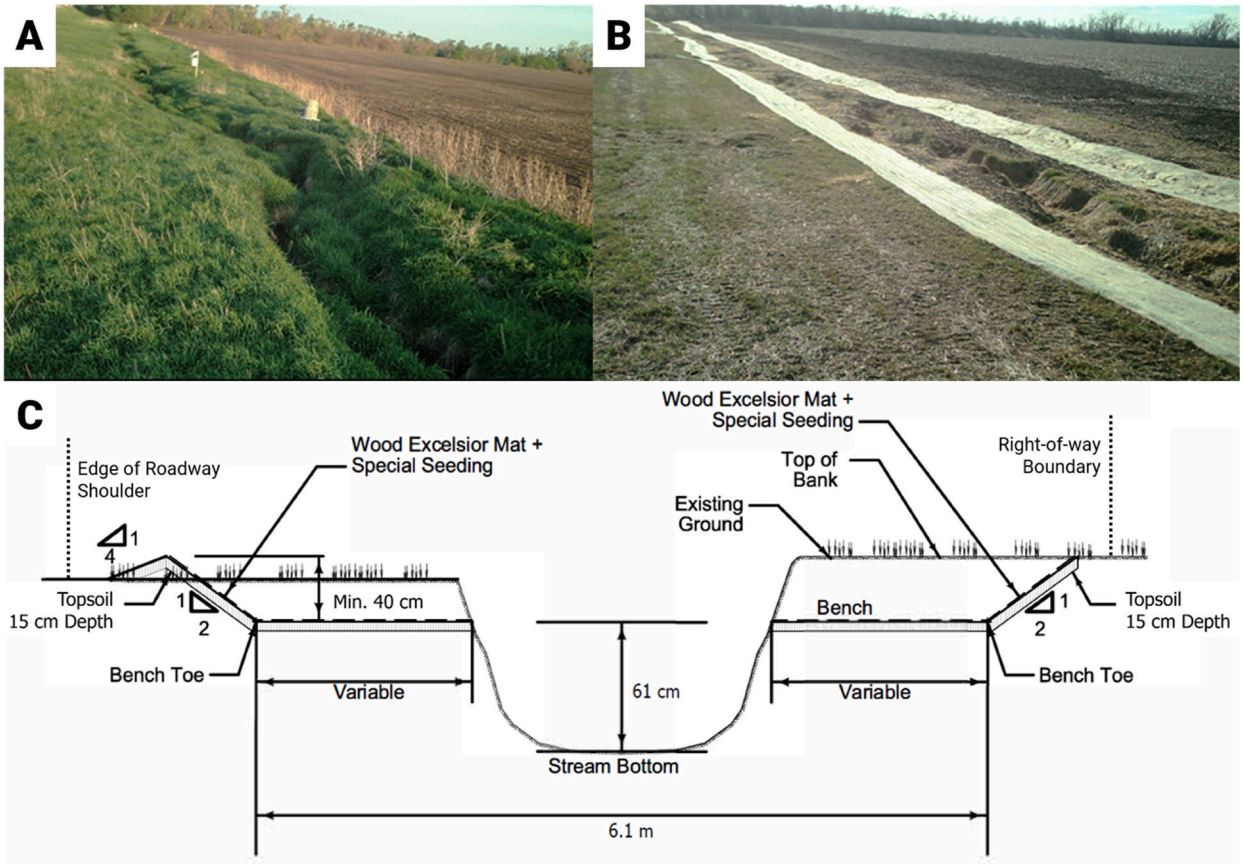


Figure 2. Details of the existing and proposed ditch designs: (**A**) photo of the single-stage ditch preconstruction; (**B**) photo of the two-stage ditch following construction (note: vegetative mat is placed on inset benches); and (**C**) typical cross-section for the existing single-stage and the constructed two-stage ditch.

The two-stage ditch design was completed in consultation with a local engineering firm, with the primary design criterion being that the proposed ditch matches or exceeds the capacity of the existing condition (3.1 cms). In an effort to ensure comparisons between the single- and two-stage ditches predominantly reflected changes in cross-sectional geometry, most ditch features (e.g., overall width and slope) remained consistent between the existing and proposed scenarios. The main parameter considered in the design was thus the height of the inset bench above the existing channel bottom, which was ultimately chosen as 61 cm.

In this design, the ditch's first stage had capacity to convey baseflow (0.17 cms), but during wet weather events, higher flows could encroach upon the second stage while remaining within the overall channel (total capacity of 4.2 cms).

Construction of the two-stage ditch took place between January and April 2022, with the schedule largely dictated by the workflow of the larger roadway expansion project. The primary construction activities were the earthwork excavation and grading needed to construct the inset bench forming the ditch's second stage. Revegetation of the ditch followed, where a mix of 50 native species was sown at a rate of ~1200 seeds/m^2. All design components and construction activities complied with technical requirements prescribed by the IDOT [24]. Further details about the ditch's design criteria and construction process have been included in the Supplementary Materials.

2.2. Modeling Framework

The HEC-RAS (Hydrologic Engineering Center River Analysis System, v6.7) 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 [25]. 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 [26]. 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 [27].

Key hydrologic parameters (e.g., roughness values and infiltration rates) 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 [24]. The Curve Number Method was used to represent infiltration rates within the catchment area and ditch. Evapotranspiration was not included in our modeling setup, as it is generally assumed to be inconsequential during large storm events.

We monitored water stage at 15-min increments during the fall of 2020—before any construction activities took place—using a water-level transducer (In-Situ-Level TROLL 400 Data Logger; In-Situ Inc., Fort Collins, CO, USA). A nearby rain gauge operated by the National Weather Service Cooperative Observer Program (gauge VNTI4, located ~24 km northeast of the ditch) was used to estimate precipitation. This monitoring recorded a significant storm event (~68 mm over 26 h) similar to the 24-h 1-year design storm (66.2 mm). We then simulated this rainfall event in our HEC-RAS model and calibrated the model's hydrologic parameters so as to increase the agreement between the model's stage elevations and the observed stage elevations near the ditch outlet. Water elevations in Prairie Creek were also monitored during this event and used as the tailwater boundary conditions during calibration. All HEC-RAS modeling efforts within this study used hydrologic and hydraulic routing timesteps of 15 min, and the SWE-ELM hydraulic routing method was utilized for each simulation.

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. Therefore, the two-stage model modified both the ditch geometry and incorporated vegetation-related hydraulic roughness changes. 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 ditch. Further details about the modeling setup have been included in the Supplementary Materials.

It should be noted that while calibration was used to guide our selection of model parameters, ensuring strong model performance compared to observed events was not a priority of our study. Rather, our focus was on comparing the hydrologic and hydraulic behavior between the single-stage and two-stage ditch environments. Thus, we did not devote substantial effort to monitoring numerous events, as a model that satisfactorily captured the existing condition's properties through the initial calibration process was sufficient to our overall goal. Additionally, we strove to make our results as generalizable as possible to reflect the typical behavior associated with installing a two-stage ditch, which is of most interest to transportation practitioners. We used normal depth as the downstream boundary condition to make the results more universal, since we did not want our comparison of the single- and two-stage conditions to be influenced by the local hydrology of the receiving stream (i.e., Prairie Creek).

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 h, 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 113.0 mm, respectively (Table 1), and rainfall intensities throughout the storms were determined using Huff curves developed for eastern Iowa [28]. Our 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 [24]. Analyses of more extreme events (e.g., the 100-year storm) were not included in our study because events greater than the 10-year storm began overtopping the ditch's top of slope and were thus not isolated to the ditch environment. Additionally, to simplify our design scenarios, no antecedent flow was included in the simulations.

Table 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-h duration for each event.

Return Period	Rainfall (mm)	Peak Flow (cms)			Total Volume (1000 m^3)		
		Single-Stage	Two-Stage	% Reduction	Single-Stage	Two-Stage	% Reduction
1-year	66.2	0.51	0.40	21.8%	18.5	17.4	5.8%
2-year	76.9	0.79	0.63	21.1%	26.9	25.4	5.5%
5-year	95.9	1.32	1.22	7.5%	45.0	42.2	6.3%
10-year	113.0	1.96	1.87	4.3%	62.8	59.5	5.2%

2.3. Flood Reduction Analysis

To determine the two-stage ditch's capacity to reduce flooding, we compared simulated flow rates between the single-stage and two-stage scenarios. Specifically, we selected a location near the downstream end of the ditch that resided within its typical cross-sectional geometry and captured nearly all the water discharged by the ditch into Prairie Creek (Figure 1). This 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 thus allowed us to estimate the amount of water discharged by an entire two-stage ditch, 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). These reported flow values completely encompassed each event, which spanned 0 to 50 h. Here, the 0 timestep corresponded to the start of the rainfall, and within 50 h, flow rates at the ditch outlet had returned to 0 cms (i.e., the ditch had become dry).

For each event, we examined two key hydrologic parameters 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. In our analysis, it is defined as follows:

$$\%Reduction = \frac{Single\ Stage - Two\ Stage}{Single\ Stage} \quad (1)$$

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

2.4. Erosion Risk Reduction Analysis

We also explored the potential of the two-stage ditch to reduce risk of erosion across its profile by quantifying changes in water velocity. A ditch's erosion risk is highly influenced by the velocity of water passing through it during a wet weather event, so changes to a ditch's geometry that reduce velocity at high flows can also reduce its erosive potential [29]. Whereas flooding concerns are almost always most prominent at a ditch's outfall, erosion risks can occur throughout the length of a ditch channel.

To quantify water velocities throughout the ditch, we placed 25 cross-sections (roughly evenly spaced) that spanned the ditch's corridor. The 1st cross-section was placed at the very upstream end of the ditch, while the 25th corresponded to the aforementioned ditch outlet. We extracted the maximum water velocity observed at each segment during each event. These maximum velocity values are cross-sectional averages of the two-dimensional flow rates. More specifically, they are area-weighted average flow velocities through the cross-section's reference line and thus reflect the complete velocity profile for each ditch location.

3. Results

3.1. 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 h. Comparing these two time series yielded a Kling–Gupta efficiency of 0.88 and a Nash–Sutcliffe efficiency of 0.55, which suggests that model calibration was satisfactory [30]. A full set of outputs associated with model calibration has been included in the Supplementary Materials.

3.2. Peak Flows and Water Volumes

Peak flow rates and total water volumes at the ditch outlet were successfully calculated for each design storm (Table 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 3 displays the simulated hydrographs for each design storm, along with the events' hyetographs. For each event, single-stage and two-stage flows were similar until they reached the 0.17 cms threshold. At this point in the two-stage design, water spread out along the second stage, resulting in a divergence between hydrographs. For the remainder of the event, flows in the two-stage condition were attenuated—generally lower and peaking after their single-stage counterparts.

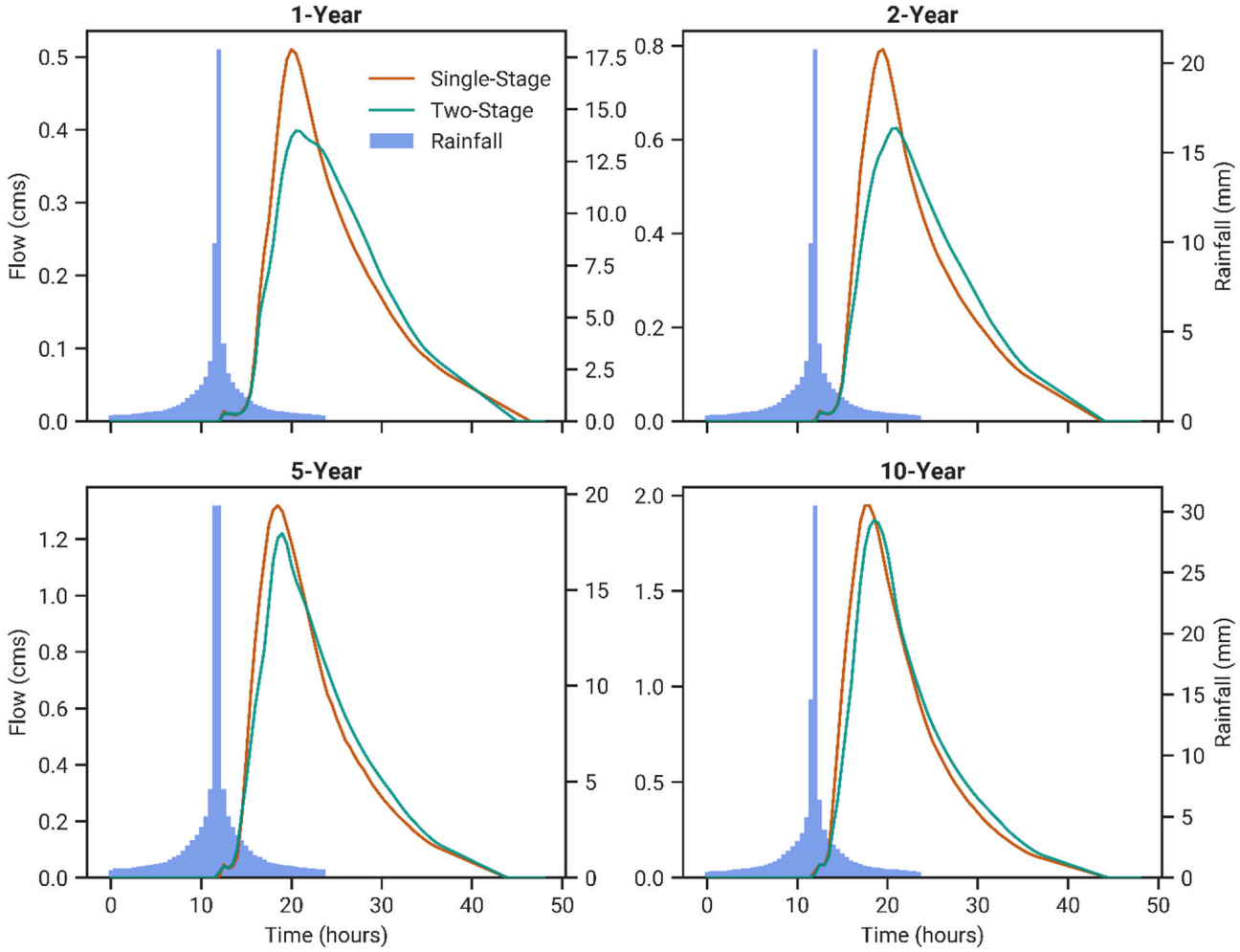


Figure 3. Rainfall and hydrographs at the ditch outlet for each simulated storm event.

For the 1-year event, peak flows decreased from 0.51 cms in the single-stage scenario to 0.40 cms in the 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 4, top). Notably, these %Reduction values monotonically decreased with larger precipitation events. The timing between peaks when comparing the single- and two-stage scenarios was approximately 30 min for every design storm. I.e., the peak flow occurred 30 min later in the two-stage condition.

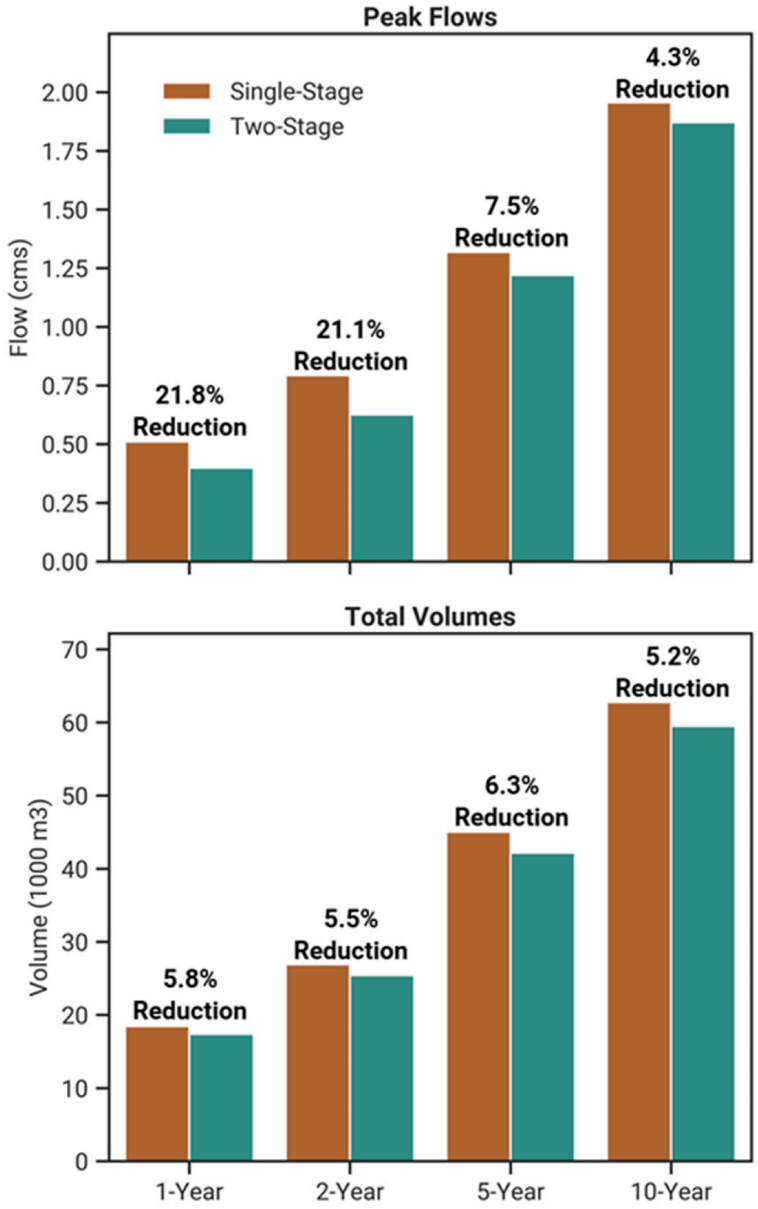


Figure 4. Peak flows (**top**) and total water volumes (**bottom**) for each simulated event. The corresponding %Reduction values are labeled.

Total water volumes also consistently declined between the single-stage and two-stage scenarios, with decreases of 18.5 to 17.4 1000 m^3 (1-year), 26.9 to 25.4 1000 m^3 (2-year), 45.0 to 42.2 1000 m^3 (5-year), and 62.8 to 59.5 1000 m^3 (10-year). %Reduction values for the water volumes were fairly consistent (Figure 4, bottom), ranging from 5.2% (10-year) to 6.3% (5-year).

3.3. Water Velocities

Figure 5 displays the locations of the ditch cross-sections and provides an example of maximum velocities for the 10-year event. %Reduction values were also calculated at each segment to compare the single-stage and two-stage conditions. Maximum velocities throughout the entirety of the ditch profile were consistently lower in the two-stage condition than in the original single-stage channel. Still, substantial variations in maximum velocities were observed at the individual cross-sections.

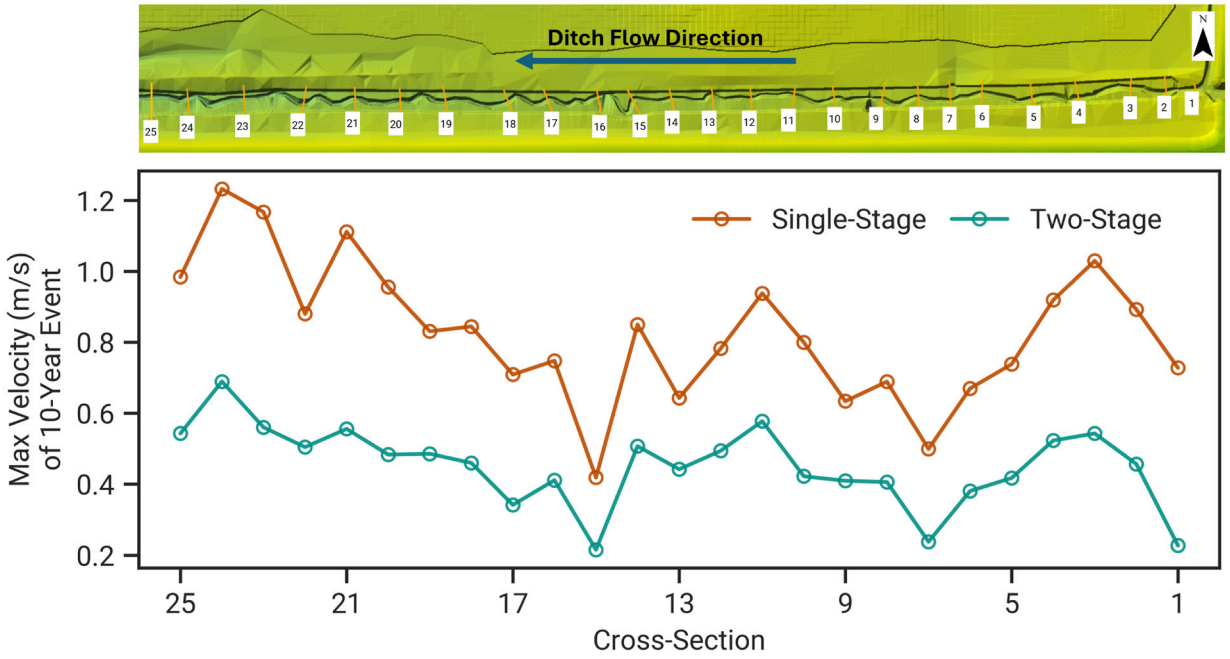


Figure 5. Maximum velocity at each cross-section for the 10-year event. Locations of cross-sections are shown in the top inset; cross-section 25 corresponds to the ditch outlet.

As with the peak flows and total water volumes, maximum water velocities declined consistently between the single-stage and two-stage scenarios (Figure 6). 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 scenario. 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.

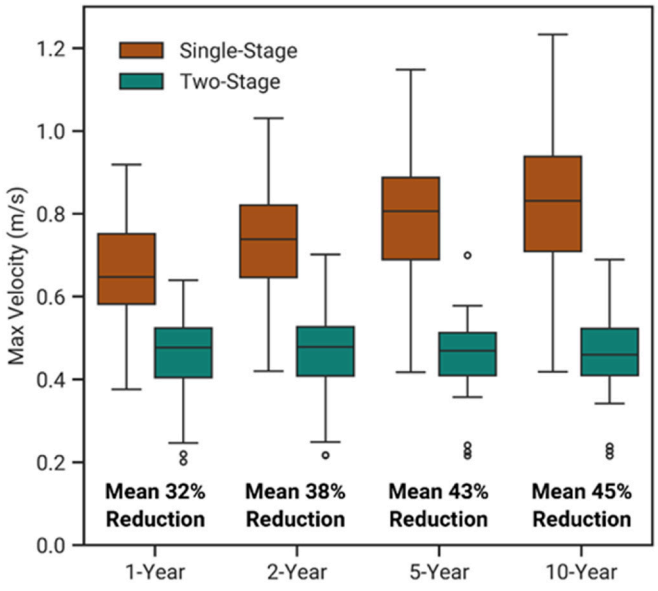


Figure 6. Boxplots of the maximum area-weighted average velocities at each of the ditch 25 cross-sections for each event. The average %Reduction values for each event are labeled.

%Reductions varied considerably among the 25 cross-sections, with no discernible spatial trends (Figure 7). Much of this variation can likely be attributed to local hydraulic properties, such as an individual cross-section's slope and geometry, which considerably influence any location's erosion potential. However, a distinct pattern was apparent in the %Reductions, with values being consistently lower for the smaller rainfall events. For example, the ditch's average %Reduction in maximum velocity for the 1-year event was 32%, while the average of the 10-year event was 45%. The increases in %Reduction of velocities were monotonic, and these were also noted in every cross-section. A full table of maximum velocity values and water depths has been included in the Supplementary Materials.

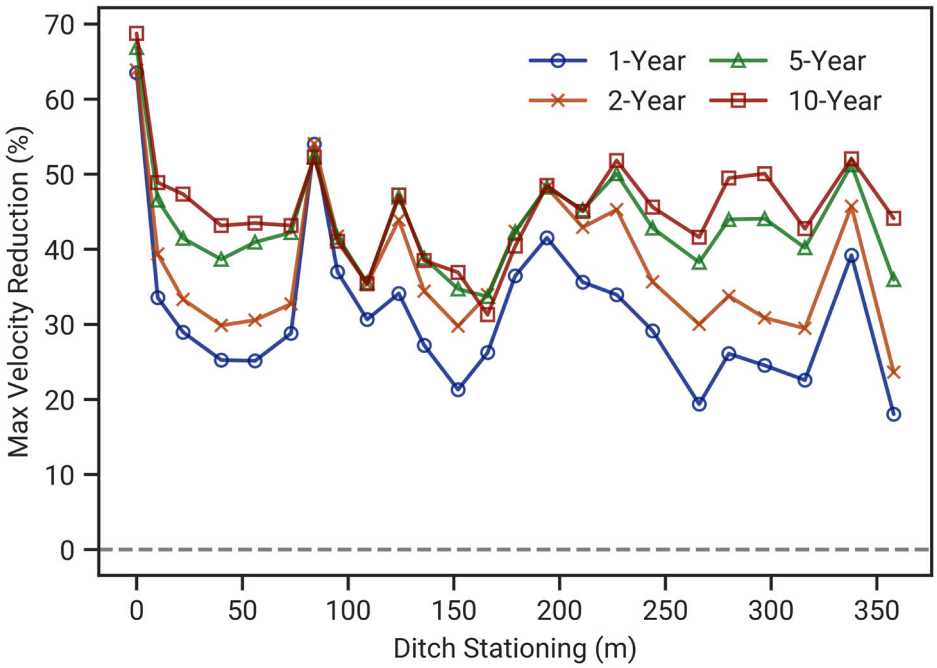


Figure 7. %Reduction in maximum velocity along the ditch profile. Ditch stationing refers to the distance from the most upstream cross-section.

4. Discussion

4.1. Impacts of the Roadside Two-Stage Design

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 [31,32].

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 the 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 [22]. Lower water levels in a roadside ditch would reduce the potential for local roadway overtopping by better containing

floodwater 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 when this has been evaluated in general catchment or river restoration studies [33–35]. 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 [16–18].

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 (5.2–6.3%) across our suite of simulated design storms (Figure 4). These steady volume reductions are likely due to the enhanced infiltration 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 [13]. 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. This results in a lengthening of water's travel time through the ditch, allowing for more infiltration [36]. 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 may remain the same for greater events, provided that the water remains confined in the ditch channel, but this should be verified with further modeling.

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 [37,38]. 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 [39]. 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 [19,40]. While roadside ditches are not natural channels, employing this concept of "bankfull" flow rates, which has proven beneficial in many streambank restoration efforts, may help guide future design considerations.

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 (Figure 6). 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 [19,41]. 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 [42], many stream channels are incised and suffer from widespread and severe streambank erosion [21,43,44]. 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 [45].

4.2. Future Exploration of a Roadside Two-Stage Ditch

While two-stage designs have been investigated for agricultural drainage ditches, application to a roadside environment has received much less attention. In our study of

a newly constructed ditch in eastern Iowa, 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 ORSs, 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.

Although encouraging, study results are model outputs from a single site, and more work is needed to document the hydrologic and hydraulic effects at multiple locales. Specifically, longer ditches (>500 m) should be studied to determine how well our results scale as a function of ditch length. Given the ubiquity of roadside ditches, opportunities to construct a new two-stage roadside ditch or retrofit an existing ditch to a two-stage design will be available. Developing a sustainable ditch design that demands less attention from roadside managers should be of interest to transportation funding agencies. For example, in the State of New York, nearly 40% of ditch management involves scraping and reshaping ditches once every 1 to 4 years [45].

Beyond simply adding new field sites, attention should be given to developing a better understanding of alternative designs and 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, 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. This could partly be achieved by isolating model simulations to focus on differences in specific components, such as cross-sectional geometry, surface roughness, and infiltration rates. This would provide better guidance on which parameters are most important to achieving the positive outcomes suggested by this study. Isolating these components would also enable a mechanism for boosting the performance of future two-stage ditches by optimizing vegetative substrates that best enhance infiltration.

Another useful approach would be conducting long-term (e.g., annual) simulations of ditch environments. Such simulations would help quantify the influence of the two-stage ditch under a wide variety of seasonal and hydrologic conditions, which would be especially useful for exploring potential volume reductions during baseflow- or snowmelt-driven conditions. Long-term modeling would also help determine whether changes in evapotranspiration are a nontrivial factor that influences ditch hydrology. While the declining velocities noted in our results suggest erosion risk has decreased throughout the ditch profile when a second stage is added, sediment transport could be explicitly simulated in future modeling efforts to better quantify these expected improvements.

In addition to these modeling exercises, future studies of two-stage ditches may wish to incorporate long-term flow monitoring to determine if the project improvements reported by model results are observable. However, given the inherent interannual variability associated with rainfall in many climates (including the Midwest), identifying hydrologic changes often takes several years of monitoring pre- and post-intervention [46,47]. Still, installing a second stage in a single-stage ditch already containing substantial flow data would likely be beneficial for comparing theoretical improvements to those captured using empirical data. Lastly, studies of two-stage roadside ditches need not be limited to agricultural settings. 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 [48–51], and a two-stage roadside ditch design may help mitigate their impacts and support more sustainable development. The promising results of this initial study argue for further exploration of these topics.

5. Conclusions

In this study, we used a HEC-RAS model to evaluate the hydrologic and hydraulic impacts associated with converting a trapezoidal single-stage roadside ditch to a two-stage design at a highway site in eastern Iowa. Simulated flow rates between the single- and two-stage scenarios were determined for four design storms corresponding to the 1-year, 2-year, 5-year, and 10-year return periods. 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. For larger 5- and 10-year storms, flood peaks decreased by approximately 7% and 4%, respectively. 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). Our analysis represents an initial exploration of the potential benefits one can expect from a two-stage ditch installation, but further work should investigate these concepts in greater detail. Still, these benefits, which include attenuating flood peaks, reducing flood volumes, and decreasing erosion risks, make the design an attractive option for federal, state, and local agencies tasked with managing roadsides for environmental sustainability. The two-stage design joins other roadway innovations, such as ORS, low-grade weirs, and vegetation management, as new technologies available to the transportation community for reducing flood risks.

Supplementary Materials: The following supporting information can be downloaded at https://www.mdpi.com/article/10.3390/hydrology13080220/s1. Data and figures documenting the calibration event; Rainfall hyetographs used for each of the design storms; Hydrographs for each of the design storms documenting flow rates and total water volumes at the ditch outlet; Maximum velocities of every design storm for each of the cross-sections; and Infiltration losses associated with each design storm.

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Abbreviations

The following abbreviations are used in this manuscript:

HEC-RAS	Hydrologic Engineering Center River Analysis System
IA	Iowa
IDOT	Iowa Department of Transportation
LiDAR	Light detection and ranging
ORS	On-road structures
US	United States

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