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Actionable Flood Warnings based on Ground-truth Data to Support Iowa DOT BridgeWatch Platform Functionality

Submitted by

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16. Abstract

The expectation of improved flood warnings has become critical for many agencies and communities at a time when flooding is increasingly severe and widespread. Formulation of flood warnings for a specific area entails three major steps: A) forecasting the flood hazards, B) delineation of the flood maps, and C) assessment of the threats to human safety and economic losses within the inundated areas. The first step is executed with hydraulic & hydrologic modeling assisted by direct measurements of various water cycle variables. The second and third steps entail specialized analyses applied to a variety of physiographic, built infrastructure, social, and economic data. Consequently, the reliability of flood warnings is directly dependent on the model skills and the quality of the input data for the modeling and specialized analyses involved. In general, flood warnings are highly uncertain. Taking advantage of the unique resources available at the Iowa Flood Center (IFC), the present research has developed an innovative path to improve the flood-warning formulation (steps B and C above) with focus on transportation infrastructure and resource allocation during flooding. Specifically, the research carried out through the present research tackled the following objectives: a) assessment of the quality of the statewide floodplain mapping at selected bridges across the state (with and without BridgeWatch warnings) by using the High-Resolution Satellite-based Maps (HRSM) available from third-party sources. The evaluation of the existing floodplain maps is an important step to gain confidence in streamflow forecasting on which the BridgeWatch warnings are based. b) Developing a long-term plan to extend the BridgeWatch functionality to all flood-prone Iowa bridges at ungagged sites based on the inferences obtained in step a) above. The extension of the BridgeWatch functionality includes the innovative use of the IFC bridge sensors data in conjunction with the streamflow forecasting protocols to inform on floodplain mapping extent at ungagged sites via the HRSM-based datasets. BridgeWatch functionality extension also entails addition of other functionalities that can significantly increase the protection for the statewide road network against the direct and indirect adverse impacts, including the loss of access to essential services during flooding.

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Executive Summary

The Iowa Department of Transportation (IDOT) is using the BridgeWatch™ technology to predict flooding conditions and proactively protect bridges at risk. One of the products ingested into BridgeWatch is the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) streamflow forecast that entails time series of the expected flood waves, including the peak magnitudes and their timing. Most of these forecasting points are at gages pertaining to the US Geological Survey's (USGS) National Information System (waterdata.udsgs.gov/nwis). By a recent count, there are about 204 USGS real-time streamflow gauges in Iowa. More recently, Iowa BridgeWatch ingests products of the Iowa Flood Center's (IFC - iowafloodcenter.org) real-time streamflow forecasting system. The latter resource uses streamflow data collected at USGS gaging stations complemented by the similar data obtained via synthetic rating curves at 275 locations where bridge-mounted sensors were installed by IFC. In total, there are about 475+ real-time forecasting points across Iowa resulting in a streamflow observational and forecasting network density that is unmatched by other states in the nation.

Despite this large number of forecasting points there are many bridges located in flood-prone areas across the state left without the much-needed forecasts. Even for the bridges with streamflow forecasting points, the provided information is restricted to the immediate vicinity of the forecasting points, i.e., flood water elevations are not predicted for areas upstream and downstream from the gage location used for forecasting. This is perceived as a limitation of the current BridgeWatch systems as, even if the forecast on flooding is accurate for the specific bridge structure, there is no information on: a) accessibility of the road leading to the bridge, b) alternatives routes to avoid the flooded bridge; and c) potential alternative routes to distribute flood-related assets during flooding in the area of forecasting points.

Needless to say, 475 forecasting points are insufficient to monitor flooding at the 23,834 Iowa bridges (public-iowadot.opendata.arcgis.com). The BridgeWatch system functionality can be extended to more flood-prone bridges of the Iowa road network if additional developments are made to the system. An important aspect of this development is the access to accurate flood mapping for various flooding scenarios. Such maps are available through the Iowa statewide floodplain mapping system developed by the IFC and the Iowa Department of Natural Resources in 2016 (iowafloodcenter.org/projects/iowa-statewide-floodplain-mapping). These maps show the probability, extent, and depth of flooding for all Iowa streams that drain more than one square mile. However, the accuracy of these maps has not been tested against ground-truth data given the cost and complexity of such a quality control process. The mapping accuracy is crucial when used for predicting hazardous water levels within a small elevation range, i.e., from elevations corresponding to the low beam of the bridge to those leading to overtopping.

The research initiated by this project aimed at a) assessing the quality of the statewide floodplain mapping at selected bridges across the state (with and without BridgeWatch warnings) by using the High-Resolution Satellite-based Maps (HRSM) available from third parties. The HRSM-validated floodplain maps can significantly increase the confidence in the quality of the existing maps and indicate where they need to be re-evaluated; b) developing a long-term plan to extend the BridgeWatch functionality to all flood-prone Iowa bridges at ungaged sites. The extension of the BridgeWatch functionality includes the innovative use of the IFC bridge sensors data to forecast streamflow at gaged and ungaged sites and to inform relevant IDOT personnel on the direct and indirect adverse flood impacts, including the loss of access to essential services needed during flooding.

1. Introduction

In order to proactively protect the vast network of bridges at risk during flooding, the Iowa Department of Transportation (IDOT) have customized the BridgeWatch™ web-based bridge monitoring software (usengineeringsolutions.com/bridgewatch) to include flood hazard predictions in its decision-support functionality. This web-platform integrated data for static infrastructure datasets (i.e., bridge location, structural details, flood maps, and ad-hoc reports on flooding occurred over time) with dynamic datasets (i.e., streamflow forecasting model ingesting predicted meteorological conditions and real-time data collected at a vast network of streamflow monitoring points) to timely issue short-time flood warnings for Iowa bridges that are distributed through electronic media (i.e., cell phones, pagers, emails, and fax).

The expectation of improved flood warnings has become critical for many agencies and communities at a time when flooding is increasingly severe and widespread (Mallakpour & Villarini, 2015). The formulation of the flood warnings for specific areas is a complex process that depends on the integration of weather, topography, land use, and man-made structures in a workflow driven by numerical modeling. The core of the workflow entails three major steps: a) delineation of the flood maps for various return floods, b) forecasting the flood hazards in real time, and c) assessment of the threats to human safety, civil engineering structures, and economic losses within the areas exposed to flood hazards. The first and third steps entail specialized analyses applied to a variety of physiographic, social, and economic data collected over large scales. The second step is executed with hydraulic and hydrologic modeling assisted by direct measurements of various water cycle variables. Consequently, the reliability of flood warnings is directly dependent on the model skills, the quality of the input data for the modeling, correct execution of the specialized analyses involved, and the professional judgments made by hydrologists that oversee the process. In general, flood warnings have a high degree of uncertainty, hence scientists are continuously seeking guidance for flood forecasting producers in the selection of the most appropriate models to reduce the warning uncertainty (Boelee et al., 2019).

The delineation of the flood maps in Iowa BridgeWatch is based on the Iowa statewide floodplain map system completed in 2016 by the Iowa Flood Center (IFC) and the Iowa Department of Natural Resources following the Federal Emergency Management Agency's standards (iowafloodcenter.org/projects/iowa-statewide-floodplain-mapping). This resource contains flood maps for all Iowa streams draining more than one square mile indicating the extent and depth of flooding for eight flood return periods. The streamflow forecasting ingested into BridgeWatch has originally been based on the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) forecasts that entails predicted time series of short duration (up to 6 days) that anticipate the trends of the flood wave propagation at various points of interest. More recently, Iowa BridgeWatch ingests the streamflow forecasting produced by the Iowa Flood Center (IFC) for the state of Iowa that are disseminated through an open-access portal to all Iowans (iowafloodcenter.org). The initial conditions for the IFC real-time streamflow forecasting system uses data from the USGS and IFC bridge-mounted gaging stations (Quintero et al. 2020; Velasquez et al., 2021). The NWS forecast points are co-located with US Geological Survey (USGS) streamflow gaging stations that provide hydrologic data for public usage in real time through the National Water Information System (waterdata.usgs.gov/nwis). By a recent count, there are about 204 USGS real-time streamflow gages in Iowa. The IFC complements the USGS stations with about 275+ other locations where IFC developed synthetic ratings using as input the stage sensors installed at bridges (Quintero et al., 2021).

The nearly 1,200 streamflow forecasting points supported by 475 real-time observational points across Iowa offer a forecasting network density that is unmatched by other states in the nation. Despite the large density of observation points available in Iowa, the quality of the modeling components leading to flood warnings in Iowa BridgeWatch continues to remain an open issue (Anderson et al., 2015). The flood maps accuracy is largely unknown despite the fact that they are crucial for prescribing water levels over large and small stage ranges, i.e., from the flood crest to elevations corresponding to the low beam of the bridge to those leading to overtopping. It is also recognized that the streamflow forecasting models are notoriously uncertain because of the numerous sources of errors in the simulations of the geomorphological and flood routing processes and the non-uniform and ad-hoc protocols used for the warning formulations (e,g., Yevdjevich. 1964, Bales & Wagner, 2009).

Ensuing from the above considerations is that the Iowa BridgeWatch system inherits weaknesses of modeling components leading to flood warning preparations with the foremost concern being the quality of the flood mapping and streamflow forecasting models linked to the system. Moreover, the coverage of BridgeWatch is insufficient to secure the much-needed information on flooding for the 23,834 Iowa bridges of which about 4,100 are under IDOT maintenance (public-iowadot.opendata.arcgis.com). Even for the bridges with streamflow forecasting points, the provided information is restricted to the immediate vicinity of the forecasting points (i.e., flood water elevations are not specified for areas upstream and downstream from the gage location used for forecasting). Consequently, the BridgeWatch system has no capabilities to inform on: a) accessibility of the road leading to the bridge, b) alternatives routes to avoid the flooded bridge; and c) potential alternative routes to distribute flood-related assets during flooding in the area of forecasting points.

Up to date there are no systematic studies to assess the accuracy of the streamflow forecasts and flood mapping using ground-truth information. The often-invoked reason for this status quo is the complexity and high cost of such a quality control process. The advancements in remote-sensing technologies, including high-resolution satellite maps (HRSM) promise to fill this gap due to their extensive spatial coverage, continuously improved resolution, and acquisition frequency. The present research describes results of the research conducted to assess the BridgeWatch system prediction accuracy and extension of its coverage to an increased number of flood-prone bridges associated with the Iowa road network.

The primary focus points tackled through this research are: a) assessing the quality of the statewide FEMA floodplain mapping at selected bridges across the state (with and without BridgeWatch warnings) using High-Resolution Satellite-based Maps (HRSM) available from third-party sources (i.e., planet.com), and, b) designing a new workflow linked to Iowa BridgeWatch to extend the functionality of the platform to an increased number of flood-prone Iowa bridges using a data-driven approach. The inferences from the flood mapping assessment will inform on the actions needed to increase the protection for the statewide road network against the direct and indirect adverse impacts, including the loss of access to essential services needed during flooding (Alabbad et a., 2021). The extension of the BridgeWatch coverage and functionality to gaged and ungagged locations is made by innovatively using the HRSM-based information with the real-time data provided by the IFC bridge sensor network.

2. Background on Iowa BridgeWatch components for supporting flood warnings

BridgeWatch is a web-based software application aimed to empower engineers and public officials to predict, identify, prepare for, and record potentially destructive events occurring at bridges (usengineeringsolutions.com/bridgewatch). The web-platform can be configured to identify the occurrence of environmental hazards and collect relevant structure information along with, practically, any relevant monitoring and modeling data available (e.g., real-time meteorological, hydrologic, seismologic data). Using specifically designed graphical interfaces, the BridgeWatch system accesses the internal resources and has the ability to communicate to key personnel from construction, engineering, and government services of potentially destructive events by linking to specified thresholds and user defined emergency response protocols.

The BridgeWatch software implementation was initiated by IDOT in 2012 as a central platform for collecting rainfall data near bridges. Subsequently, it has been progressively enhanced by adding inventory data, personnel contact information, and structure specific thresholds related to other hydrological and environmental conditions. When bridges monitored with BridgeWatch are at risk, Iowa DOT personnel are automatically notified so they can closely monitor the bridge structure safety and decide timely on appropriate emergency measures. Flood alerts are sent via email, pager, fax, or text message when thresholds are met for specified locations. A major benefit of this software is that it provides a historic archive of flood events and event performance system’s capability to protect against hazardous, costly, and potentially catastrophic events. The flood warnings issued by the Iowa BridgeWatch system rely on several external data and information resources. Among the datasets connected to the BridgeWatch for this purpose are data collected from National Oceanic & Atmospheric Agency (NOAA), U.S. Geological Survey USGS), National Weather Service National Radar Data (NWS NEXRAD), and Natural Resource Conservation Service (NRCS). In the last several years, multiple datasets and tools developed by the IFC for the state of Iowa have been connected to BridgeWatch (D. Claman, personal communications, September 2021). As can be noticed from above, the accuracy of the flood warnings emitted by the system’s core functionality is entirely dependent on the quality of the "external" constituents of this platform. The components currently connected to the IDOT customized BrodgeWatch system are briefly described below.

Iowa Bridge Inventory of the Iowa Department of Transportation is housed in a commercial product labeled Structure Inventory and Inspection Management System (SIIMS). This comprehensive bridge management system was customized to fit the conditions and specific needs of the BridgeWatch software for assisting in the challenging task of bridge management. SIIMS is a searchable database that plays the role of the single source location for entering all the relevant features about road structure from its location to geometrical structural features, details about crossing of waterways, and data collected during field inspections. The main role of the bridge inventory and the inspection data is to enable the formulation of network-wide preservation and improvement policies for use in evaluating the needs of each bridge in a network. Using SIIMS allows IDOT to make consistent and cost-effective decisions for their bridge maintenance, rehabilitation, and replacement program, and makes recommendations for which projects to include in an agency's capital plan for deriving the maximum benefit from limited funds.

Iowa Statewide Floodplain Mapping (ISFM). Delineation of the flood maps is a key component of the flood hazard warning linking the streamflow forecast modeling with the flood damage assessment. This process is executed with models and customized Geographic Information Systems (GIS) tools. A new program for developing the flood mapping for Iowa was initiated in 2010 to replace the outdated maps in use for more than 30 years (IDNR, 2021). The new revision of the floodplain mapping is based on the statewide LIDAR data collection over Iowa and modeling work conducted by IFC for Iowa streams draining more than 1 sqm for a range of flow return periods (https://ifis.iowawis.org/newmaps). The modeling conducted by IFC entails execution of 1D models constructed around a profile baseline and cross section along the streams. The IFC inundation models were calibrated and validated using measured water surface profiles and high-water marks measured by IFC engineers, pro-vided by the community, or reported in USGS flood investigation studies (e.g., Linhart & Eash 2010). This level of detail is sufficient for addressing the requirements for Federal Emergency Management Agency's Flood Insurance Rate Maps (FIRMs) regulatory mapping and for supporting informed decision-making on managing floodplain areas. With additional funding the IFC developed maps for 2-, 5-, 10-, 25-, 50-, and 200-year floods. Completed in 2016, these maps are a critical resource to help citizens, emergency managers, and other community decision-makers identify and communicate Iowa's flood hazards (iowafloodcenter.org/projects/iowa-statewide-floodplain-mapping).

Currently, Iowa Department of Natural Resources has initiated a new revision of the statewide floodplain mapping program, labeled 2D Base Level Engineering (2D BLE), that includes risk analysis to better understand flood hazards, to more adequately rate flood insurance, and to improve planning for mitigation. The 2D BLE is not confined to the profile baseline and cross sections. It instead takes the whole surface into account. This modeling uses 2D rain-on-grid made possible by HEC-RAS 6.0 software, which relies on a user defined mesh and high-resolution terrain data to capture the flow of runoff through an entire watershed. By using newly acquired LIDAR data during the 2019-2021 period (IDNR, 2022).

Real-time Streamflow Forecasting provides the short-term prediction of the river streamflow and stages. Traditionally, the streamflow forecasts connected to BridgeWatch were released by the Advanced Hydrologic Prediction Service of the NOAA' National Weather Service (https://water.weather.gov/ahps) that predict river stages every 15 minutes at about 4,000 locations across the nation. For the state of Iowa, there is a complementary forecasting system developed by the IFC (Krajewski et al., 2017). The IFC fore-casting system makes hydrograph predictions for all streams in Iowa, but the IFC only outputs predictions for about 2,400 points on the river network. These include over 2,000 communities and other "points of interest," such as river crossings at major roads. These forecasts are outcomes of a complex multi-component modeling process whereby direct observations on precipitation and river levels at 549 real-time stream sensors available across the state are ingested in hydrologic models. Major components of the IFC's real-time flood forecasting system include rainfall and evapotrans-piration inputs and a rainfall–runoff distributed model with streamflow routing. The model is data intensive, but not calibrated. Streamflow predictions are communicated to the public via the Iowa Flood Information System (IFIS). The IFC researchers are continuously checking for forecast discrepancies and applying professional judgment to continuously improve the modeling results.

Real-time Stream Stage Sensor Network is key for nowcasting and is the primary data source for assimilation in the flood hazard forecasting models. This network tracks continuously water surface elevations in streams of various sizes with data recorded with high frequency (most often at every 15 minutes). The network entails USGS and IFC probes; the first type of sensors determines elevations with a submersed probe (e.g., bubbler system) located in a stilling well on the riverbank (Buchannan & Somers, 1996) while the second type measures the distance to the water free surface from the location of the probe installed on a bridge structure (Kruger et al., 2016). Both systems operate unattended for long time intervals irrespective of the season and communicate the recorded data to central servers that subsequently share them via the internet to users. The USGS stage network has been typically used to estimate discharges via a stage-discharge rating constructed with a large dataset of directly measured discharges paired with stages recorded at the same time. More recently, the IFC prototyped and subsequently developed synthetic rating curves for almost all the deployed IFC bridge sensors using the slope conveyance method and/or HEC-RAS model applied to a short reach in the vicinity of the probe (Quintero et al., 2021). The complementary USGS-IFC network of stream sensors is spread over 549 locations in Iowa's stream.

3. Data and Sample Analysis

This section delves into the core methodologies and findings of our study. Initially, we present the data, detailing the specific sites, historical flood events, and high-resolution imagery utilized in our analysis. Following this, we explore the process of manual data extraction, where we meticulously analyze the satellite imagery to determine the flood extents. Finally, we present our preliminary results, offering insights and interpretations from the data gathered and the manual extraction process.

3.1 Data

The success of an effective flood warning system fundamentally depends on the careful selection of study sites and the thorough gathering of relevant data. This section outlines the systematic approach adopted in our research to identify the suitable locations in Iowa for our flood warning framework. The criteria for site selection were comprehensive, with a focus on the presence of bridges, geographical diversity, historical flood data significance, and the presence of reliable sensor data in the area. The ensuing discussion details the rationale behind choosing each site and the strategic compilation of data resources, setting the stage for a comprehensive analysis of flood impacts and the development of a tailored flood warning system.

In our study, we initially identified three sites in Iowa, each equipped with a bridge and an upstream USGS sensor, vital for analyzing the impact of flood events. The first site is in the City of Fredericksburg, Chickasaw County, situated at latitude 42.97 and longitude -92.21, near a branch of the Wapsipinicon River. USGS stream gauge, 05421000, is used for this location. The second site, located in the City of Traer, Tama County, is characterized by its coordinates at latitude 42.20 and longitude -92.47. It is linked with USGS stream gauge, 05464220. The third site is in the vicinity of the City of Basset, Chickasaw County, situated at latitude 43.07 and longitude -92.55 on the Cedar River. The USGS stream gauge, 05458000, is used for flood information in the area. For a detailed breakdown of each site's geographical location, bridge specifics, USGS Sensor ID, and flood stage data, please refer to Table 1.

Table 1: Site Information for Flood Event Analysis

Site Name	Site Location	Location of Bridge (latitude, longitude)	USGS Sensor ID	Flood Stage (ft)
Site #1	Fredericksburg, Chickasaw County	(42.97, -92.21)	05421000	12
Site #2	City of Traer, Tama County	(42.20, -92.47)	05464220	12
Site #3	City of Basset, Chickasaw County	(43.07, -92.55)	05458000	10

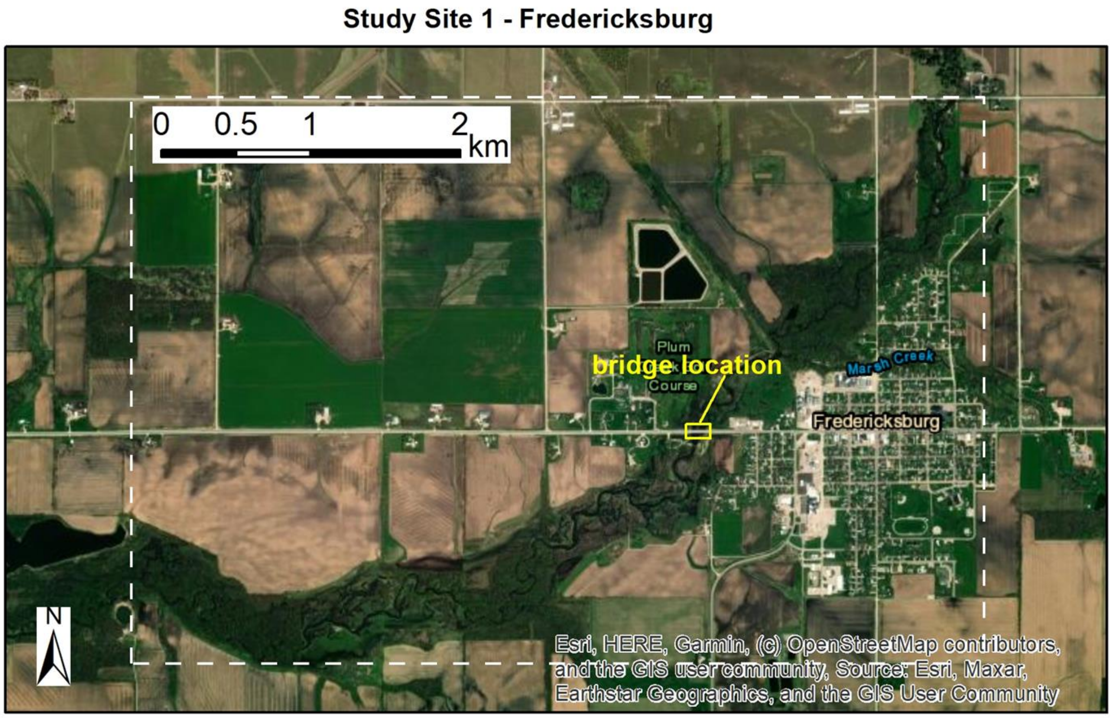
Our initial step involved pinpointing flooding times using data from these USGS sensors, accessed through the National Weather Service. This data provided the specific periods of interest necessary for our analysis. Following the retrieval of USGS sensor data, we identified a total of 22 flood events across the three sites. Specifically, for Site #1 in the City of Fredericksburg, Chickasaw County, we selected 9 distinct flood dates for analysis. Site #2, situated in the City of Traer, Tama County, had 7 notable events. And for Site 3, 6 flood events were identified as significant for our study. This comprehensive identification of flood events allowed us to focus our high-resolution imagery analysis on the most impactful instances of flooding at each site, ensuring a detailed and relevant study. For each site, specific details on the flood dates, measured flood stages, and the applicability of each event are provided in Table 2. This table offers a clear overview of the flood events considered in our analysis.

Table 2: Flood Event Data for Selected Sites

Site #1		
Event Date	**Stage (ft)**	**Acceptable**
08/31/2021	13.95	Yes
06/10/2020	12.01	Yes
03/15/2019	13.37	Yes
09/05/2018	16.86	Yes
07/23/2017	15.43	Yes
09/25/2016	19.29	Yes
05/29/2015	7.35	No
06/20/2014	13.21	Yes
05/31/2013	14.46	Yes
05/09/2012	6.84	No
03/02/2011	9.40	No
07/24/2010	18.77	Yes
Site #2		
03/09/2021	5.45	No
06/23/2020	17.11	Yes
03/15/2019	15.93	Yes
09/02/2018	12.70	Yes

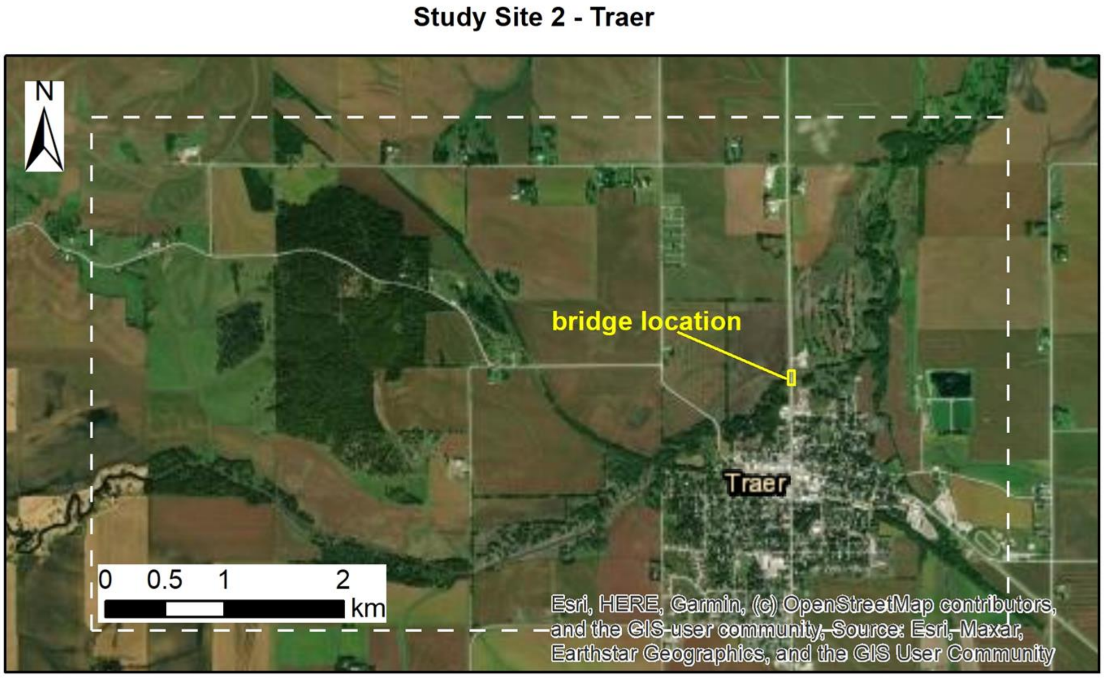
04/16/2017	6.04	No
01/20/2017	9.28	No
12/16/2015	10.69	No
06/21/2015	7.38	No
07/01/2014	14.13	Yes
05/27/2013	16.21	Yes
04/15/2012	5.83	No
02/18/2011	8.03	No
03/12/2010	12.34	Yes
Site #3		
07/22/2017	13.56	Yes
09/24/2016	13.96	Yes
08/25/2016	15.55	Yes
05/21/2013	18.41	Yes
03/24/2011	10.31	Yes
03/13/2010	13.16	Yes

Following date selection, we focused on acquiring high-resolution satellite imagery from PlanetScope, specifically targeting images from one week before and after the identified flood dates. This approach was designed to capture the full progression of each flood event. However, as we delved into the data, it became apparent that only two of these sites – Site #1 and Site #2 – had usable high-resolution imagery for a significant flood event each. More specifically, we selected the flood event on July 23, 2017, for Site #1, and the event on March 15, 2019, for Site #2, as only these instances had high-quality imagery available. This limitation in the availability of imagery data for all events at all sites led us to narrow our study's focus to these two locations. Figures 1 and 2 depict the geographical locations of the selected study sites, as well as the precise positions of the bridges within these areas.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 1. Study site of Fredericksburg, Iowa.



Esri, HERE, Garmin, (c) OpenStreetMap contributors, and the GIS user community, Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 2. Study site of Traer, Iowa.

The final stage in our site selection process involved integrating digital elevation models from the Iowa Flood Center. These models were crucial for our automatic flood map extraction, providing essential insights into the terrain of each site. The process of data collection and analysis ensured our study was grounded in accurate and comprehensive information available, forming a robust foundation for the development of an effective flood warning system.

3.2 Sample analysis on the reliability of flood mapping using HRSM

The assessment of road structure vulnerability to flooding is solely based on the outcomes of numerical simulations (streamflow modeling, flood frequency analysis, climate scenarios). The warnings are based on flood design graphs (e.g., 100-year flow or 1% annual exceedance-probability discharge -AEPD) that entail a mixture of historical data and climate projection data. The flood warnings are executed with models and customized Geographic Information Systems (GIS) tools in conjunction with the flood maps previously developed. It is found that while the IFC flood maps are superior to those produced across the country, their accuracy is adequate only for outreach, advisory, and display purposes not for actionable flood emergency warnings (Anderson et al., 2015). Flood relevant info from actual measurements at stage gage stations and from ground-based geo-referenced images of flood inundations can be helpful to verify and enhance the quality of the flood models but the costs associated with the data collection for an extended number of sites is prohibitive.

A more cost-efficient solution for testing the accuracy of the flood maps is the use of **High-resolution Satellite Maps (HRSM).** The most commonly used remote sensing imageries to map inundation areas include optical images and radar images (Li et al. 2022). While the latter refers to the Sentinel-1 SAR images in most previous studies, the former comes with a greater variety. Widely used open-access optical images include Sentinel-2, Landsat series, and MODIS. In addition, there are commercial optical remote sensing imagery providers (e.g., Planet, Quickbird, Ikonos, and Worldview) that can provide rapid, accurate, and large-scale images for flood mapping. In particular, PlanetScope images provided by Planet are acquired from multiple satellites (+150) to cover large areas with high-spatial resolution (e.g., 3 m) and high sampling rates (several times per day). The increased availability of satellite data in high spatial and temporal resolution provides new opportunities for operational use. Satellite remote sensing provides an explicit spatial-temporal framework for detecting flood extent, measuring flooding severity, and assessing flooding hazard and post-flood loss and recovery (Li et al., 2022). Satellite-based mapping of historical flood events can be efficiently used to investigate and improve the calculations for determining which areas close to the river are at risk from flooding. In the present research, we will use PlanetScope images (planet.com).

3.2.1 Manual Flood Map Extraction

In our research, we focused on manually extracting flood maps using high-resolution imagery exclusively from Planet.com. This manual process involved a detailed visual analysis of the imagery to identify and delineate the extent of flooding. Given the high spatial resolution of Planet's imagery, we could discern subtle variations and anomalies that indicate flooding, although challenges such as cloud cover and similar color patterns in the terrain occasionally required educated guesses to accurately map flood extents.

This manual approach complements automated flood mapping techniques, bringing a critical human element to the interpretation of satellite data. Despite being labor-intensive, it's invaluable in instances where automated algorithms may not fully capture the complexities of flood scenarios, especially in cloud-affected areas. By enhancing the precision of flood mapping through this method, we aim to provide more actionable insights for flood risk management and emergency response planning.

3.2.2 Evaluate Flood Inundation Extent with Reference Maps

The extracted maps will be compared with the 100-year flood inundation maps pixel by pixel. Since the reference map and the manual maps are vectors, we first rasterized those vectors using the scope and pixel resolution of the remote sensing images. We then adopted the following indexes to measure the similarity between the predicted flood extent maps and the reference map.

Accuracy is the ratio of correct pixels versus all pixels on the prediction map (i.e., the manual and automated map). It demonstrates the overall accuracy of the prediction map without distinguishing the prediction classes. Accuracy ranges in [0, 1] with 1 being the best possible value. It calculates as

$$Accuracy = \frac{TP+TN}{TP+FN+FP+TN}$$

TP, TN, FP, and FN are the number of correct flood pixels, correct dry pixels, incorrect flood pixels, and incorrect pixels, respectively.

Hit Rate (H), different from Accuracy, focuses on the positive (flood, in our case) predictions and measures the ratio of correct positive predictions versus all positive pixels in the reference map. Same as Accuracy, H also ranges in [0, 1] with 1 being the best value. H calculates as

$$H = \frac{TP}{TP + FN}$$

F1-score (F1) considers both precision (the accuracy of positive predictions) and recall (the completeness of positive predictions, also H in our case). It ranges in [0, 1] with 1 being the best value. F calculates as

$$F1 = \frac{2TP}{2TP + FP + FN}$$

Bias is the ratio of flood pixels on the prediction map versus flood pixels on the reference map. It shows whether the prediction is overestimated or underestimated in general (Li et al., 2022). Bias is a non-negative value with 1 indicating the overestimation and underestimation by the model are equal. As readers can tell, Bias, compared to other indexes introduced above, does not measure the goodness of the prediction but demonstrates the quantitative relationship between two types of incorrect predictions. Bias is calculated as

$$Bias = \frac{TP+FP}{TP+FN}$$

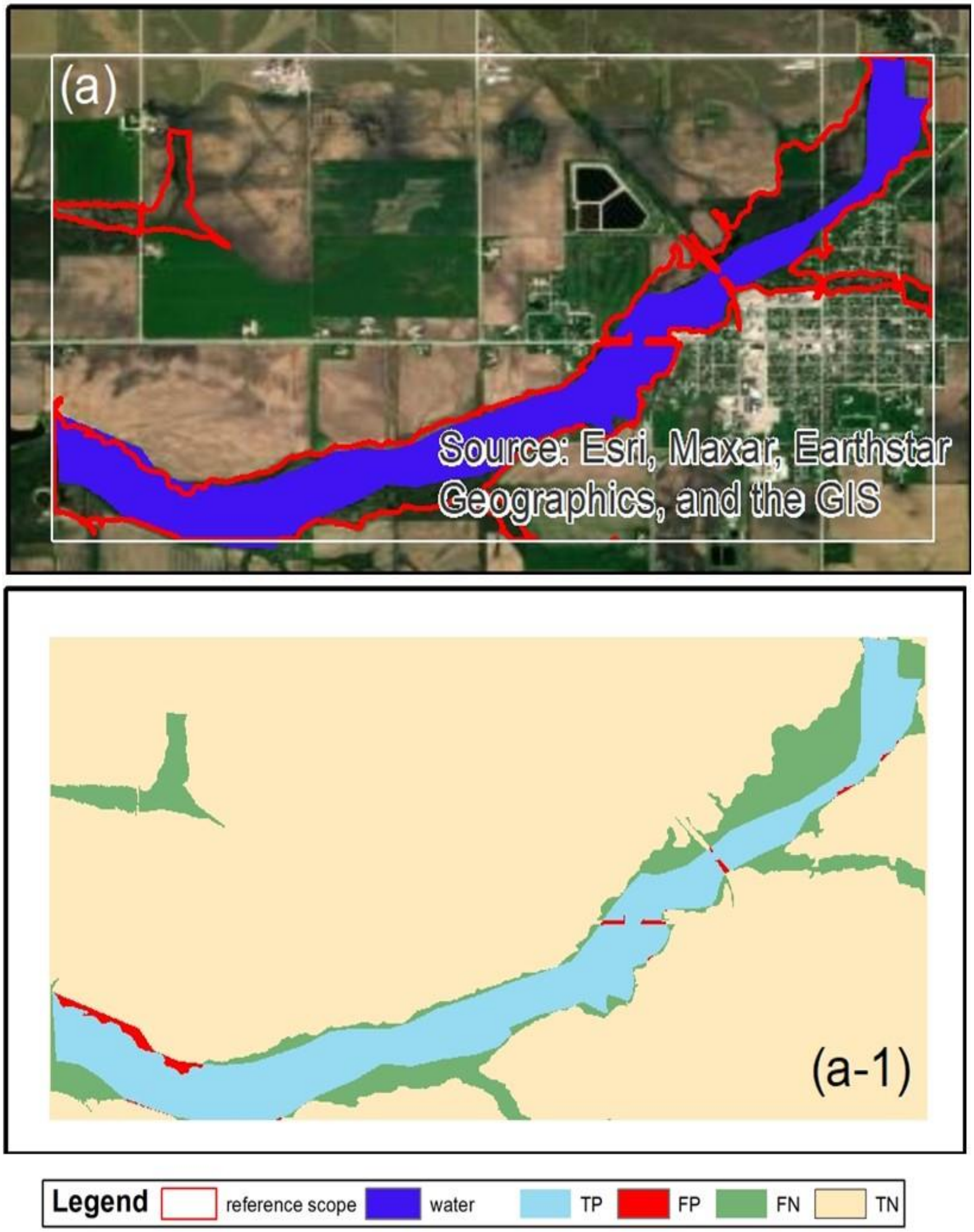
3.3 Preliminary Results on Comparison between Automated and Manual Flood Extraction

We conducted some pilot analyses to investigate the usefulness of automated flood extent extraction which corresponds to task b defined in section 4). Figures 3, 4, 5, 6 depict the manual and automated flood extent maps and the pixel-level evaluation against the reference in the two pilot sites.

As indicated in the previous sections, the closer the Accuracy, H, and F1 are to 1, the more satisfying the model's performance is. In addition, the closer the Bias is to 1, the more balanced the model is in terms of the amount of underestimation and overestimation. As shown by Figures 3 to 6, and Table 3, the automated flood maps are noticeably more consistent with the reference maps in both sites. Compared to manual delineations for which the scene is noticeably underestimated, the automated maps are more balanced in terms of over- and under-estimations as indicated by Bias. In addition, as manual delineation is quite time-consuming, the automated approach is more favorable. Table 3 lists quantitative evaluation of the manual and automated flood maps for the two study sites.

Table 3. The quantitative evaluation of the manual flood map and automated maps in Fredericksburg (F) and Traer (T).

	TP (count)	**FP (count)**	**FN (count)**	**TN (count)**	**Accuracy**	**H**	**F1**	**Bias**
F_manual	195,713	6,904	127,939	1,424,010	0.92	0.60	0.74	0.63
F_QFR	259,849	37,600	63,803	1,393,314	0.94	0.80	0.84	0.92
T_manual	626,403	5,925	202,505	1,880,887	0.92	0.76	0.86	0.76
T_QFR	800,054	180,337	28,854	1,706,475	0.92	0.97	0.88	1.18



Source: Esri, Maxar, Earthstar Geographics, and the GIS

Figure 3. Manual delineation of flood extent (a) and its evaluation against the reference (a-1) in Fredericksburg site.

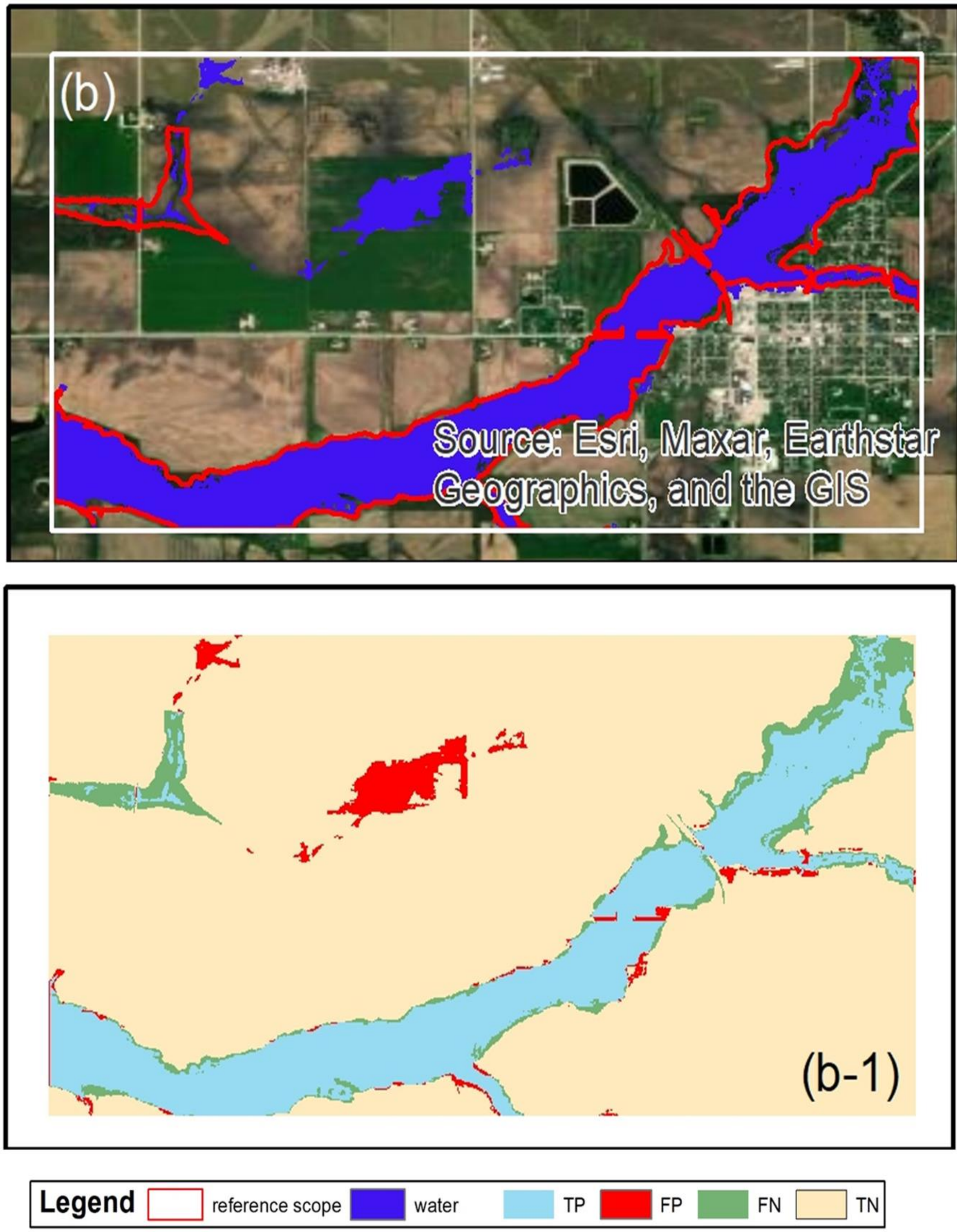
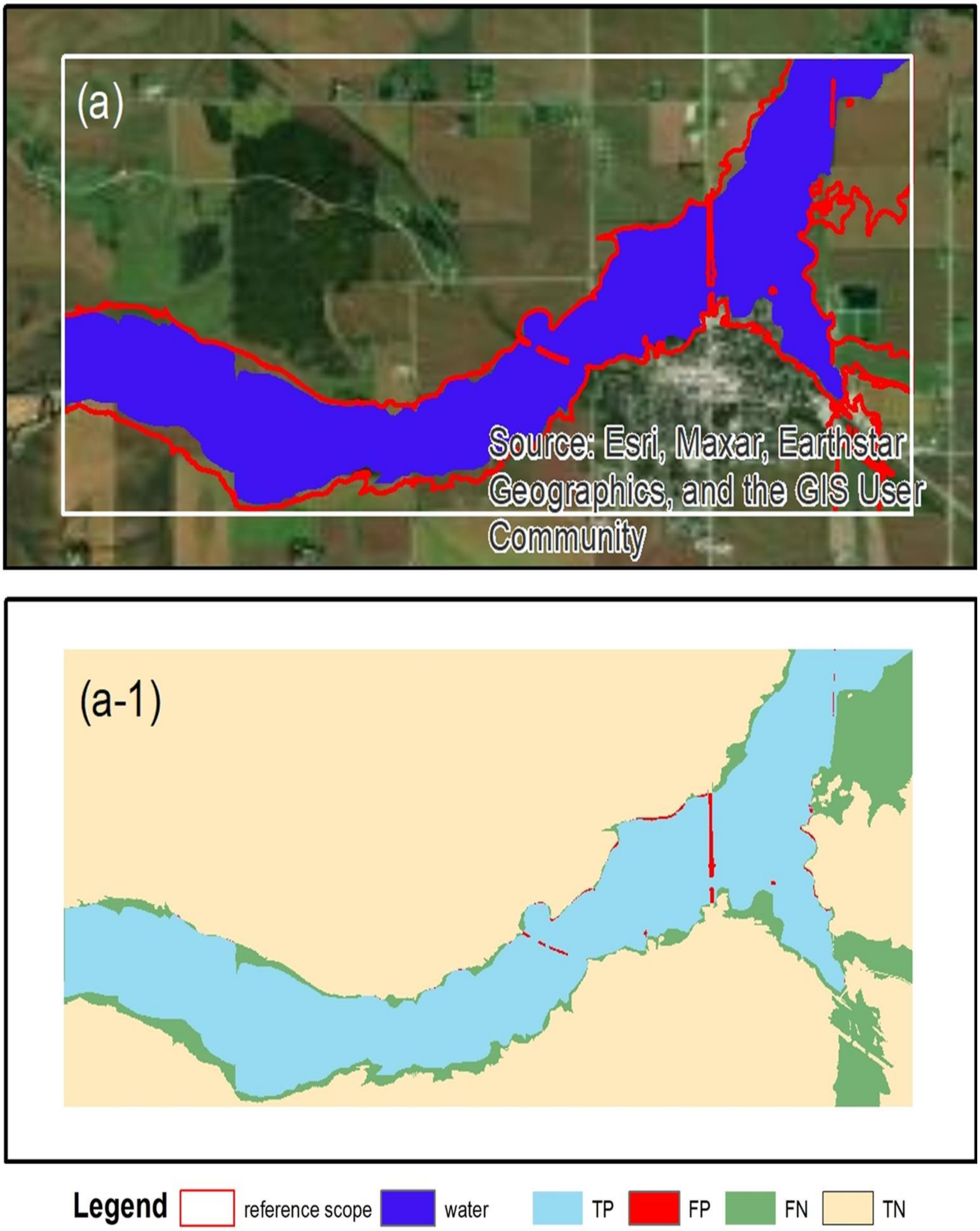
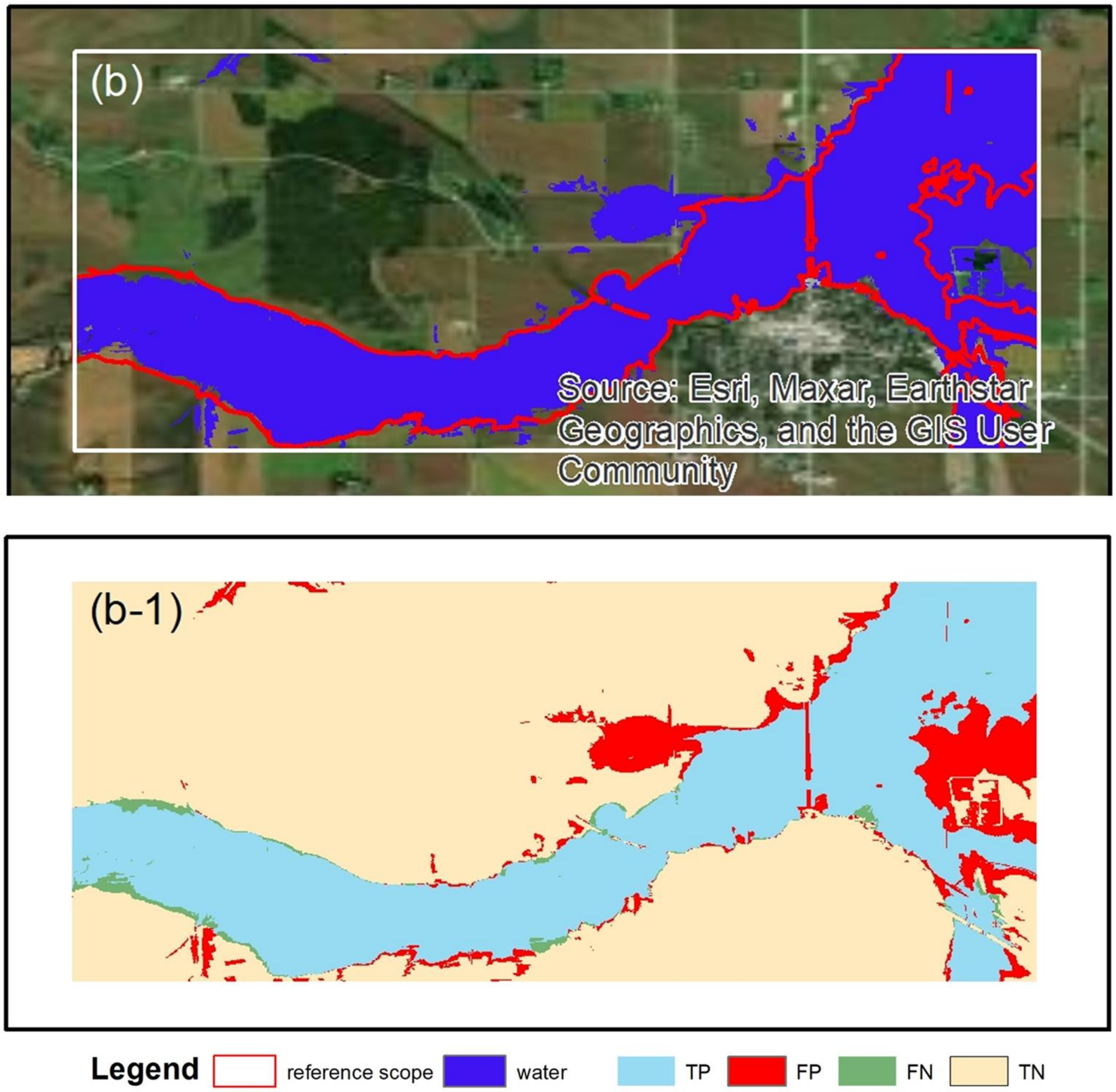


Figure 4. Automated flood map with the QFR postprocessing (b) and its evaluation against the reference (b-1) in Fredericksburg site.



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 5. Manual delineation of flood extent (a) and its evaluation against the reference (a-1) in Traer site.



Source: Esri, Maxar, Earthstar Geographics, and the GIS User Community

Figure 6. Automated flood map done with the QFR postprocessing (b) and its evaluation against the reference (b-1) in Traer site.

4. Extension of Iowa BridgeWatch Flood Warning Capabilities

In the previous section we illustrated the protocols for manually retrieving HRSM flood maps with the purpose of validating the model-derived inundation area for specific return periods. The HRSM-validated flood maps are subsequently linked to the flood hazard forecasts issued in real-time by the IFC for the entire state of Iowa to improve the quality of flood warnings issued by Iowa BridgeWatch at all 2,400+ forecasting points.

In this section we propose additional research to further extend the BridgeWatch system capabilities with information provided by HRSM. The impetus for the system's extension is motivated by the continuous increase of HRSM products in terms of the number of data providers, type of remote-sensing approaches assembled in the synthetic products, and, most importantly for the present context, the finer spatial-temporal granularity of the satellite-based maps. The first line of development is the automation of the map extraction for all the bridges located in flood-prone areas across the state of Iowa. The automated flood map extraction with HRSM in the two pilot sites shows great potential, as shown in Figures 4 and 6. More importantly, the automated approach has better scalability for large areas and can therefore be applied to the entire state with noticeably lower costs. As shown in Figures 7 and 8, flood hazard has been creating continuous economic losses and interrupted normal social activities over decades. Development of this new data-driven approach is not meant to replace the current workflow for the release of flood warnings embedded in the Iowa BridgeWatch. Instead, by making recourse to the HRSM-based flood maps, it is aimed at ground-truthing the flood mapping currently available from IFC-DNR with the purpose of continuously evaluating and enhancing their quality in areas where the comparisons are poor.

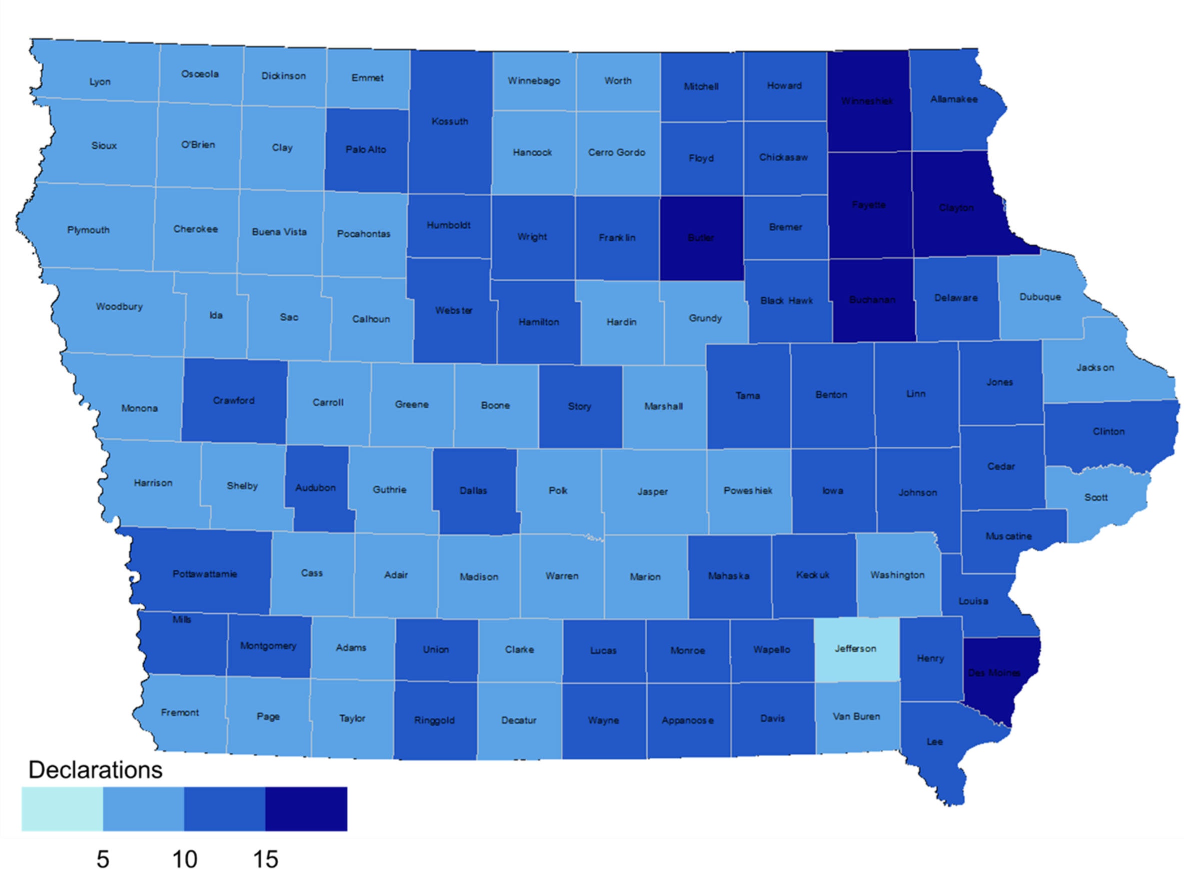


Figure 7. Flood-related presidential disaster declaration in Iowa by counties 1989-2020.

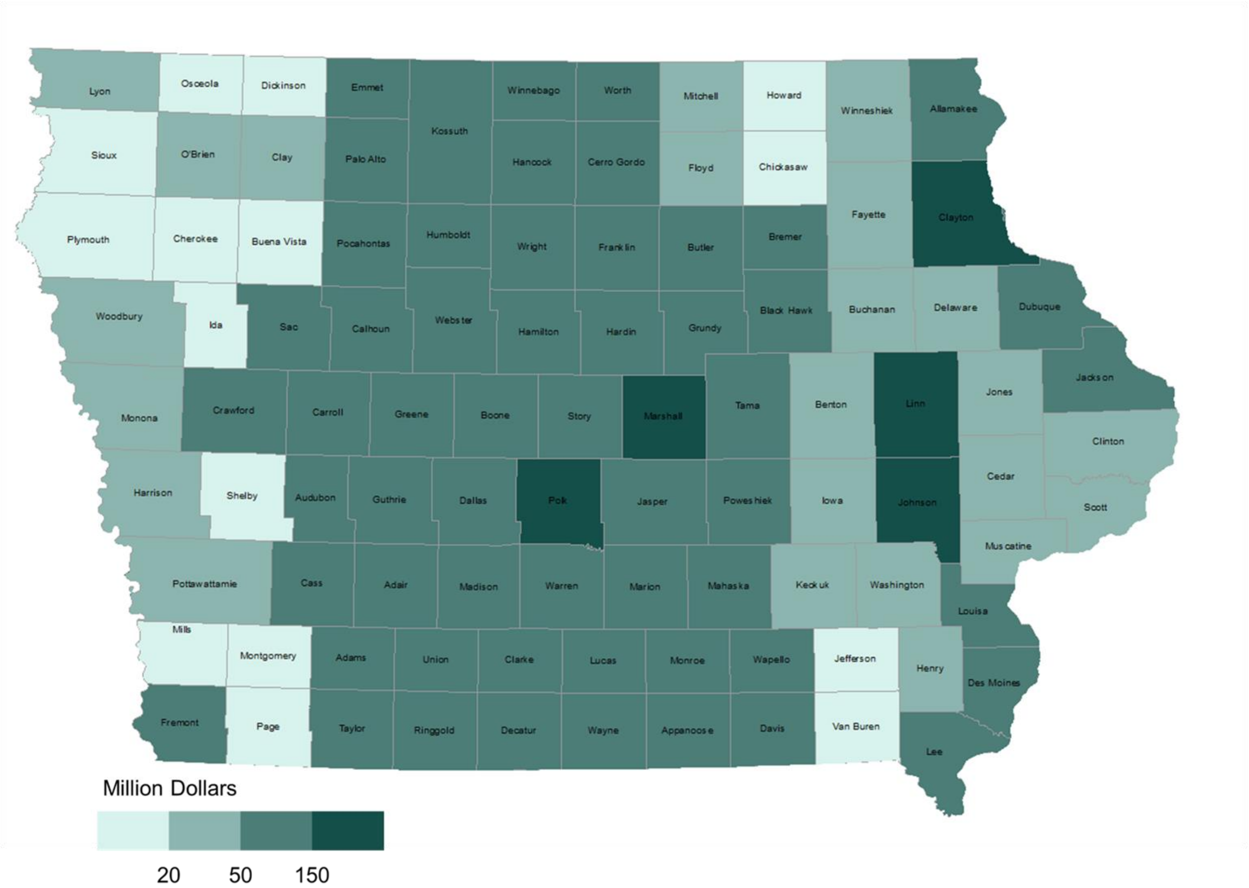


Figure 8. Flood-related economic losses in Iowa by counties 1989-2020.

The second line of research takes advantage of the increased availability and quality of the satellite images, to propose a new, data-driven approach supported by machine learning to attain a cost-efficient solution for stage forecasting at sites where there is no modeling for predicting streamflow. This line of research is suggested by some early proof-of-concept whereby flood forecasting models were developed using exclusively remote-sensed HRSM images and a few other open-source geo-spatial information layers (Li & Demir, 2024; Li et al., 2023). To attain this goal, we link the trends in the stage time series at the 549 real-time stream sensors available across Iowa with the spatial extent of the inundation area surrounding Iowa bridge structures located in flood-prone areas as determined from high-spatial resolution satellite imagery. A machine-learning algorithm will be designed and developed to relate the trends in stage time series preceding the flooding event with the extent of the HRSM flooding. The outcome of this research line is the capability to predict stages at bridge locations in flood-prone areas where we do not have streamflow forecasts (there are 23,834 bridges and only 2,400 have forecasting points from IFC). It is deemed that the implementation of this algorithm will provide data-driven forecasting at a significant number of bridges not currently covered by IFC streamflow forecasts.

The third line of research builds on the first two and on the outcomes of previously developed research for transportation projects (Alabbad et al., 2021; 2023; Mount et al., 2018) with the aim to expand the overall Iowa BridgeWatch functionality with new features currently not available in the system. Specifically, we aim at including in the Iowa BridgeWatch flood warning additional information on asset management in the bridge vicinity as well as the impacts on traffic disturbance in case of failure at a specific bridge along with the best routes for intervention at the damaged bridge and alternative routes to ensure traffic mobility in all directions.

To achieve these goals the new approach includes the following tasks:

a) identification of flood-prone areas that are critical for transportation network based on existing flood maps and survey of the data at stage sensors (IFC, US Geological Survey, and Bridge Watch) available in these areas

b) develop an automated process for extraction of the flooding extent using HRSM-based maps in the flood-prone areas identified across the state (item a) and compare them with IFC-DNR flood maps. The areas with large differences are proposed for flood remapping using conventional modeling. Some previous studies have proven the efficacy of a powerful post-processing technique called Quantile-based Filling & Refining (QFR) in improving the quality of flood extent maps derived from HRSM in areas with complex hydraulic and vegetation conditions (Li & Demir, 2023a). We employed a standard water body extraction workflow with Otsu thresholding and occupied the QFR procedure for enhanced performance to generate the automated flood extent map. Figure 9 is the workflow that includes the standard water extent extraction and the QFR post-processing.

c) develop a data-driven approach to link legacy time series of stages recorded at IFC bridge-mounted sensors or with stages in the drainage area leading to the bridge, where there are no stage sensors, with the stages indicated by the IFC flood mapping verified with HRSM. The surrogate data-driven approach will target stages that can be connected to various levels of structural vulnerability.

d) evaluation of the flood impact on the transportation infrastructure (i.e. bridges, roads, culverts) using a suite of data analytic products for food damage assessment (direct and indirect economic analysis) and disruptions (rerouting, evacuation, accessing amenities, etc.). (Alabbad et al., 2021; Duran et al., 2023)

e) develop a decision-support system to identify and forecast potential risk levels at the transportation infrastructure and recommend priorities for management of resources during flooding (Alabbad et al., 2023)

f) develop intelligent communication tools to timely and widely disseminate the outputs from the system and actionable information to general public and transportation staff using voice recognition and artificial intelligence

Tasks a) and b) are meant to improve the accuracy of the current Iowa BridgeWatch flood warnings. Taks c) is aimed at providing stage forecasts at bridges that are not currently linked to Iowa BridgeWatch. Tasks d), e, and f) are meant to expand the functionality of Iowa BridgeWatch with new features that empower flood-defense agencies and the general public with actionable information that protect life and property at bridges with or without stage sensors.

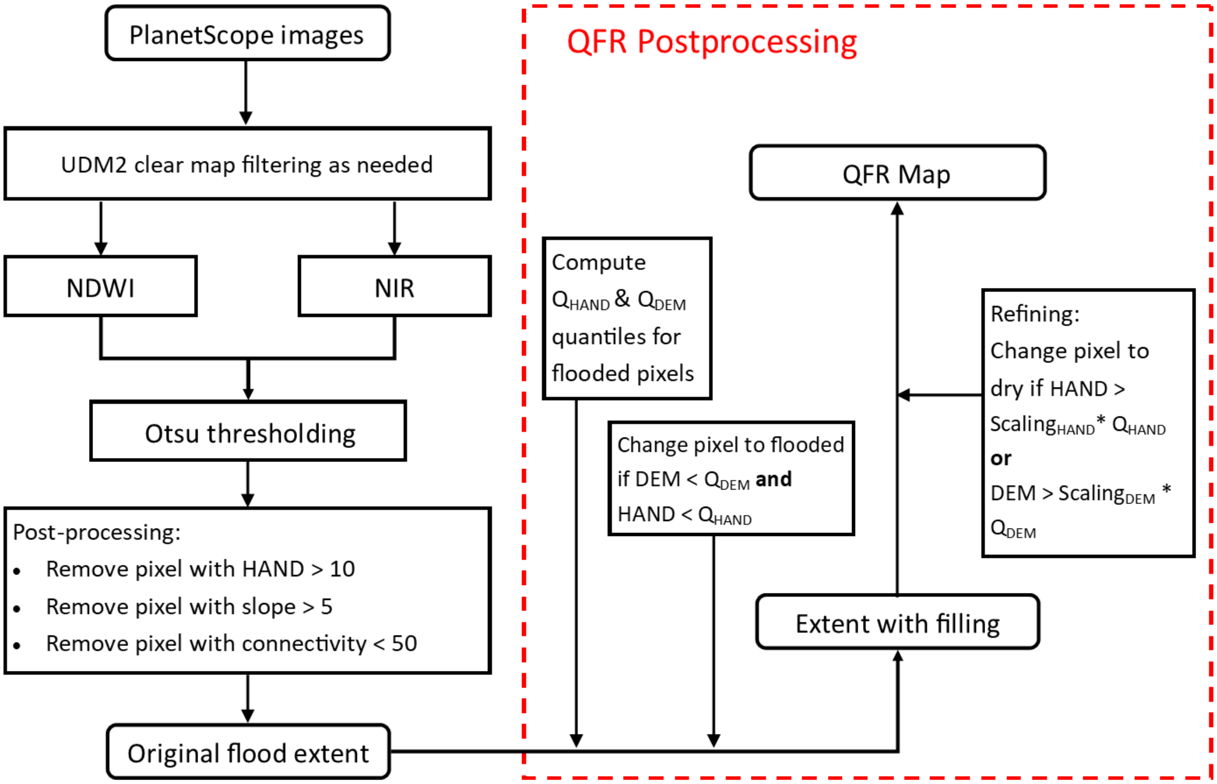


Figure 9. The flood inundation mapping workflow including the QFR postprocessing adopted to generate automated flood maps.

For accomplishing tasks, a) and b) above, the proposed design uses all the components currently linked to Iowa BridgeWatch to formulate flood warnings (see Section 2). These components complemented by the automatic flood map extraction from HRSM are assembled in an external workflow conceptually sketched in Figure 10. In essence, maps available in the Iowa Statewide Floodplain Mapping will be compared against the High-resolution Satellite Maps to check for their feasibility to issue flood warnings sufficiently accurate for bridge protection. Following the initial comparisons, we will make inferences on the existing flood mapping accuracies and propose correction methods if needed. The extent of the ground-truthed floodplain maps will be geographically assigned to flood-prone bridge locations with and without stage-discharge ratings for a set of return flows (i.e., 2-year, 5-year, etc.). The ground-truthed flood maps are used in conjunction with the IFC streamflow forecasting system to assign the predicted levels with actual water elevations on the bridge structure to evaluate the severity of the threat for the structure.

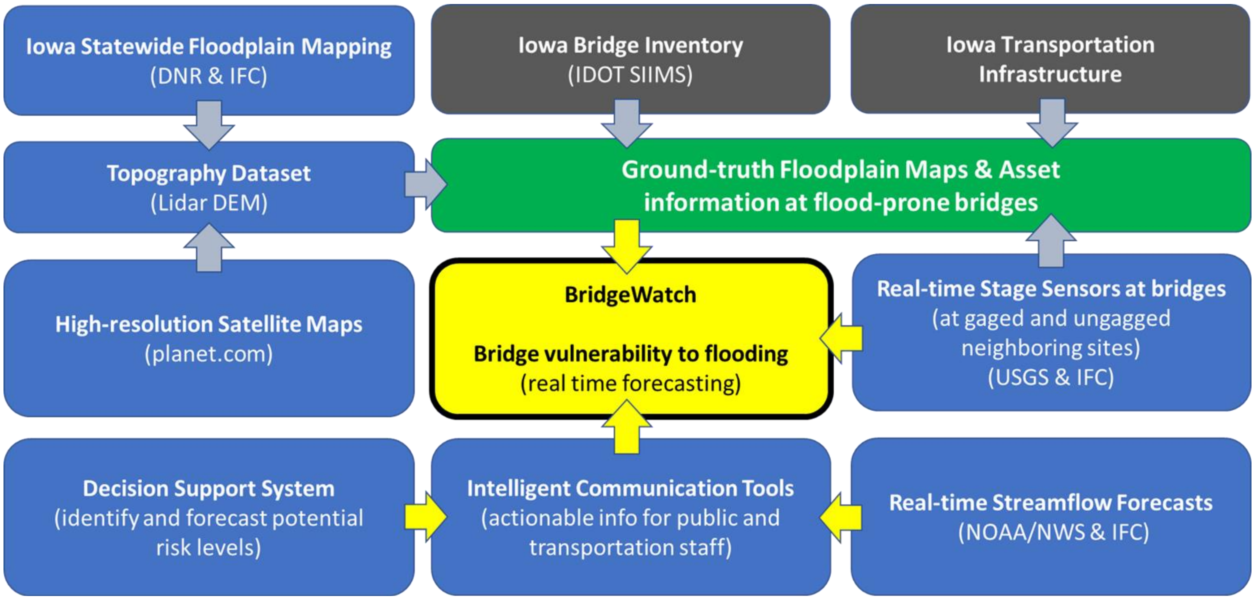


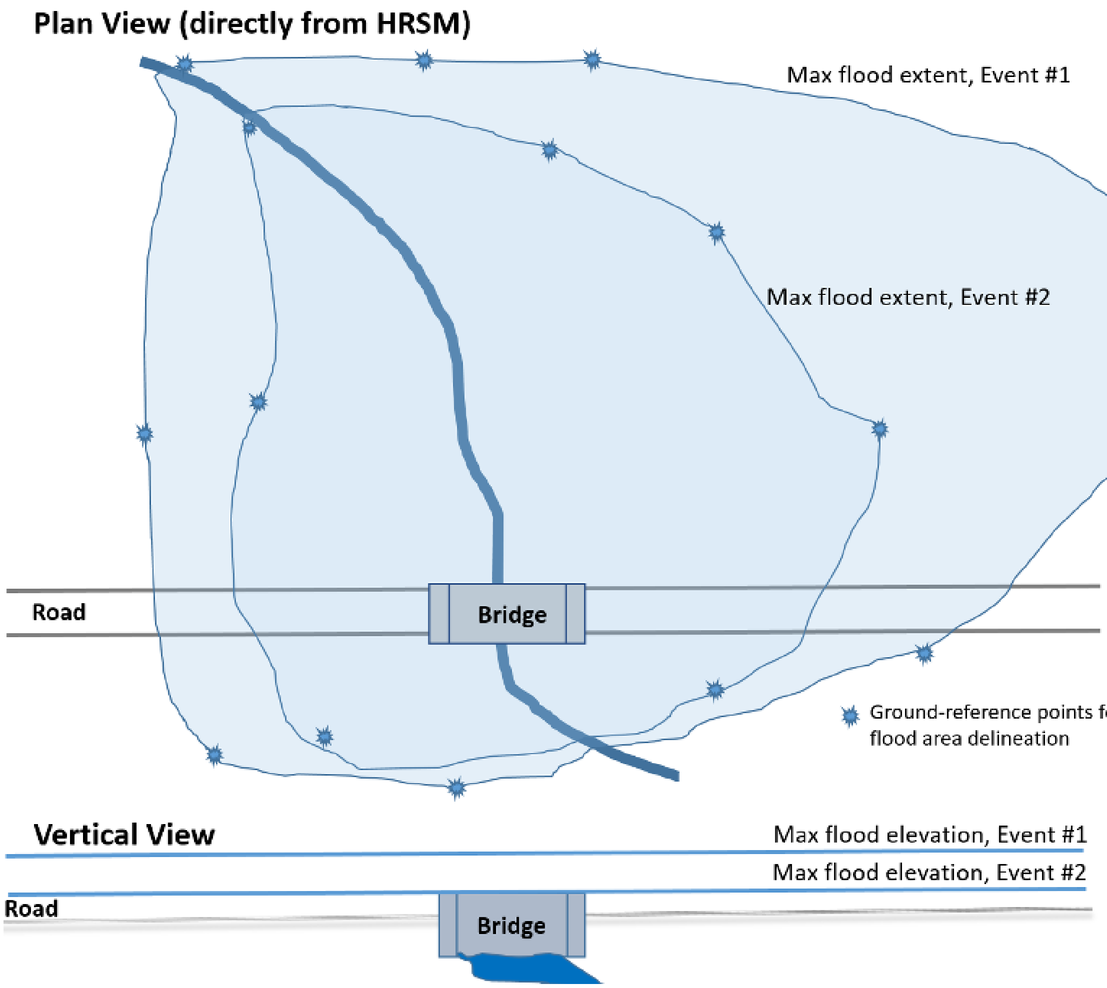
Figure 10. Components and workflows to be linked to the Iowa BridgeWatch system

For accomplishing task c) we rely on the hydrologic inference algorithm illustrated in Table 4. The data-driven approach used for this purpose emulates the flow routing schema executed by hydrologic models that in essence track the water movement through the channel network. The data driven approach is not actually calculating water movement, but it is instead focused on “routing” the stages in the stream network sensors in the drainage areas leading to the bridges, regardless if it is equipped with a gauge sensor or not. This approach does not account for discharge calculations being exclusively focused on determining data-driven multivariate correlations of previous time series of stream stages recorded at IFC and USGS located upstream from a specific bridge site. For enhancement of the algorithm robustness, a downstream gauge can be included in the multivariate relationship. The underlying hypothesis of the data-driven approach is that the possibility of obtaining prediction of the stage at a specific bridge is sufficient for flood warning purposes as the stage is the primary stressor for the road infrastructure. The multivariate relationships will be developed for a series of events (possibly linked to various return flows) to create stage-discharge rating curves at each bridge (Teng et al, 2017). In short, this task will produce vulnerability ratings at bridges that relate stage variation at the bridge location with various levels of structural vulnerability by.

Table 4. Proposed research tasks

<table>
<tr><th>Task</th><th>Task Details</th></tr>
<tr><td colspan="2">Task #1: Extract flood maps from High-Resolution Satellite Maps (HRSM)</td></tr>
<tr><td colspan="2">Role: Determine the extent of the inundated area and its elevation from the bridge and road infrastructure and from the ground up using the sequence of High-Resolution Satellite Maps (HRSM) recordings leading to a flood peak

Data needed:
● HRSM time series acquired during flood events at the location of interest

Protocols:
● Use automated tools to determine the maximum extent of the flooding from the sequence of HRSMs (use both high- and lower-resolution images)
● Time stamp each flood max extent
● Formulate warning levels for the structure vulnerability to floods (either using construction details or flood design as criteria)</td></tr>
<tr><td colspan="2">
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Task #2: Compare HRSM with Iowa Statewide Floodplain Mapping flood maps

Role: to establish the degree of accuracy of the modeled maps vs, ground truth information

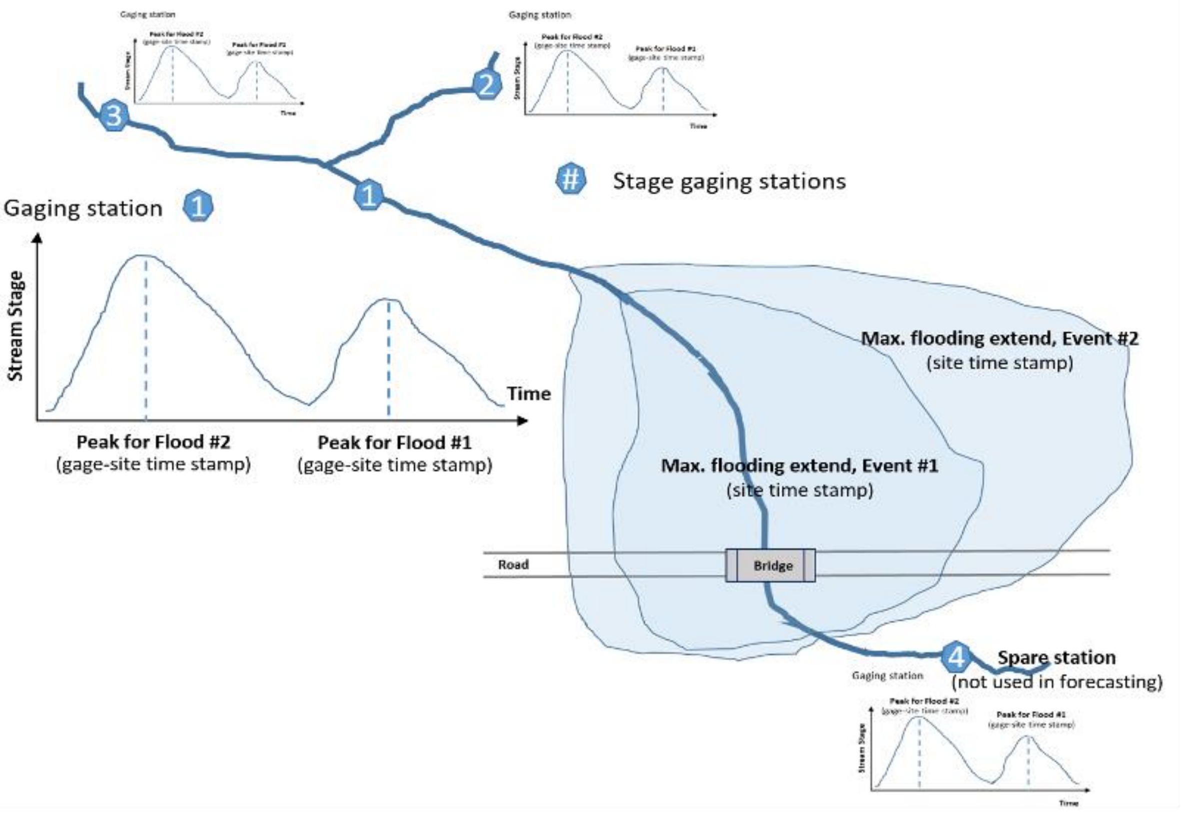
Data needed:
- IDNR Floodplain maps
- LIDAR DEM

Task #3: Assemble hydrological info at ungagged bridges using data available at stage sensors in the vicinity of the bridge (preference of upstream sensors).

Role: Relate stream stage hydrographs with max flood elevations at the bridge site using the Maximum Flood Extent (MFE) determined from HRSM images

Data needed:
- Information on flood map elevations from Task #1
- Time series of gage recordings from neighboring USGS or IFC sensors

Protocols:
- The analysis is conducted only for peaks on the stage hydrographs.
- Sensors should be located immediately upstream from the bridge. The best gage candidates are those on the same stream reach with the bridge without tributaries entering the reach (e.g., station 1 rather than stations 2, 3)

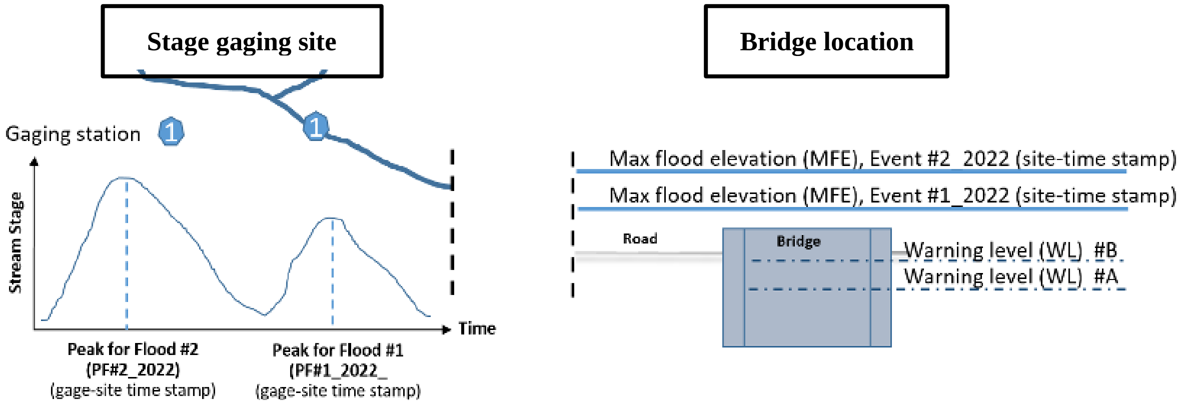


Task #4: Relate the peaks of the stage hydrographs at neighboring stage gages and the associated maximum flood elevations at the bridge & road infrastructure. Include information about timing of the peaks and other assets in the bridge vicinity.

Role: preparation of the ratings for peak elevations, timing of the peaks, and extent of the flooded area at the bridge location as functions of neighboring gaging station records. The ratings allow to relate the forecasted levels with the stage at the bridge location.

Data needed:

- Road and structure design info & other assets



Task #5: Develop vulnerability ratings for the bridge and road infrastructure using information currently available in BridgeWatch (for bridges and roads).

Role: connect the warning levels at the road structure with the associated stage gaging station to develop:

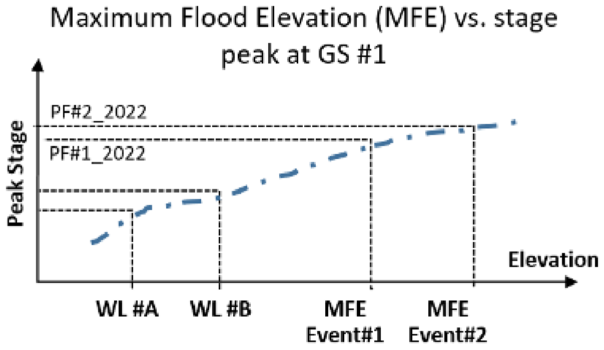
a) Maximum Flood Elevation vs. corresponding stage peak in the stage-gaging station for critical floods

b) Time lag between time of occurrence of the stage hydrographs peak and the occurrence of the maximum flooding elevation at the bridge structure for critical floods

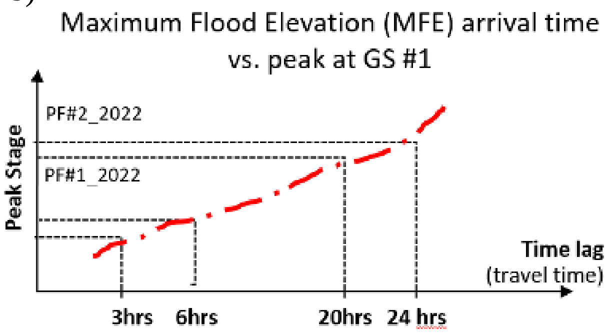
c) The extent of the flooded area in the vicinity of the bridge (as a Shape file) and the corresponding peak in the stage-gaging station time series.

Ratings a), b), and c) can be developed for multiple stage-gaging stations in the vicinity of the flooded area.

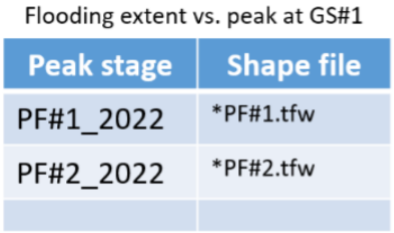
a)



b)



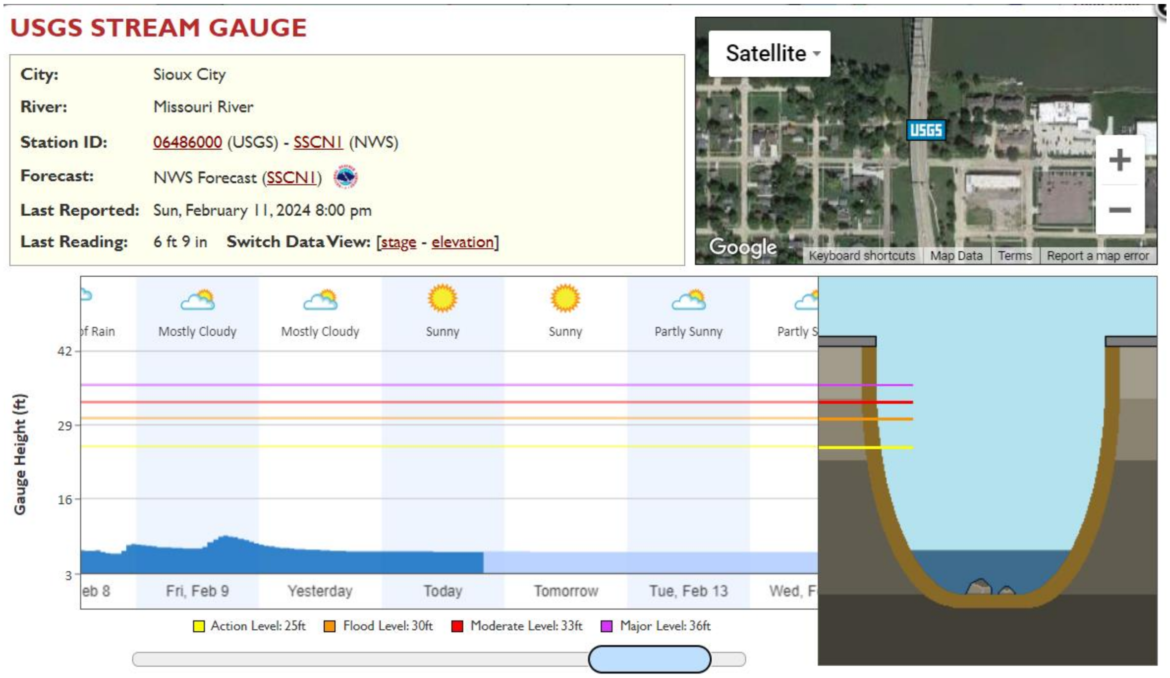
c)


Flooding extent vs. peak at GS#1

Peak stage	Shape file
PF#1_2022	*PF#1.tfw
PF#2_2022	*PF#2.tfw

Task #6: Using information assembled in Task #4 and streamflow forecasts available in IFIS, the warnings on the vulnerability of bridge and road structures to flooding can be continuously produced in real-time at 500+ locations in Iowa.

Visualization interfaces currently available in IFIS will be customized with warning levels established in Task #4. Warning levels above overtopping are based on HRSMs. Warning levels below overtopping are established by IDOT engineers commensurate with the level of threat posed by river stage at the bridge location for the stability and integrity of the bridge structure or road infrastructure flooding. The streamflow forecasting is provided in IFIS for 500+ USGS and IFC bridge sensors using a 5-day lead time. Also available will be the travel time of the peaks from the stage sensor to bridge location and the extent of the flooding in the vicinity of the bridge. The latter information is based purely on ground-truth data without making recourse to modeling. The lead time for these forecasts are determined by the distance between the bridge location and the closest upstream gaging station.



USGS STREAM GAUGE

City: Sioux City
River: Missouri River
Station ID: 06486000 (USGS) - SSCN1 (NWS)
Forecast: NWS Forecast (SSCN1)
Last Reported: Sun, February 11, 2024 8:00 pm
Last Reading: 6 ft 9 in **Switch Data View:** [stage - elevation]

5. Conclusion

In today’s data-rich environment, the integration of high spatial resolution imagery with flood inundation modeling allows robust and temporally consistent flood propagation simulations of superior quality. Use of High-Resolution Satellite Maps and distributed networks of high density, such as is the case for the statewide stream stage sensor network, is the best alternative to ground-truthing the numerical simulations that are typically affected by multiple sources of uncertainties. In addition, the BridgeWatch platform can potentially ingest more remote sensing products (including land cover datasets, civil and socio-economic infrastructure), along with social media data to further enhance geographical and situational awareness for command and control for flood detection and subsequent hazard assessment. Adequately combining data from both radar and optical systems and other “Big Data” systems is of great potential in future flood assessment.

The initial results from the two pilot sites demonstrate that both manual and automated flood inundation maps have satisfying consistency with reference maps. The automatically extracted flood maps, compared to the manual ones, have the advantage of being more scalable and more robust against systematic errors that may exist in manual maps, such as the tendency of over- or under-estimation.

The immediate practical benefit of the research carried out so far combined with the new additions to the BridgeWatch platform prescribed in the second part of the study can better inform decision makers on the:

- Added value of the HRSM usability for flood mitigation
- Quality of the currently used inundation maps obtained with numerical simulations.
- The potential of the IFC bridge sensor network to serve both monitoring and forecasting functions using data-driven approaches.
- new means for informing decision-makers on the potential risk levels for accessing, intervening, and securing the fluency of the traffic for the management of resources during flooding in the vicinity.

A possible next phase of the initiated research on predicting flood extension from integrated hydrologic-hydraulic modeling and remote sensing might lead to more beneficial insights into how to improve the BridgeWatch platform. It is envisioned that such a new research phase will entail working closely together with TAC and partners at IDOT as they possess the more specific knowledge for interpreting and evaluating performance, functionality, and usability of BridgeWatch. We believe that the results of this first exploratory study and of the new study extension will place IDOT in a leading position in the nation by demonstrating with science-sound evidence that there are solutions for a road structure problem that was for a long time neglected because of its complexity.

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