Assessing the Flood Reduction Benefits of On-Road Structures

Final Report
July 2024

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IOWA STATE UNIVERSITY
Institute for Transportation

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16. Abstract

Conventional culverts are mainly designed to transport water underneath roadways with minimal headwater buildup, resulting in low to moderate peak flow attenuation. On-road structures (ORS) offer an alternative by using the roadway embankment as a dam, restricting flow into the culvert to provide flood storage during large precipitation events.

In this project, statewide geographic information system (GIS) analyses were conducted that identified approximately 250,000 potential ORS locations with a combined storage capacity of 2 million acre-feet and a pool area covering 900,000 acres, representing about 2.7% of Iowa. A methodology was developed to automate the hydrologic design of individual ORS, enhancing the identification of those that offer significant peak flow reduction benefits. In addition, the peak flow reduction benefits were quantified at the HUC12 watershed scale for ORS systems. For a 50-year storm event, peak flows at watershed outlets were reduced by approximately 18%.

The research outcomes are accessible through a web portal named the Iowa Department of Transportation (DOT) On-Road Structures (IDOT-ORS) information platform. This platform facilitates the dissemination of results, allowing various stakeholders to view information on ORS locations, expected pool and drainage areas, structure designs, and inflow and outflow hydrographs for several return periods. The platform can be accessed at https://hydroinformatics.uiowa.edu/lab/idot-ors/.

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ASSESSING THE FLOOD REDUCTION BENEFITS OF ON-ROAD STRUCTURES

Final Report
July 2024

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EXECUTIVE SUMMARY

Conventional culverts are mainly designed to transport water underneath roadways with minimal headwater buildup, resulting in low to moderate peak flow attenuation. On-road structures (ORS) offer an alternative by using the roadway embankment as a dam, restricting flow into the culvert to provide flood storage during large precipitation events.

In this project, statewide geographic information system (GIS) analyses were conducted that identified approximately 250,000 potential ORS locations with a combined storage capacity of 2 million acre-feet and a pool area covering 900,000 acres, representing about 2.7% of Iowa. A methodology was developed to automate the hydrologic design of individual ORS, enhancing the identification of those that offer significant peak flow reduction benefits. In addition, the peak flow reduction benefits were quantified at the HUC12 watershed scale for ORS systems. For a 50-year storm event, peak flows at watershed outlets were reduced by approximately 18%.

The research outcomes are accessible through a web portal named the Iowa Department of Transportation (DOT) On-Road Structures (IDOT-ORS) information platform. This platform facilitates the dissemination of results, allowing various stakeholders to view information on ORS locations, expected pool and drainage areas, structure designs, and inflow and outflow hydrographs for several return periods. The platform can be accessed at https://hydroinformatics.uiowa.edu/lab/idot-ors/.

1. PROBLEM STATEMENT AND OBJECTIVES

One of the main objectives of traditional culvert design is to allow flood waves to pass from one side of the road to the other with relatively low headwater elevation, leading to low to moderate peak flow attenuation (Schall 2012). During heavy precipitation events, flows passing quickly through upstream culverts are more likely to combine and potentially overwhelm downstream culverts; damage bridges, roads, and infrastructure; and impact downstream communities and farms.

On-road structures (ORS) present a viable alternative to traditional culvert design and have the potential to mitigate flood impacts. ORS utilize the roadway embankment as a dam, restricting flow into the culvert to provide flood storage for significant peak flow events (e.g., up to the 50- or 100-year return period). Figure 1 presents examples of ORS built in Northeast Iowa. Several counties in Iowa have implemented ORS in HUC12 watersheds, and anecdotal evidence suggests that these structures have reduced the flood impacts of recent extreme rainfall events. However, Iowa lacks a detailed statewide geospatial database identifying which existing culverts are suitable candidates for conversion to ORS. Additionally, a HUC12-scale assessment of the potential for peak flow reductions of a system of ORS has not yet been conducted.

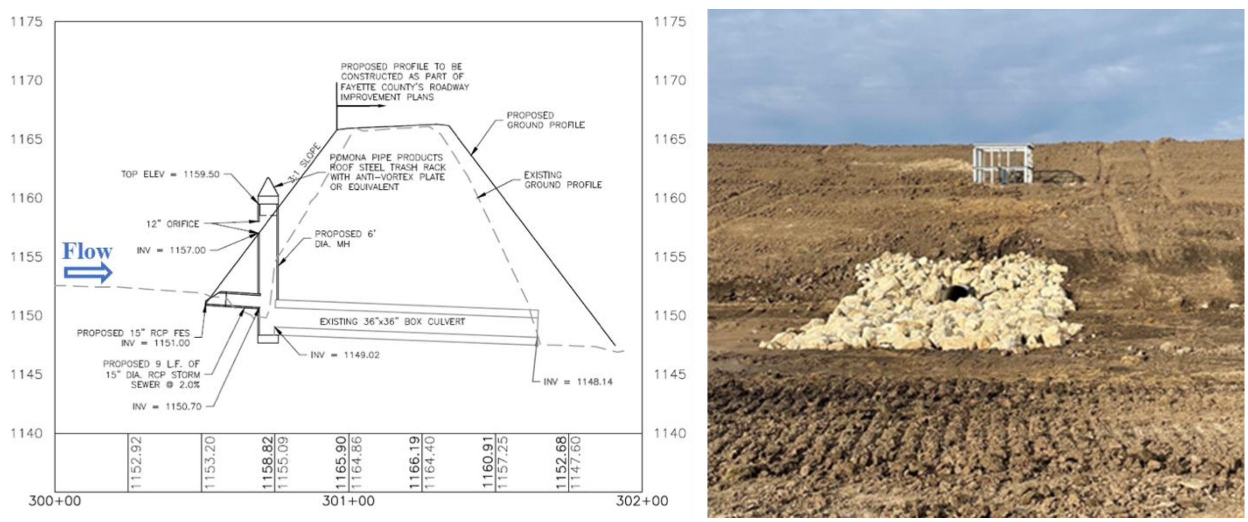


Figure 1. Examples of on-road structures located in Northeast Iowa

This project addressed these knowledge gaps by integrating geographic information system (GIS) and hydrologic analysis, rainfall runoff modeling, and hydroinformatics. Specifically, the objectives of this project were as follows:

1. Construct a statewide geospatial database identifying suitable locations for the construction of ORS, including information on flood storage, expected pool areas, and drainage areas.
2. Develop a methodology to programmatically complete planning designs for the individual ORS identified in Objective 1. These designs will allow for the estimation of structure-level peak flow reductions under different design storm scenarios. This work was completed in six selected HUC12 watersheds.

3. Assess the HUC12-scale flood reduction benefits of a system of ORS. To achieve this, the research team used the process-based hydrologic model Generic Hydrologic Overland-Subsurface Toolkit (GHOST) described in Politano et al. (2023). This work was also completed in six selected HUC12 watersheds.
4. Leverage the research team’s expertise in hydroinformatics to develop a web platform to communicate the results of Objectives 1 through 3.

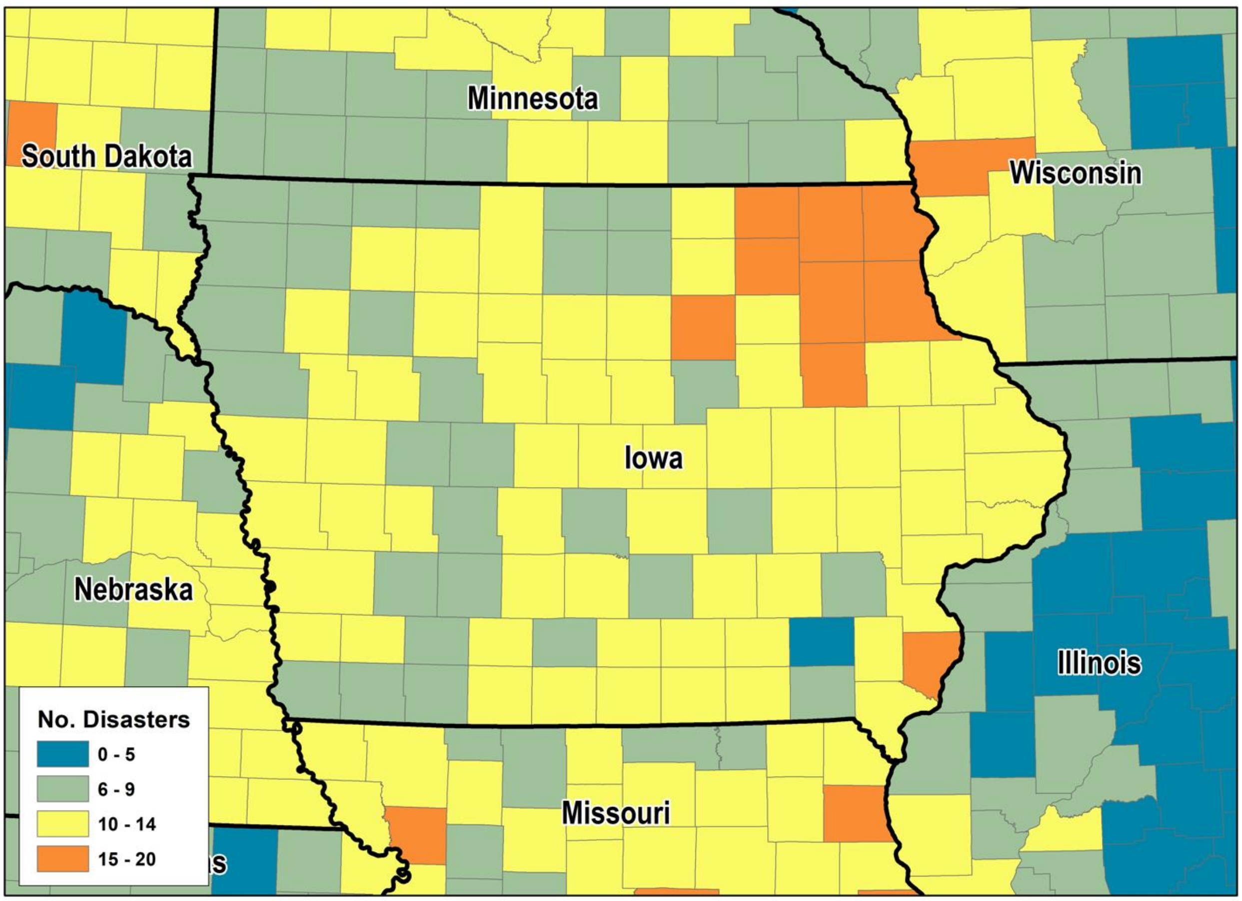
In this project, the research team worked closely with the Iowa Department of Transportation (DOT) and the project’s technical advisory committee (TAC) to select the HUC12 watersheds for the hydrologic simulations, find ways to best communicate the results of the hydrologic and statewide GIS-based analyses, and design the proposed website to disseminate the project’s results.

2. BACKGROUND INFORMATION

This chapter outlines the magnitude and severity of the flooding problem in Iowa, provides examples of existing ORS, and discusses the application of hydrologic modeling to evaluate flood mitigation strategies. Additionally, it highlights the use of web-based information systems in Iowa to support these efforts.

2.1. Flooding in Iowa

Flooding is one of the most pressing challenges facing Iowa. Records maintained by the Federal Emergency Management Agency (FEMA) indicate that out of the approximately 1,300 federally declared disasters in Iowa counties from 1989 to 2022, approximately 80% were related to flooding (Figure 2).



Raw data from https://www.fema.gov/

Figure 2. Flood-related disaster declarations in Iowa counties (1989–2022)

Iowa's estimated losses from flooding are substantial. The SHELDUS database (1988–2015) reports $13.5 billion in direct property losses and $4.1 billion in direct crop losses (https://cemhs.asu.edu/SHELDUS/). In 2019 alone, the National Oceanic and Atmospheric

Administration (NOAA) estimates that extreme weather generated losses of approximately $1.9 billion in Iowa, with flooding being the main driver of these losses. Improving Iowa's resilience to flooding will require significant investment, creative thinking, and innovation. ORS are an example of how infrastructure repair or replacement investments can be used to lessen the future impacts of flooding. By temporarily retaining water runoff from high-intensity precipitation events, ORS can reduce damage to county roads, bridges, and culverts and protect downstream communities and farmland.

2.2. Examples of On-Road Structures in Iowa

The North Bear Creek HUC12 watershed spans Allamakee and Winneshiek Counties in Iowa, as well as Fillmore and Houston Counties in Minnesota. This watershed has pioneered the installation of ORS in both Iowa and Minnesota, with stakeholders identifying 56 locations suitable for constructing these structures (Figure 3).

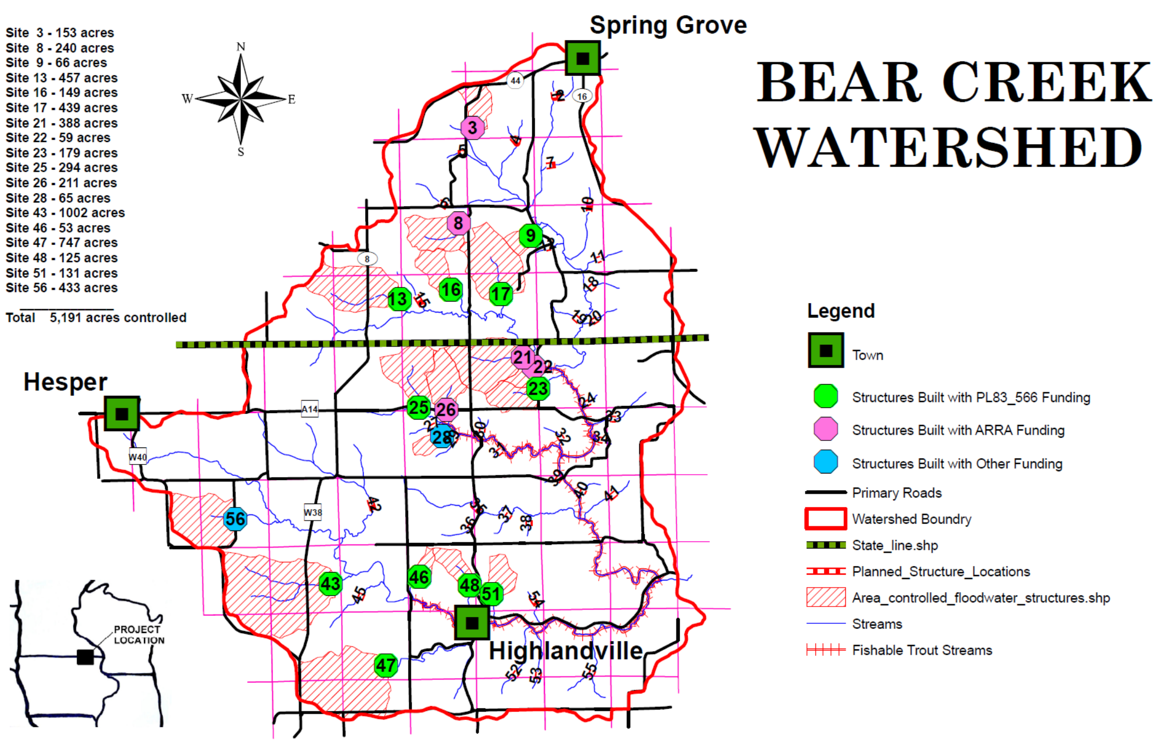


Figure 3. ORS in North Bear Creek

The U.S. Department of Housing and Urban Development funded the Iowa Flood Center (IFC) to lead the Iowa Watersheds Project (IWP) (Weber et al. 2018). The IWP focused on selected Iowa watersheds, developing comprehensive watershed plans, and collaborating with local volunteers to design and build water management projects. In its second phase, the IWP supported the construction of five ORS, along with several ponds and water and sediment control basins (WASCOBs) in the Otter Creek HUC12 watershed in Fayette County (Figure 4). Analyses presented by the IFC (2016) demonstrated that ORS were the most effective option for reducing peak discharges, providing an estimated 30% peak flow reduction for 50-year recurrence flows in some tributaries.

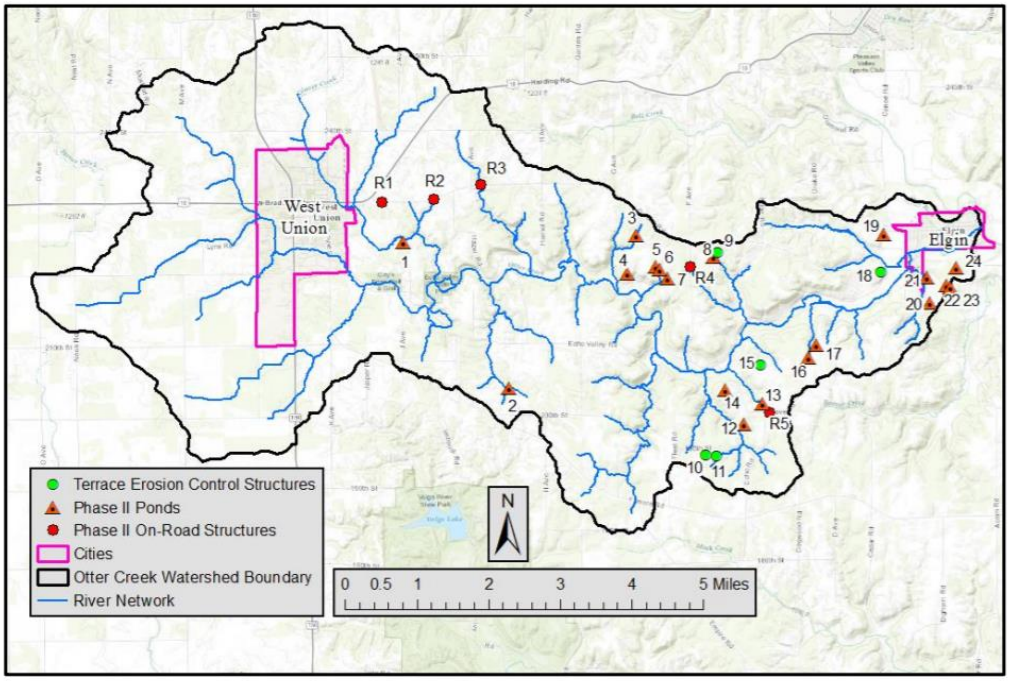


Figure 4. IWP Phase II project locations in the Otter Creek Watershed

More recently, the Iowa Watershed Approach project, funded through the National Disaster Resilience Competition, has also sponsored the construction of ORS in Iowa (https://iowawatershedapproach.org/).

2.3. Distributed Storage and Hydrologic Modeling

Several studies have demonstrated the efficacy of distributed storage systems in mitigating flood impacts (Thomas et al. 2016, Ayalew et al. 2017). While the flood reduction benefit from a single detention structure may not be significant at the watershed scale (e.g., at the outlet of a HUC12), the combined effect of multiple structures can be substantial. In recent years, three projects in Iowa have extensively evaluated hypothetical and constructed detention structures (mostly off-road structures) located in watershed headwater catchments: the Iowa Watersheds Project (Weber et al. 2018), the Iowa Watershed Approach (https://iowawatershedapproach.org/), and the Des Moines River Upstream Mitigation Study (Arenas et al. 2020).

2.4. Web-Based Information Systems

The following are examples of user-friendly, interactive, web-based information systems designed to communicate environmental and geospatial information in Iowa and the United States (Xu et al. 2019, Demir and Krajewski 2013, Demir et al. 2018):

- The Iowa DOT Culvert Platform provides information on culverts throughout the state of Iowa. https://apps.iowadot.gov/culverts/.
- The Iowa Flood Information System is a comprehensive web-platform to access community-based flood conditions, forecasts, visualizations, inundation maps, and flood-related information. http://ifis.iowafloodcenter.org/ifis/.
- The Iowa Water Quality Information System integrates real-time water-quality data collected by IIHR–Hydroscience & Engineering and the U.S. Geological Survey, along with a variety of watershed-related information such as precipitation, stream flow and stage, soil moisture, and land use. https://iwqis.iowawis.org/.

3. METHODOLOGY

The objectives of this project were accomplished following the methodology described below.

3.1. Statewide GIS Analyses

The statewide GIS analyses were developed using 2-meter digital elevation models (DEMs) for all of the HUC12 watersheds in Iowa. For each watershed, the DEMs were modified to ensure that the elevation datasets accurately reflected how water moves across the landscape by following a hydroenforcement or hydroconditioning process. Special attention was given to the intersections of roadways and waterways, where cuts were added to the DEMs at crossings as needed. Following this, flow paths starting at a drainage area accumulation of 10 acres were generated, as presented in Figure 5.

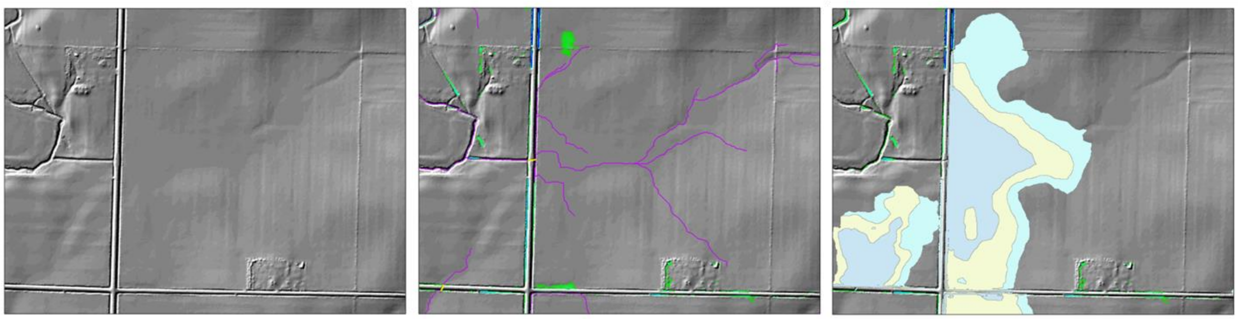


Figure 5. DEM before hydroenforcement (left), cuts (culverts) added and flow paths generated (middle), and storage pools estimated assuming ORS elevations of 50%, 70%, and 90% of the road height (right)

Eight steps were followed to calculate storage volumes behind ORS:

1. **Create intersection points**. Use the flow path and intersect it with the road coverage (Analysis Tools > Overlay > Intersect) to create intersection points.
2. **Buffer and clip road coverage**. For each point in the intersection coverage, create a 10-meter buffer (Analysis Tools > Proximity > Buffer). Clip the road coverage with the buffer (Analysis Tools > Extract > Clip).
3. **Obtain road elevation**. Run Zonal Statistics (Spatial Analyst Tools > Zonal > Zonal Statistics as Table) on the clipped road segment to obtain the elevation of the road. Use the median value as the road elevation and the minimum value as the base elevation. Calculate the road height as the median elevation minus the minimum elevation. Calculate the height of the overflow structure as a percentage (50%, 70%, or 90%, as shown in Figure 5) of the road height, with 50% as the default. Make the percentage variable so it can be adjusted as needed.
4. **Snap intersection point**. Snap the intersection point (Spatial Analyst Tools > Hydrology > Snap Pour Point) to the Flow Accumulation grid using a 2-meter tolerance.

5. **Create watershed**. Use the snapped intersection point to create the watershed for the point (Spatial Analyst Tools > Hydrology > Watershed).
6. **Convert watershed grid to polygon**. Convert the watershed grid to a polygon with "no simplify" (Conversion Tools > From Raster > Raster to Polygon). Calculate the area of the polygon in acres.
7. **Create storage pool area grid**. Use the overflow structure height to reclassify the DEM and create a grid of the storage pool area (Spatial Analyst Tools > Reclass > Reclassify). Use two values: the structure height for the first value and NoData for everything higher. Set the extent and mask values to the watershed polygon to limit the reclassification to that area.
8. **Calculate depth and volume of storage pool**. Use Raster Calculator to subtract the DEM from the pool elevation grid, creating a grid of the storage pool depth. Calculate the volume of each pool elevation value using the following formula: Ac_ft = ((Count * 4) / 4046.856) * (([Value] * 3.2808) / 100). Run Statistics on Ac_ft to sum the values and calculate the total storage volume of the pool. Convert the storage pool grid to a polygon, add the storage volume to the polygon, and append the polygon to the HUC12 coverage of the storage pools.

The process described above was completed using Esri software and the Agricultural Conservation Planning Framework preparation tools (https://acpf4watersheds.org/).

3.2. Planning Designs

To complete the planning designs, the ORS were conceptualized as a system comprising a horizontal pipe at the bottom (D1), a vertically positioned orifice (D2), and a riser pipe (D3) that can be adjusted to different elevations. Figure 6 provides a schematic representation of this system. These outlets operate in stages, activating progressively as water levels increase, which ensures efficient water management during varying storm intensities. The design and analysis of these ORS were automated using Python scripts in ArcGIS, enabling the programmatic design of many ORS. The text below describes the implementation and functionality of these scripts.

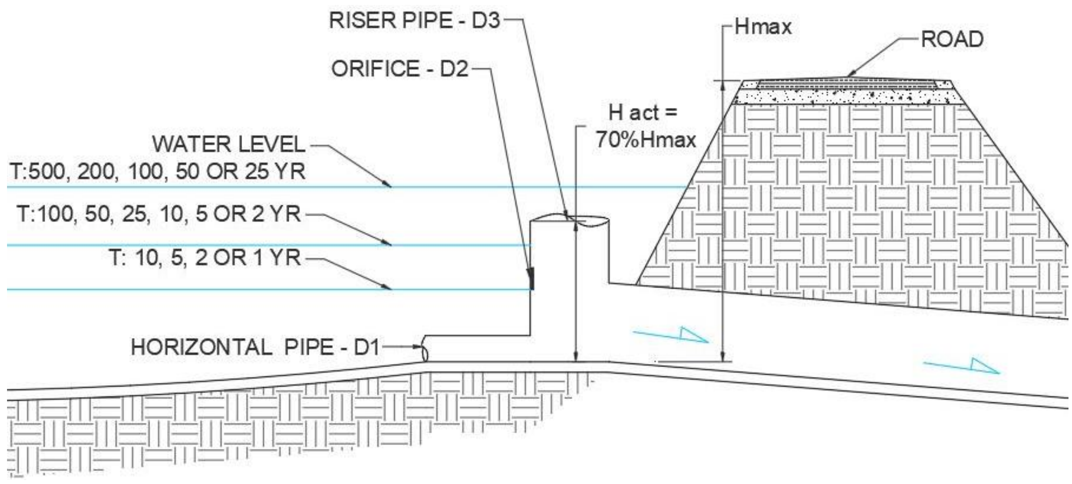


Figure 6. Typical ORS, showing the three outlets (D1, D2, and D3), their activation levels, and the different storms considered during the iterative design process

The structure presented in Figure 6 operates with varying activation levels as the water surface rises in response to different design storms. The first outlet (D1) handles the less severe design storms. As storm intensity increases, the second outlet (D2) is activated to manage higher runoff levels. Finally, the third outlet (D3) comes into play during the highest storm intensities to manage maximum runoff. This tiered response ensures effective water management and flood control for the on-road structures.

A systematic approach was adopted using three Python scripts within ArcGIS to automate the design and analysis process of the ORS. These scripts operated in stages, starting with initial data derived from the statewide GIS analyses described above.

3.2.1. Script 1

In the first stage, hydrological analysis was performed to generate files with hydrological information. The inputs were DEMs, ORS locations, and soil and land use information. The script performed the flow length generation using Flow Length (a module within the ArcGIS Spatial Analyst toolbox) and the Curve Number (CN) method (USACE 2022). For each area that drains to the ORS, the script computed the composite CN by analyzing gridded data on soil type and land cover. The input and output data are displayed in Table 1.

Table 1. Script 1. Input and output data

	File	**Type**
Input Data	DEM	Raster file
	On-road structures (ORS)	Point shapefile
	Drainage areas (DA)	Polygon shapefile
	Land use	Raster file
	Soil type	Raster file
	Table CN versus landcover	Table
Output Data	DEM fill	Raster file
	Flow direction	Raster file
	Flow length	Raster file
	DA with CN composite values	Polygon shapefile

3.2.2. Script 2

The second script focused on hydrologic modeling using the rational method (Chow et al. 1988) and the CN model. The script followed these steps:

1. **Hydrological Values Computation**. Hydrological parameters relevant to the design of ORS were computed. These values included time of concentration, precipitation excess, rainfall intensity, and runoff coefficients for each watershed.

2. **Peak Discharge Calculation (Q)**. The rational method (Chow et al. 1988) was applied to calculate each watershed's peak discharge (Q). This calculation was performed for multiple return periods for different storm events.

The input and output data are displayed in Table 2.

Table 2. Script 2. Input and output data

	File	**Type**
Input Data	DEM	Raster file
	DA	Polygon shapefile
	Flow length	Raster file
	Pool area (50%, 70% or 90%)	Polygon shapefile
	Precipitation raster files (1, 2, 5, 10, 25, 50, 100, 200, 500 YR)	Raster file
Output Data	DA	Polygon shapefile
	Table DA	Table with the following values: Q (1, 2, 5, 10, 25, 50, 100, 200, 500 YR), delta elevation, length, road elevation, time of concentration

3.2.3. Script 3

The final stage involved determining D1, D2, and D3 (Figure 6). The script executed the following processes:

1. **Inflow hydrograph**. Using the data generated in the previous steps and applying the unit hydrograph methodology (USDA NRCS 2007), along with the SCS Type II Rainfall Distribution, the inflow hydrograph to the ORS was generated.
2. **Iterative outlet sizing**. The script was developed to perform the following iterative design process:

   - The bottom outlet (D1) is the initial discharge point, handling the initial runoff. The design process involved iterative testing of pipe diameters ranging from 4 to 24 inches and return periods of 1, 2, 5, and 10 years. The process involved finding the appropriate diameter and return period for which the water surface elevation did not activate the second outlet (D2). The criterion for this first outlet (D1) was that it should not exceed 30% of the road elevation. Once this step was completed, D1 was fixed, allowing the dimensioning of the remaining two outlets.
   - The second outlet (D2). The horizontal pipe (D1) and the orifice (D2) work together when the water level rises to a moderate level, effectively managing increased runoff during more intense storms. The design process for D2 involved iterative testing of pipe diameters ranging from 4 to 24 inches and return periods of 2, 5, 10, 25, 50, and 100 years. The process involved finding the appropriate diameter and return period for which the water surface elevation did not activate the third outlet (D3). The criterion for D2 was

that it should not exceed 30% of the road elevation. Once this step was completed, D2 was fixed.

- The third outlet is the riser pipe (D3), which can be at 50%, 70%, or 90% of the road height, depending on the evaluated pool. This outlet engages during significant storms, allowing the structure to manage maximum flows without overtopping the road. The design process involved iterative testing of pipe diameters ranging from 24 to 72 inches and return periods of 25, 50, 100, 200, and 500 years. The process involved finding the diameter and return period for which the water levels were below 90% of the road height.
- As a result of the design, the outflow hydrograph was obtained for multiple return periods, which allowed for the quantification of the peak flow reductions associated with each of the ORS. Once D1, D2, and D3 were found, stage-storage-discharge curves for each ORS were generated.

The input and output data are displayed in Table 3.

Table 3. Script 3. Input and output data

	File	**Type**
Input Data	DEM	Raster file
	DA with an attribute table containing design values	Polygon shapefile
	Unit hydrograph NRCS	Table
	Rainfall distribution (SCS Type II)	Table
Output Data	Stage, storage, and discharge	Curves and tables
	Inlet and outlet hydrographs (D1, D2 and D3 outlets)	Curves and tables

3.3. HUC12-Scale Hydrologic Modeling

For the six selected HUC12 watersheds depicted in Figure 7, the GHOST model was utilized to evaluate the flood reduction benefits of ORS at the watershed scale. GHOST is a rainfall runoff model extensively validated across various watersheds in Iowa. It is designed for both event-based and multi-year simulations in small catchments and large basins, employing finite volume techniques. Within GHOST, surface flows are simulated using a 2D diffusive wave approximation of the Saint Venant equations, while water depth in canals and streams is computed using a 1D approach. The model also simulates unsaturated zone dynamics under a vertical dominant flow assumption, and groundwater flow is governed by Darcy's law. Processes such as infiltration, exfiltration, recharge, and lateral mass exchanges between surface and groundwater domains are accounted for in the flux calculations. Figure 8 highlights the key hydrologic processes incorporated within the GHOST model.

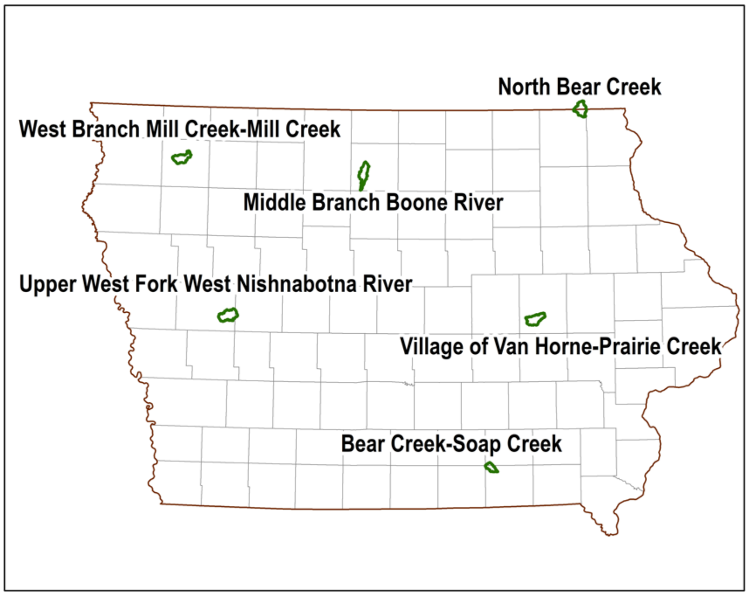


Figure 7. Selected HUC12 watersheds for the generation of planning designs for the ORS (Objective 2) and watershed modeling (Objective 3)

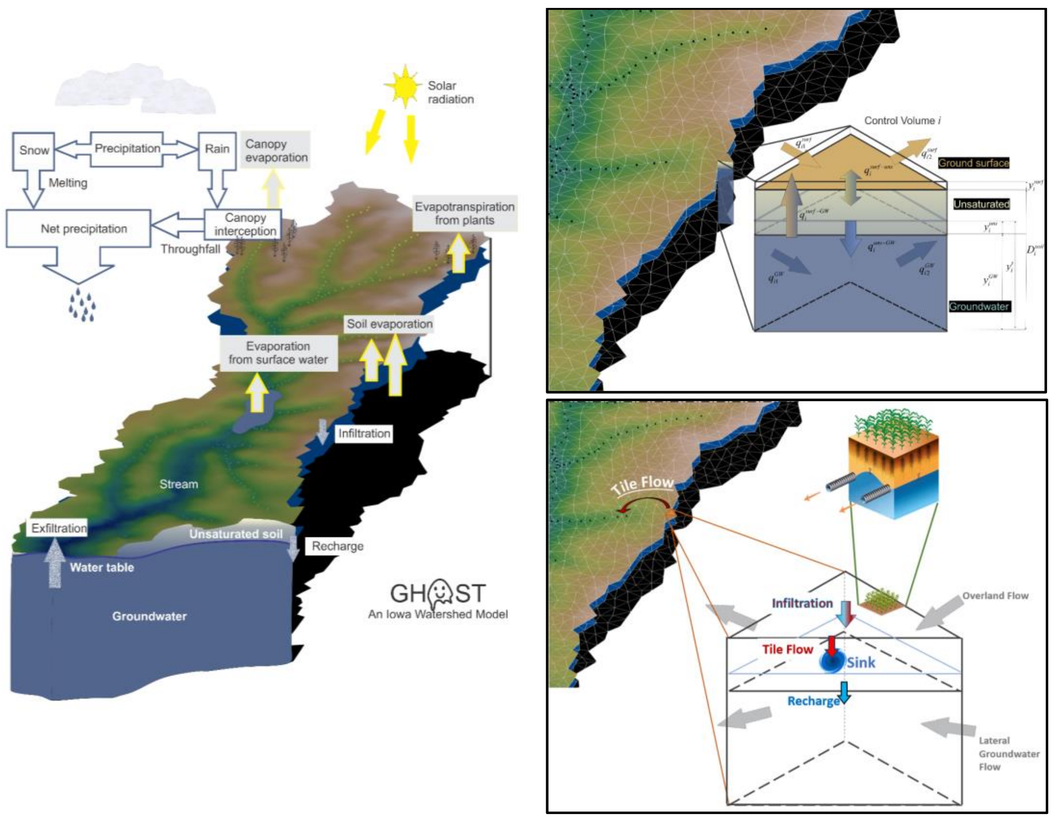


Figure 8. Hydrologic processes, domains, and fluxes modeled in GHOST

The predictive capabilities of GHOST have been extensively validated across various watersheds in Iowa, encompassing diverse soil types, topographies, land covers, geological histories, and hydrologic conditions. For this project, existing GHOST models that were previously calibrated were leveraged, obviating the need for additional model calibration or parameter estimation. Further details on the GHOST model and its performance across Iowa watersheds can be found in Arenas et al. (2020), Weber et al. (2023a), Weber et al. (2023b), Young et al. (2023), and Politano et al. (2023).

In the study of the six selected HUC12 watersheds (Figure 7), the research team assessed the hydrologic model's ability to predict peak flows by comparing modeled outputs against data from StreamStats (Ries III et al. 2017). The comparison revealed that the best agreement between peak flows predicted by GHOST and StreamStats occurred at the 50-year return period, which was consequently chosen for the analyses.

3.4. Web Platform

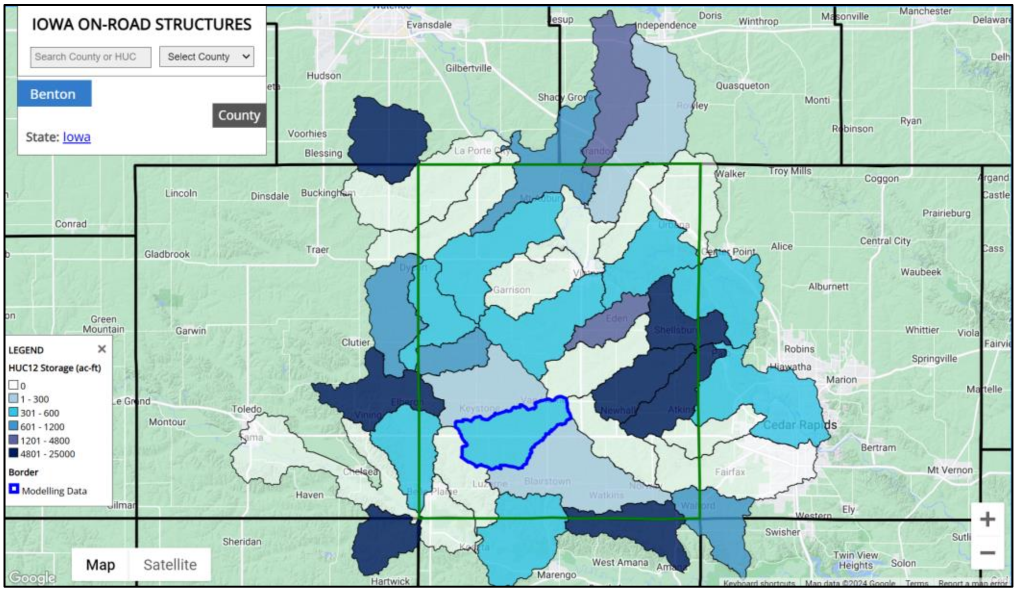
In this project, cyberinfrastructure concepts were used to develop the Iowa DOT On-Road Structures (IDOT-ORS) information platform, available through this URL: https://hydroinformatics.uiowa.edu/lab/idot-ors/.

This platform facilitates access to the locations and the pool and drainage areas of existing and potential on-road structures in Iowa. In addition, in selected HUC12 watersheds (Figure 7), the results of the planning designs are displayed.

The core functionalities and capabilities of the system include the following:

1. Web-based cyberinfrastructure designed for information sharing and communication regarding on-road structures. The system features advanced visualization and filtering tools supported by a relational database housing data and model outputs from the data analytics subsystem.
2. Data analytics components for modeling and analysis. These components evaluate the flood reduction benefits of existing and potential on-road structures and estimate the flood storage potential from ORS.

The web platform enables users to visualize project results across various spatial scales. For watersheds without planning designs, users can view the locations of viable ORS identified through statewide GIS analyses, along with corresponding pool polygons, drainage areas, and flow paths. Additionally, aggregated total storage can be visualized at the HUC12 scale, as depicted in Figure 9. Moreover, for HUC12 watersheds with planning designs, users can access final design results, including values of D1, D2, and D3 (referenced in Figure 6), as well as hydrographs showing inflows and outflows for multiple return periods.



https://hydroinformatics.uiowa.edu/lab/idot-ors/

Figure 9. IDOT-ORS information platform, showing aggregated flood storage at the HUC12 level

The platform serves as a pivotal integration point among the project components, facilitating the communication of data and modeling outcomes. Recent initiatives among the research community underscore the importance of deploying information and communication technologies to advance environmental and geoscience research. Data within the natural sciences are frequently high dimensional, posing challenges in comprehending and extracting meaningful patterns. One effective strategy to enhance comprehension involves providing visual insights into analyzed datasets. Data and information visualization offers graphical, often interactive representations of multidimensional datasets, empowering users to grasp and extract information for further investigation. The IDOT-ORS platform enables users to explore and evaluate analysis results through an interactive user interface. It provides accessible information on the flood reduction benefits of existing on-road structures and estimates the flood storage potential from new ORS in a user-friendly and intuitive environment.

4. RESULTS

4.1. Statewide GIS Analyses

The statewide analyses identified approximately 250,000 ORS with a combined storage capacity of 2 million acre-feet and a pool area covering 900,000 acres, which accounts for about 2.7% of the state of Iowa. Interesting patterns emerge when the results are aggregated at the HUC12, HUC8, and county levels, as shown in Figures 10, 11, and 12. The HUC12 watersheds with the highest storage volumes are predominantly located in North Central Iowa and certain areas of the Missouri and Mississippi River floodplains. However, these areas also exhibit relatively high pool area values, which might generate resistance to ORS implementation among landowners due to the larger areas inundated during heavy precipitation events. The maximum number of ORS found at the HUC12 , HUC8, and county levels was 364, 12,513, and 4,216, respectively.

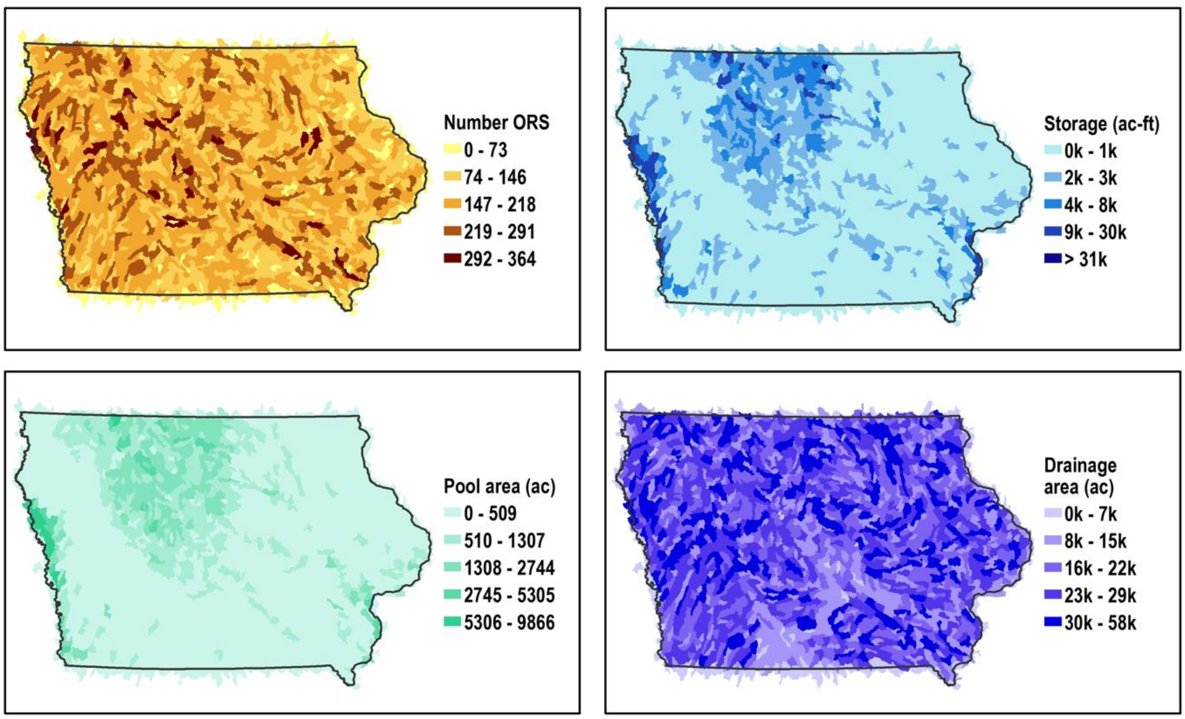


Figure 10. Statewide GIS analyses aggregated at the HUC12 level: number of ORS, flood storage (acre-feet), pool areas for the 70% ORS (acres), and drainage areas (acres)

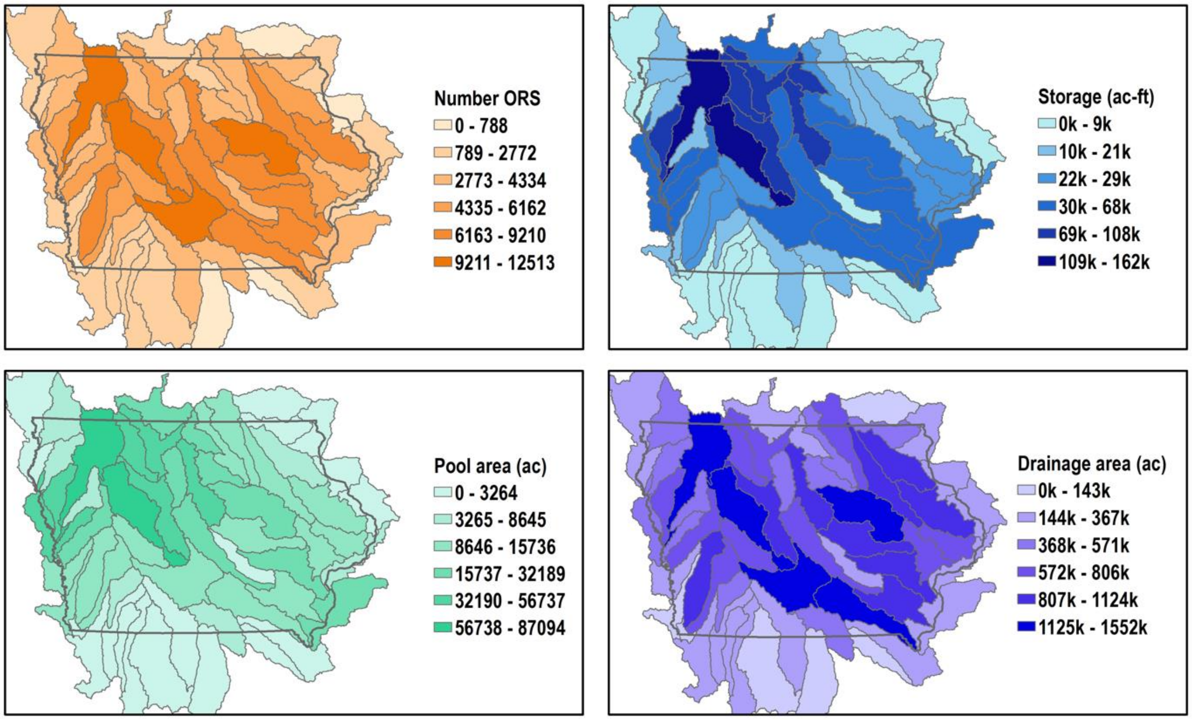


Figure 11. Statewide GIS analyses aggregated at the HUC8 level: number of ORS, flood storage (acre-feet), pool areas for the 70% ORS (acres), and drainage areas (acres)

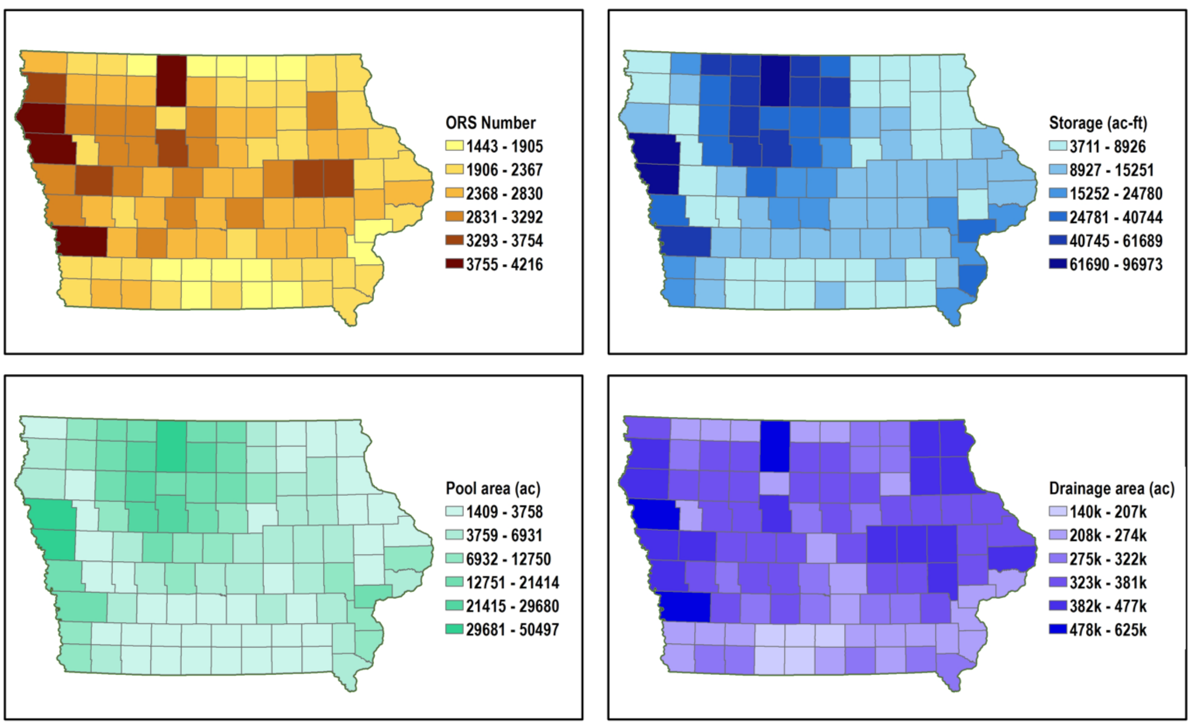


Figure 12. Statewide GIS analyses aggregated at the county level: number of ORS, flood storage (acre-feet), pool areas for the 70% ORS (acres), and drainage areas (acres)

4.2. Planning Designs

The Python scripts were executed for the six selected HUC12 watersheds (see Figure 7) and can be visualized through the web platform. The design methodology could not finalize a design (e.g., values of D1, D2, and D3) for every ORS identified by the statewide GIS analyses. This outcome was expected, since the GIS analyses did not include hydrologic considerations (e.g., design storms, time of concentration, runoff generation mechanisms) but rather served as a preliminary prioritization approach. In simple terms, the GIS analyses identified good candidate locations for ORS implementation, and the hydrologic analysis involved in the planning design methodology identified the best locations among these candidates. Figure 13 summarizes the information generated by the planning design scripts for a selected ORS in Mill Creek. This figure shows the structure location, expected pool, and corresponding drainage area identified through the statewide GIS analyses. Additionally, it presents the values for D1, D2, and D3 calculated using the planning design methodology, as well as the inflow and outflow hydrographs for the 500-year storm, demonstrating an approximate peak flow reduction of 20%.

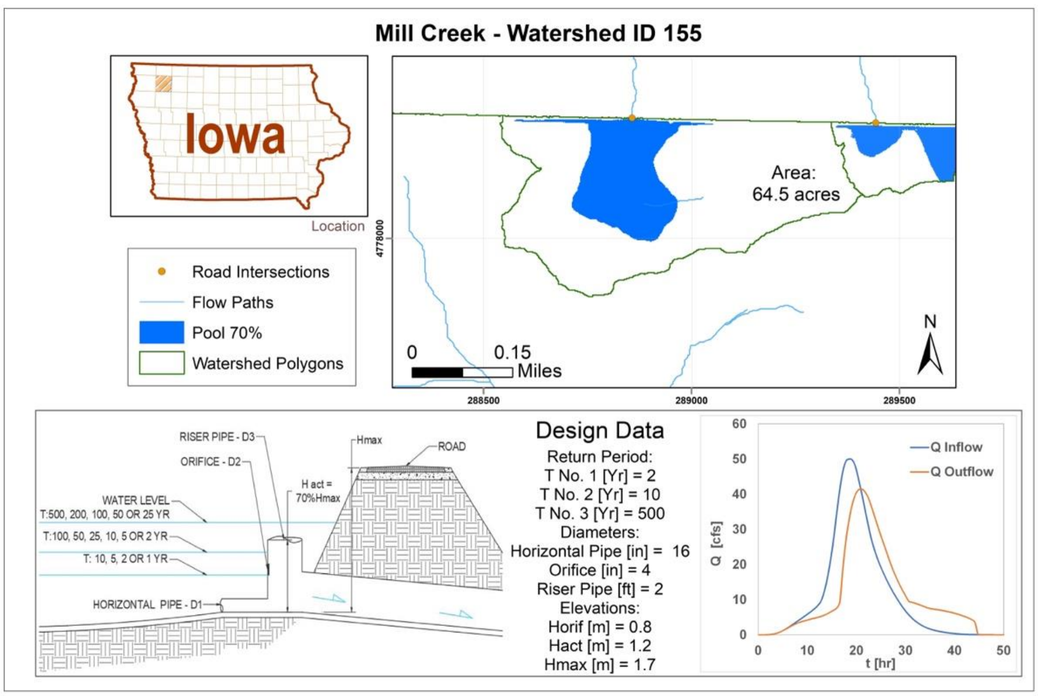


Figure 13. Example of the information generated by the planning design scripts

4.3. HUC12-Scale Hydrologic Modeling

The hydrologic simulations were based on high-resolution computational grids that enable the accurate identification of streams, watershed boundaries, and roads. The smallest computational elements cover an area of approximately a quarter of an acre, with larger elements away from the stream channel approaching five acres in size. This high spatial resolution was crucial to capture the effect of the ORS on the hydrologic response of the HUC12s to heavy precipitation events.

Each computational surface element was assigned spatially variable land use and topographic information that relates the location to overland roughness and land surface slopes. The National Land Cover Database, 2-meter DEMs, and the Soil Survey Geographic Database (SSURGO) were used to describe the properties of both the saturated and unsaturated regions. Models were forced with 50-year design storms generated using data from the NOAA Atlas 14 and the SCS Type II rainfall distributions. All of the simulations were run for nine days (216 hours), and the design storm was applied during the fourth day. ORS were incorporated using stage-storage-discharge relationships.

For each of the six selected HUC12 watersheds (Figure 7), Figures 14 through 25 provide information on various aspects. These include the dominant land cover, the computational mesh, the selected ORS for the simulations, and a comparison of flow peaks predicted by GHOST and estimated from StreamStats for 10-year, 50-year, and 100-year return periods. Additionally, two hydrographs are presented for each watershed that show the GHOST model outputs at the watershed outlet during the 50-year storm. The hydrographs illustrate both the baseline conditions (without ORS) and the model predictions after implementing the selected ORS. By analyzing the differences in hydrograph peaks, the flood reduction benefits of the chosen ORS at the HUC12 scale can be quantified.

4.3.1. North Bear Creek

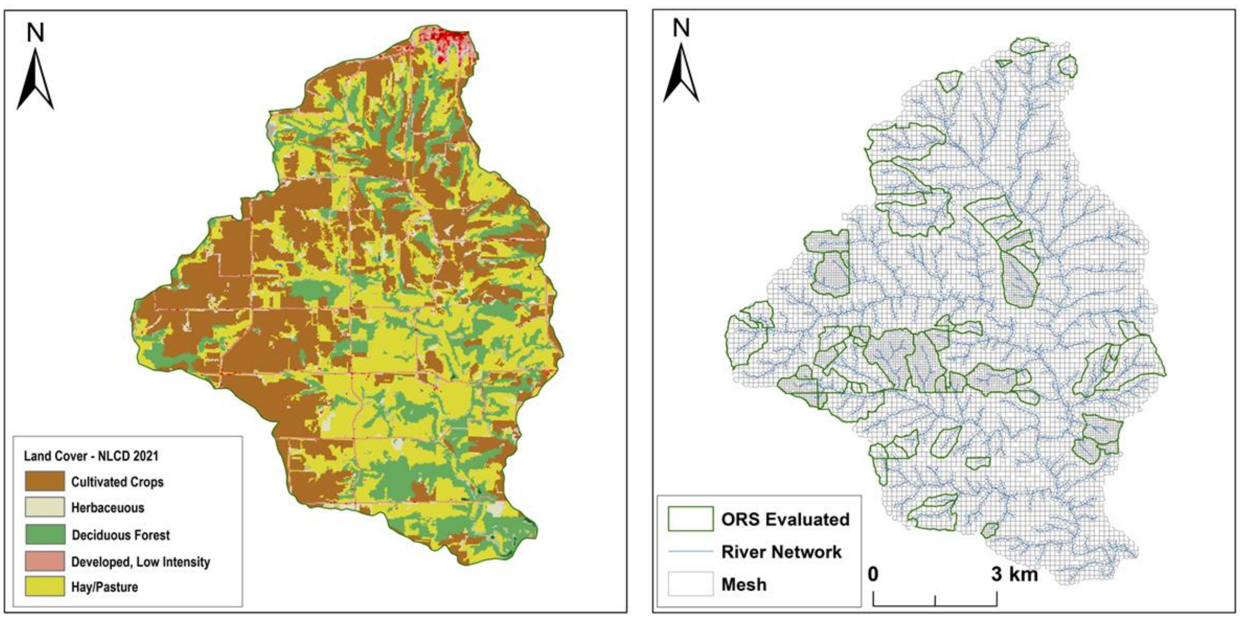


Figure 14. Dominant land uses in the North Bear Creek watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

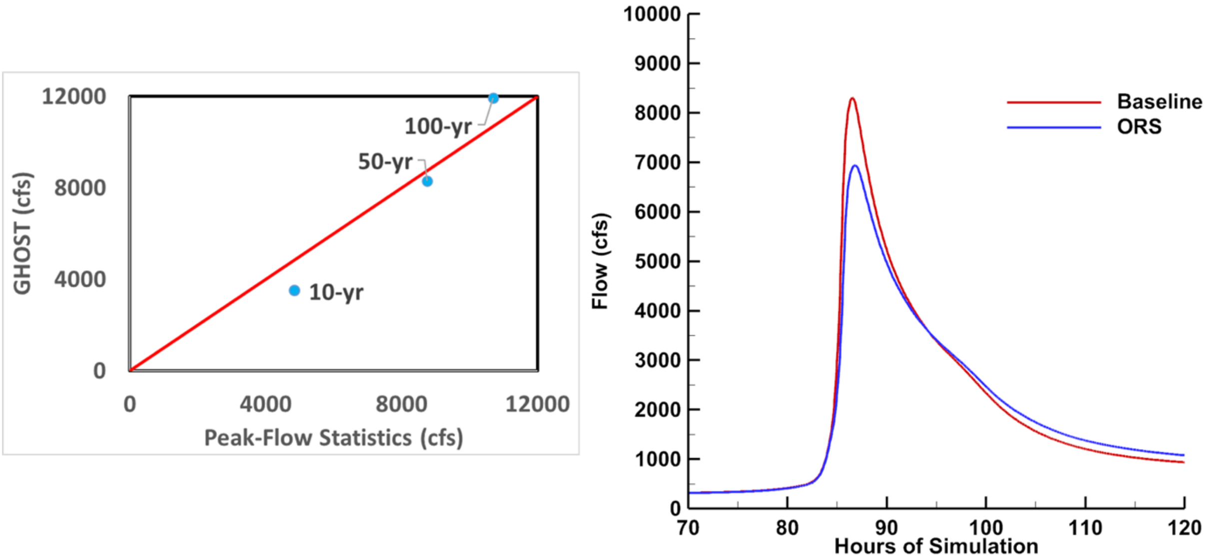


Figure 15. Peak flow comparison at the North Bear Creek watershed outlet, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

4.3.2. Bear Creek – Soap Creek

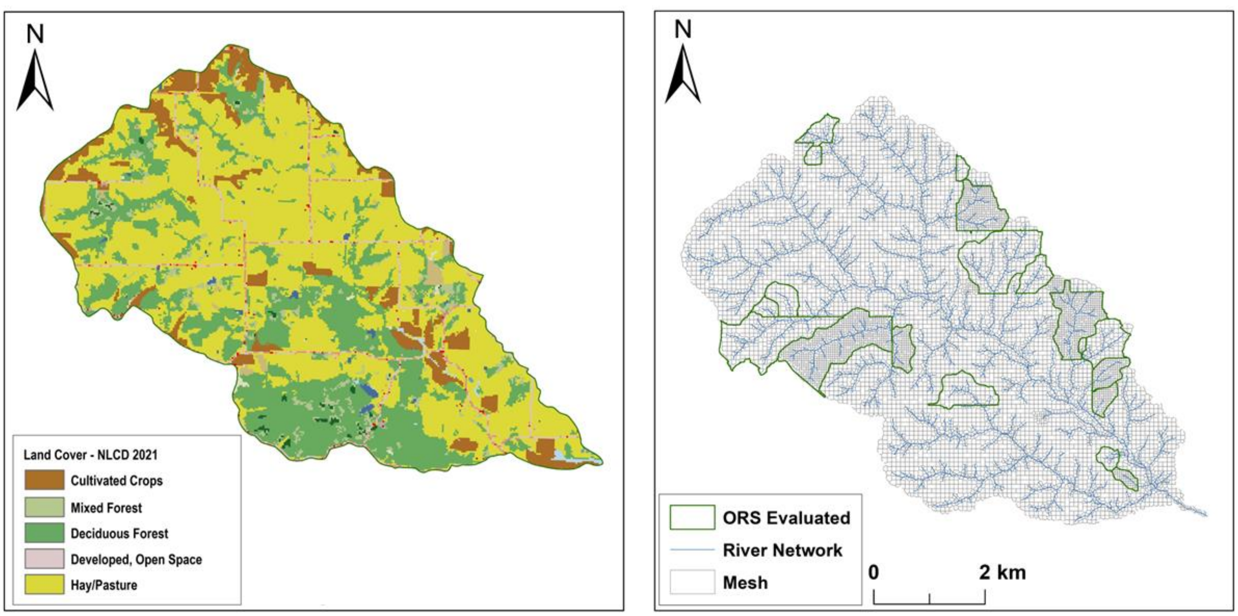


Figure 16. Dominant land uses in the Bear Creek – Soap Creek watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

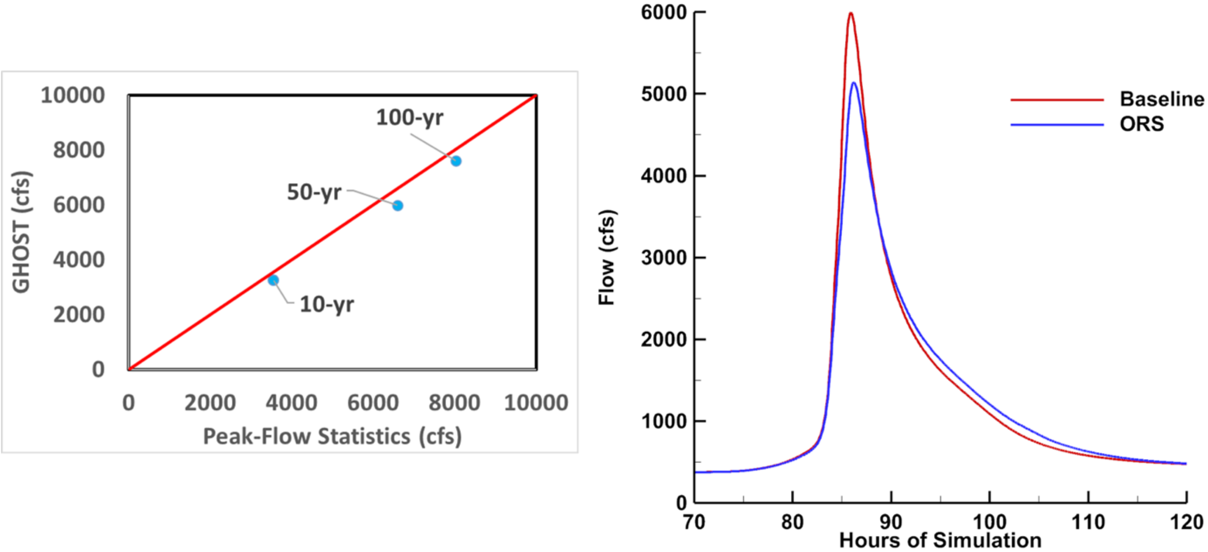


Figure 17. Peak flow comparison at the Bear Creek – Soap Creek watershed outlet, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

4.3.3. Middle Branch Boone River

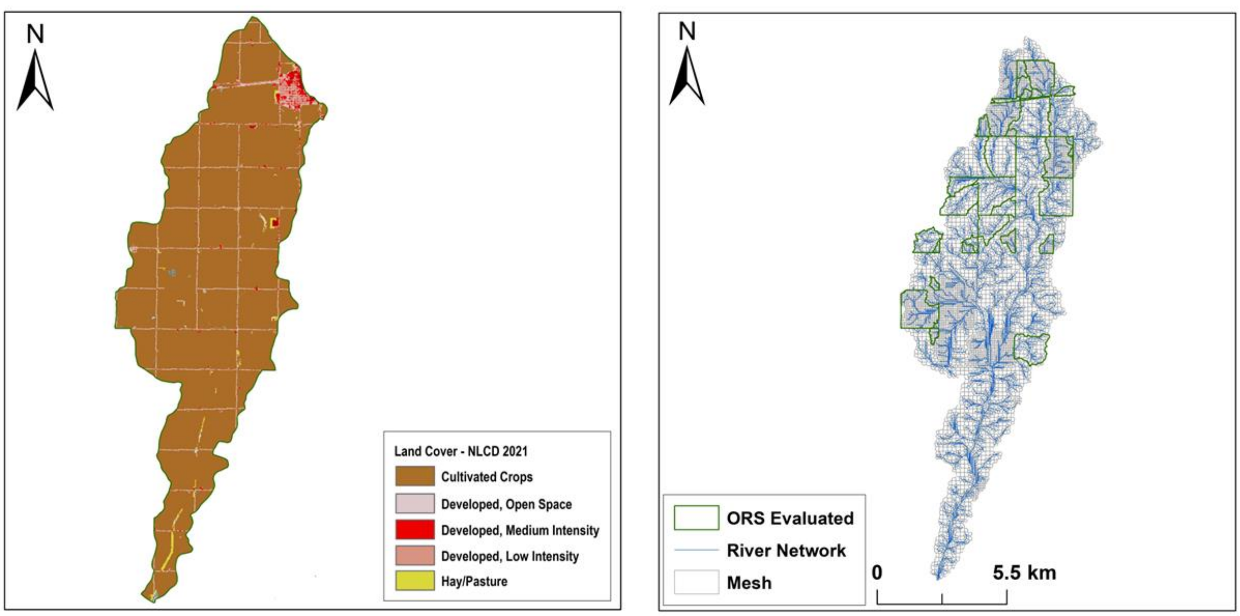


Figure 18. Dominant land uses in the Middle Branch Boone River watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

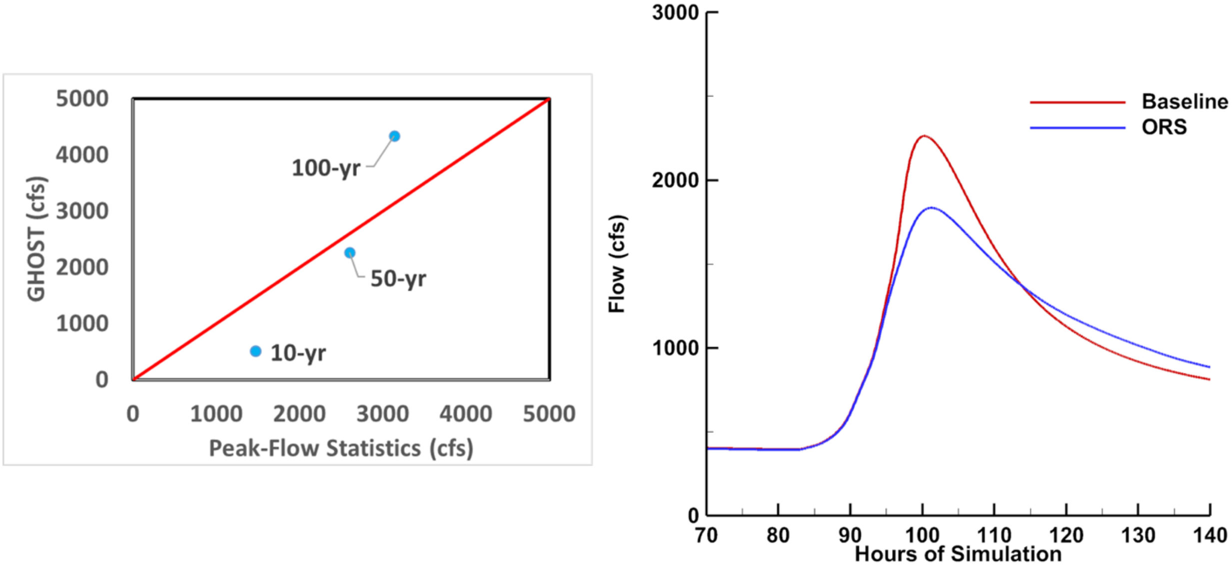


Figure 19. Peak flow comparison at the Middle Branch Boone River watershed outlet, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

4.3.4. Village of Van Horne – Prairie Creek

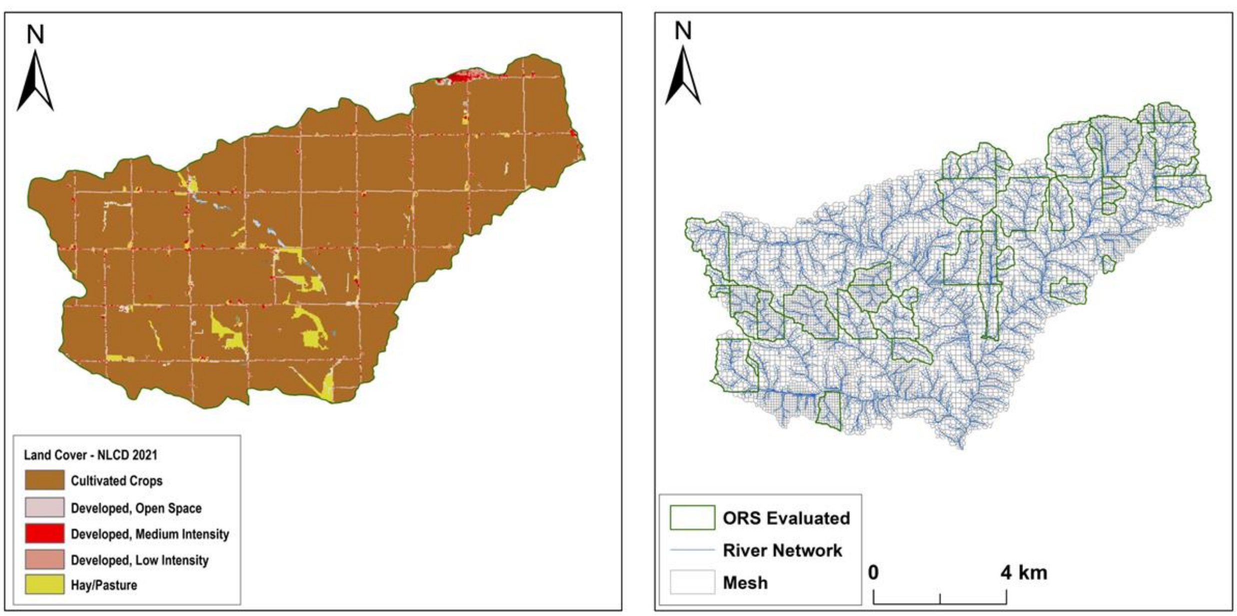


Figure 20. Dominant land uses in the Village of Van Horne – Prairie Creek watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

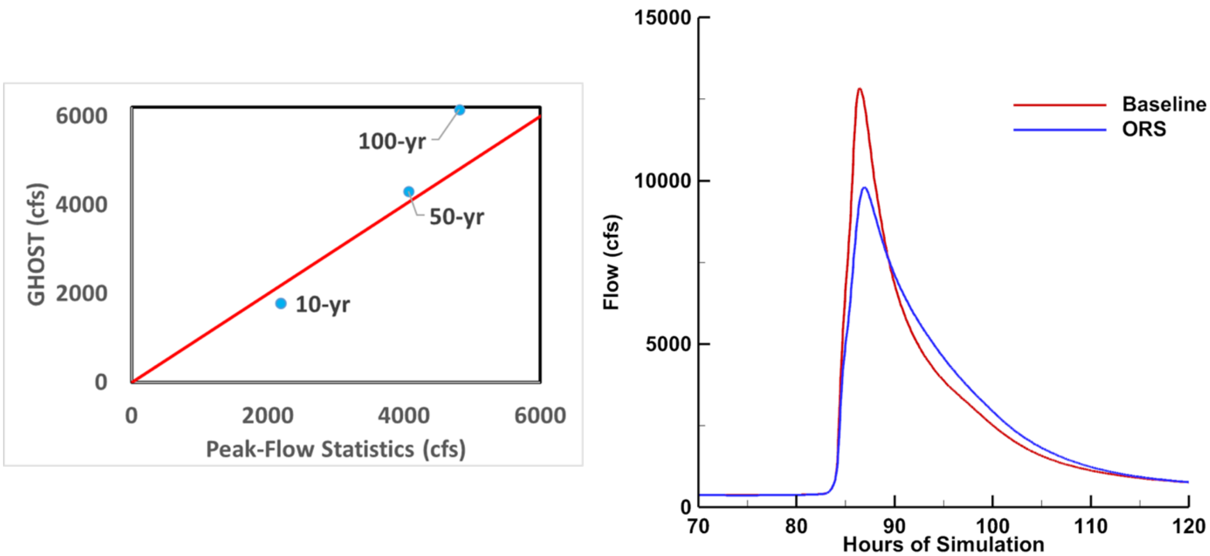


Figure 21. Peak flow comparison at an interior point in the Village of Van Horne – Prairie Creek watershed, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

4.3.5. West Branch Mill Creek – Mill Creek

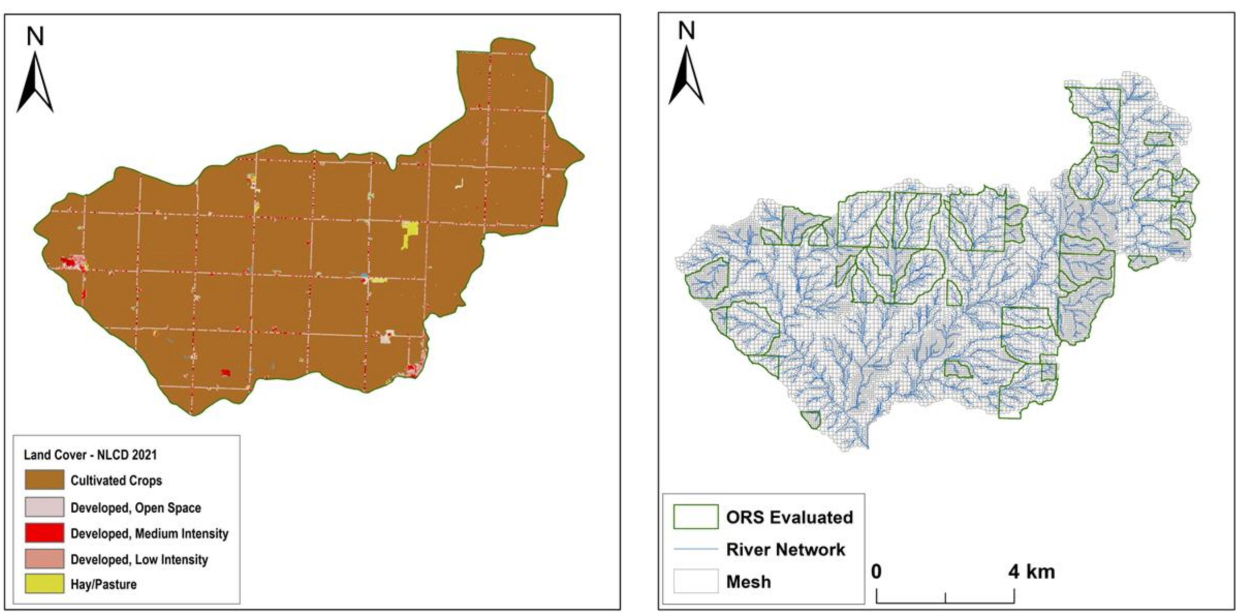


Figure 22. Dominant land uses in the West Branch Mill Creek – Mill Creek watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

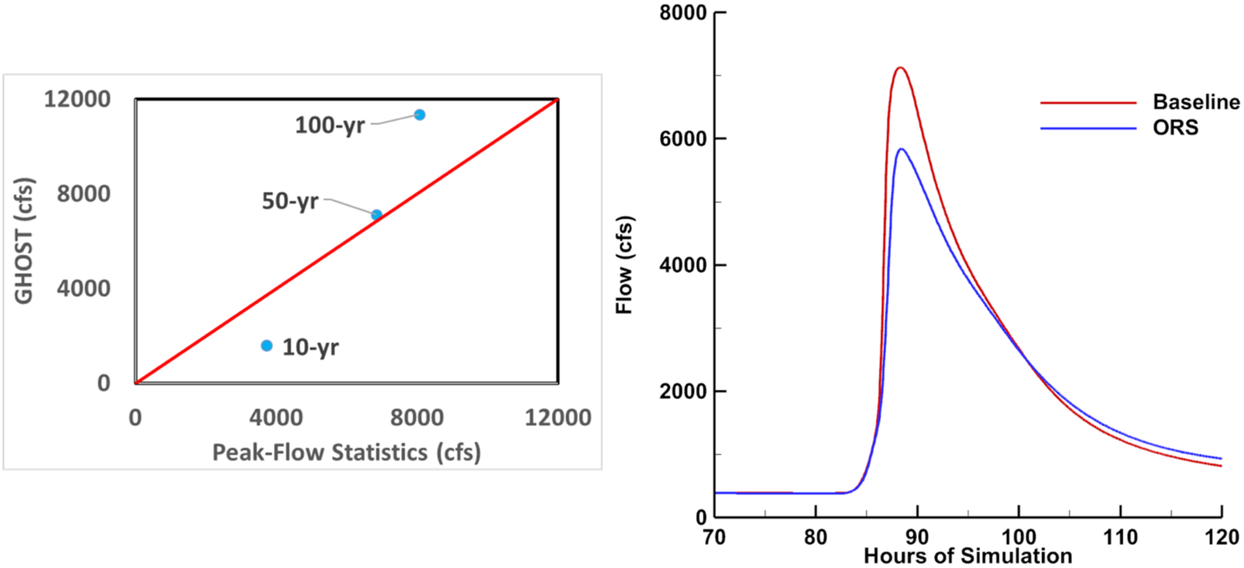


Figure 23. Peak flow comparison at the West Branch Mill Creek – Mill Creek watershed outlet, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

4.3.6. Upper West Fork – West Nishnabotna River

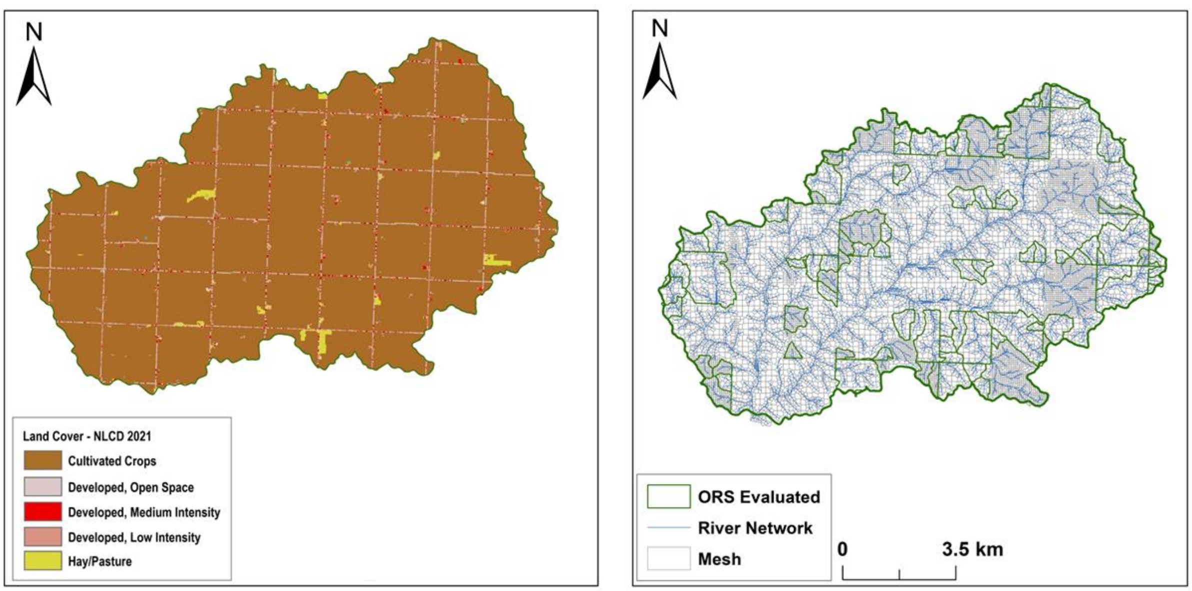


Figure 24. Dominant land uses in the Upper West Fork – West Nishnabotna River watershed (left) and computational mesh and drainage areas contributing to the evaluated ORS (right)

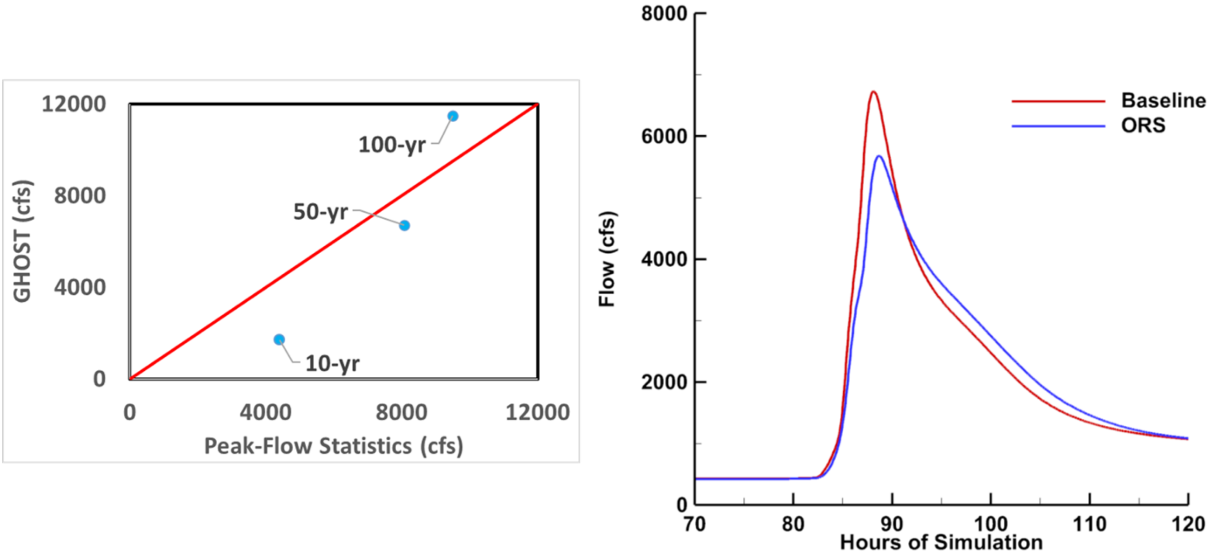


Figure 25. Peak flow comparison at the Upper West Fork – West Nishnabotna River watershed outlet, showing modeled values (vertical axis) versus estimates from regionalization and regression equations (StreamStats) (left), and hydrographs at the watershed outlet depicting model predictions for the 50-year storm with ORS and without ORS (baseline) in place (right)

Table 4 and Figure 26 present a summary of the HUC12-scale hydrologic simulations. On average, the evaluated ORS systems provided an 18% peak flow reduction at the watersheds' outlets. It is important to note that only a subset of the ORS identified through the statewide GIS analyses was tested with the hydrologic models. Therefore, there is potential for greater peak flow reduction if more structures are evaluated. However, an important conclusion from the modeling results indicates that guiding conservation or watershed planning efforts based on the number of ORS may not be advisable. Figure 26 (left) shows that a larger number of ORS does not necessarily correlate with additional peak flow reductions. The results suggest that a metric better correlated with peak flow reduction is the percentage of the watershed regulated by the ORS, as shown in Figure 26 (right).

Table 4. Summary of the HUC12-scale hydrologic modeling

HUC12 Name	Area (acres)	Number of ORS	DA (acres)	Regulated Area (%)	Peak Flows, 50-Year Storm Baseline (cfs)	ORS (cfs)	Reduction (%)
North Bear Creek	20,335	53	5,282	26.0	8,304.6	6,942.9	16.4
Bear Creek – Soap Creek	10,044	19	2,020	20.1	5,994.7	5,140.0	14.3
Middle Branch Boone River	21,706	29	5,788	26.7	2,261.9	1,834.2	18.9
Village of Van Horne – Prairie Creek	22,333	41	7,945	35.6	12,825.2	9,796.3	23.6
West Branch Mill Creek – Mill Creek	19,857	45	7,684	38.7	7,127.0	5,842.8	18.0
Upper West Fork West Nishnabotna River	25,642	71	8,118	31.7	6,729.2	5,682.1	15.6

DA represents the accumulated area contributing to the ORS.
Peak flows were extracted from the hydrographs presented in Figures 15, 17, 19, 21, 23, and 25.

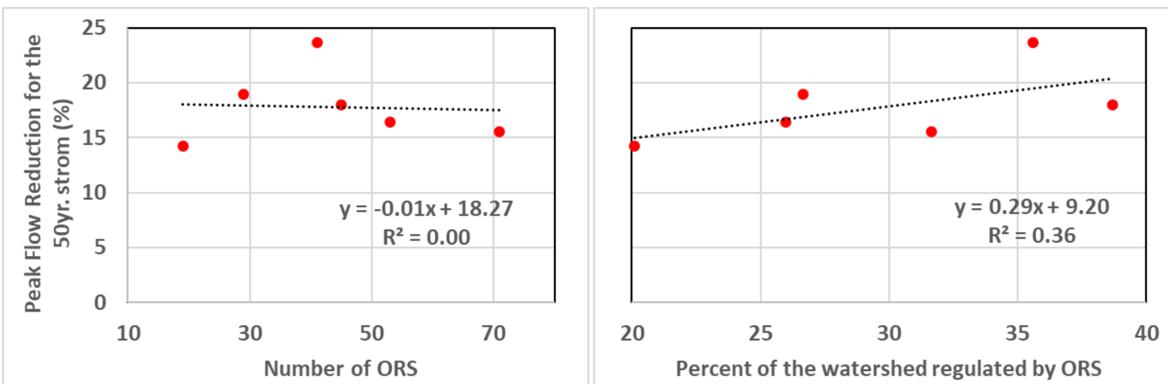
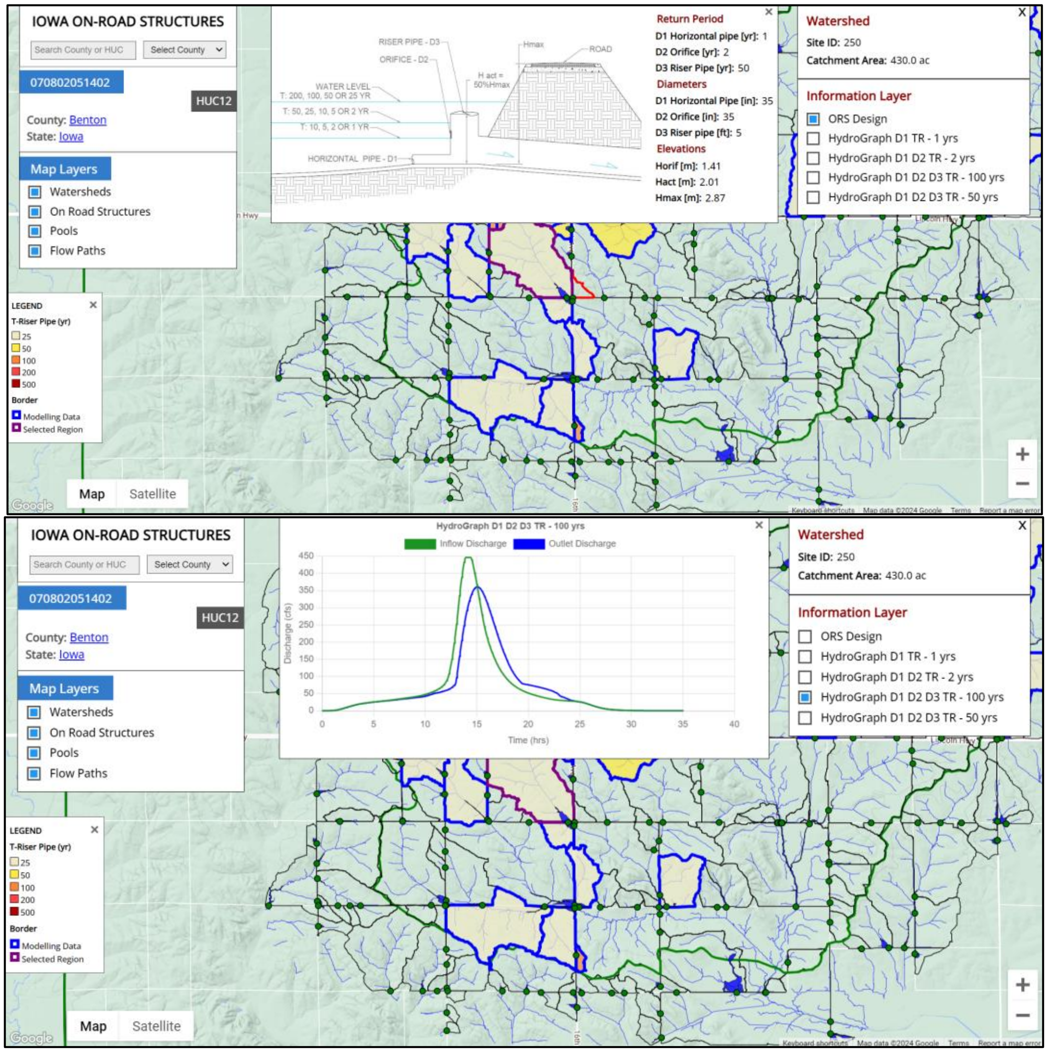


Figure 26. Number of ORS versus peak flow reduction (left) and percent of the watershed regulated versus peak flow reduction (right)

Furthermore, it is important to note that the peak flow reductions presented in the analyses were estimated at the watershed outlet. Significantly higher peak flow reductions (e.g., >25%) exist in some of the tributaries, particularly immediately downstream of the ORS. This suggests that if county engineers identify a culvert or bridge repeatedly impacted by flood events and receiving water from a relatively small area, a system of ORS upstream from the impacted area can provide significant flow reduction and potentially lessen the frequency and magnitude of infrastructure damages.

4.4. Web Platform

The IDOT-ORS platform combines visual and data analytics to provide a desktop-like environment for managing, visualizing, and analyzing large volumes of geospatial data through web-based mapping and visualization features (Figure 27). By using web service application programming interfaces (APIs), the platform ensures interoperability across various information systems. A client tool for these web services guarantees consistent data access. These web services are unified to serve model data consistently, allowing end users to access data through a standardized API, regardless of their system.



https://hydroinformatics.uiowa.edu/lab/idot-ors/

Figure 27. Planning designs (top) and inflow and outflow hydrographs for the 100-year storm (bottom)

The platform stores the geospatial layers developed during the statewide GIS analyses and planning design efforts described above. The layers are visualized using the Google Maps API, delivering data and spatial layers in formats like KML, geoJSON, or other international standards from the Open Geospatial Consortium (OGC). To simplify access, a client library of tools that enable users to interact with IDOT-ORS web services was developed. This highlights the interoperability of systems adhering to consistent data and API specifications. Additionally, new visualization and communication tools were created using JavaScript and Canvas. Figure 27 illustrates the information accessible via the IDOT-ORS platform. At the top are results from planning designs for a selected structure, while at the bottom are inflow and outflow hydrographs for the 100-year storm.

5. CONCLUSIONS AND FUTURE WORK

The primary goal of the current research was to develop tools to guide, facilitate, and enhance the adoption of ORS in Iowa. This project examined various aspects of ORS, which are modified culverts that use road embankments as temporary dams to store water and reduce flood impacts. Statewide GIS analyses identified approximately 250,000 potential ORS implementation sites. The geospatial datasets created in this project are a valuable resource for anyone considering ORS implementation in Iowa. These datasets provide information on ORS locations, expected pool areas, and the drainage areas associated with the structures, offering a comprehensive foundation for planning and decision-making.

Additionally, a methodology and Python scripts were developed to automate the hydrologic design of individual ORS, improving the identification of ORS that offer significant peak flow reduction benefits. This project also quantified the peak flow reduction benefits at the HUC12 watershed scale for ORS systems, revealing that for a 50-year storm event, peak flows at watershed outlets were reduced by approximately 18%. Our modeling results suggest that the area regulated by ORS is a more effective parameter than the number of ORS alone for estimating peak flow reductions at larger spatial scales.

Lastly, the research outcomes are accessible and can be visualized through a web platform integrated with Google Maps. This platform facilitates the dissemination of results and allows various stakeholders to understand the potential of ORS in mitigating flood impacts effectively.

Several additional analyses can be built upon the findings and products of this research, including the following:

- **Expansion of planning designs**. Extend the planning design scripts beyond the initial six selected HUC12 watersheds to cover all (approximately 1,600) HUC12 watersheds in Iowa. This broader analysis will enhance the selection of ORS that can provide optimal peak flow reduction benefits. The outcomes can be integrated into the IDOT-ORS platform.
- **Hybrid modeling approach**. Introduce a hybrid approach combining the process-based hydrologic modeling used in this project with machine learning techniques. This approach can efficiently assess a larger number of HUC12 watersheds across various hydrologic scenarios and implementation levels of ORS, enhancing both accuracy and computational efficiency.
- **Alignment with the POWAR concept**. Coordinate additional research efforts with ongoing flood resiliency planning initiatives in Iowa, such as the POtential of using a Watershed Approach for Reducing floods (POWAR) concept developed by the Iowa Department of Homeland Security and Emergency Management. This concept focuses on mitigating flood damages through constructed storage (e.g., ORS) upstream of vulnerable communities. Aligning additional research on ORS with the POWAR concept can guide mitigation investments effectively.
- **Economic analysis of ORS**. Conduct economic analyses once the flood reduction benefits of ORS are quantified, and perform loss-avoidance or benefit-cost analyses to provide counties and communities with data necessary for securing funding to enhance flood resilience.

- **Water quality analysis**. Explore the water quality aspects of ORS, particularly the impacts of ORS on phosphorus movement from agricultural fields to streams. ORS, by slowing down water flows, can enhance sediment deposition and potentially reduce the phosphorus quantities reaching bodies of water. Future research efforts can try to quantify these effects to understand their environmental benefits.

These potential research areas broaden the scope of the initial research, addressing critical aspects of flood mitigation, economic feasibility, and environmental impacts related to ORS implementation in Iowa.

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