Report R1A: Summary of Key Points for the Final Report

Project 0-7095 Evaluate Improved Streamflow Measurement at TxDOT Bridges

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Introduction

This project is entering is final phase and will be completed in August 2023. This report R1A is the first of two reports summarizing the project, the second one being Report R1B due on August 31, 2023. Report R1B will be the main final report on the project and summarize the technical content behind the project's accomplishments, findings and recommendations. The purpose of this report R1A is to make a summary of key points for inclusion in report R1B, focusing on the accomplishments, findings and recommendations from the research. The intent is that this can be done in a sufficiently succinct form that it can easily be read and understood by the project team and by TxDOT staff, so as to make adjustments in the direction and content of the final report.

The main mechanism by which the project has kept TxDOT staff updated about the project's progress during the work period has been a series of Quarterly Reviews, held each three months for two hours at a time, and typically attended by about 40 people. Detailed meeting minutes of these reviews have been prepared which capture the substance of the discussion at each review as well as summarizing the slides. The presentations at the ten Quarterly Reviews held to date comprise a total of 638 slides, which can be seen at:
https://www.caee.utexas.edu/prof/maidment/StreamflowII/QuarterlyReview/QuarterlyReview.htm

The main accomplishments, findings and recommendations of the project are summarized under five headings:

1. **Streamflow Measurement** – building and operating the RQ-30 stream gauge network
2. **Roads and Bridges** – geospatial representation of the Texas road and bridge system
3. **Forecast System** – the KISTERS Datasphere, the real-time numerical data hub of the project
4. **Uncertainty Assessment** – forecast error and data assimilation to produce improved forecasts
5. **Response Exercises** – large scale table top exercises with TxDOT Maintenance staff

For each of these six topics, a sequence of accomplishments, findings and recommendations are presented, defined as follows:

Accomplishments – what we have achieved in terms of products or processes developed;

Findings – what have we learned that we didn't know when we started the project;

Recommendations – what do we recommend for additional steps to be taken in the future.

Streamflow Measurement

Accomplishments for Streamflow Measurement:

- Identified gauge sites that met TxDOT needs and Streamflow gauge installation criteria (matching data needs with locations where the equipment could work).
    - This produced a better idea of where these sensors work and do not work, and better ideas of where to site such instruments.
- Successfully installed 80 RQ-30 real-time reporting velocity streamflow gauges
    - Surveying cross sectional areas
    - Differential levels
    - Bring navd88 datum to the site
    - Identifying low chord elevations
    - Preliminary uncalibrated discharges (computed from day 1 of the installation at most sites).
    - Coordinated and streamlined installation efforts, sometimes installing 8 gauges in a single week.
    - 3 supplemental camera systems installed.
- Established a redundant telemetry system with KISTERS NA to deliver timely stage data.
- Made 202 discrete discharge measurements to calibrate and verify RQ-30 velocimetry discharges.
- Made 853 field visits to ensure equipment reliability and stage accuracy.
- Started developing processes for externalizing the computation of discharge outside of the Q-commander software.
- Conducted a pilot study for different types of measurement methods to determine discharge using recorded velocity values.
- Identified the usefulness of velocity data for backwater affected and tidally influenced streams.
- Established the largest USGS cell phone data network in Texas.
- Targeted approach to gauge calibration established and used as a best practice in national USGS velocimetry training.

Findings for Streamflow Measurement:

- Recorded stage-height at the gauge sites has minimal drift over time.

    - Stage values from all the RQ-30 radar gauges were left uncalibrated through the project and have stayed within 0.05 feet accuracy.
- Low surface velocities cause the RQ-30 to be less reliable for discharge determination when the velocity drops below 1 ft/sec and in particular when it falls below 0.7 ft/sec. This makes the gauge less useful for recording low flows (not a priority for this flood data project).
- Large river systems may require multiple velocimetry sensors to determine reliable discharge.
    - Wind spikes over large areas can cause erratic velocities resulting in inaccurate discharge values.
- Targeted gauge calibration method
    - Measurements at specific geometries of the channel can calibrate the RQ-30 faster than traditional stage-discharge rating development.
- Most stream cross sections at high flow stayed stable through the project.
    - Channel construction was the main contributor to channel cross sectional changes.

Recommendations for Streamflow Measurement:

- Evaluate longer intervals between site visits for stage verification.
- Continue to evaluate the targeted approach to verify discharge calibration accuracy over time by making measurements periodically.
- Combine physical discharge measurements with modeling to estimate a total discharge at sites for flood forecasting and road inundation.
- Continue efforts to externalize processes for the computation of discharge using recorded velocity data.

Bridges and Roads

This section is divided into two parts, this first section dealing with bridges and the following section with roads.

Accomplishments for Bridges:

1. **Flood Inundation Libraries –** Delivered three flood inundation libraries created from 2-dimensional hydraulic models at RQ-30 gauge installations. This included the development of a 'quasi steady-state' synthetic rating curve at the gauge location. These models were delivered to the USGS and integrated into the Interagency Flood Risk Management (InFRM) Flood Decision Support Toolbox (FDST).

2. **Bridge Extraction** – Developed a methodology for determining simplified characterization of each bridge's geometry. TX-bridge (pronounced as "Texas Bridge") is a software repository designed to extract and derive geospatial bridge hulls and envelopes of bridges from publicly available LiDAR points classified as 'bridge'. TX-bridge uses programmatic geospatial tools to create a data inventory of bridge information that can be paired with real-time and predictive stream flow modeling to provide warnings regarding the impact of flooding on gauged and un-gauged bridge structures. Specifically, it was built to conflate bridges to the National Water Center's National Water Model (NWM) hydrofabric.

3. **Bridge Taxonomy** – Created a schema for the description of each bridge found in the bulk LiDAR collection search. This includes:
    a. spatial geometric limits
    b. description elements – stream name, road name, etc.
    c. elevation – cross sectional profile data of the bridge.
    d. quality assurance metrics - measures that define how closely a computed bridge characteristic matches a known value

4. **Bridge Warning Service** - Currently it is not financially feasible to install a stream gauge on every bridge that crosses a National Water Model (NWM) stream. However, with contiguous classified LiDAR coverage within the state it is possible to extract a 'bridge envelope' at each of these bridges. The National Water Center computes and broadcasts the current and predicted flow rates for over 100,000 stream segments within the State of Texas. If a bridge crosses one of these streams, it is possible to extrapolate the current and predictive water surface on each of these bridge envelopes. Delivering the bridge extracted data in compliance with the defined bridge's data schema, a continuously operational flood warning service was 'stood-up' on KISTERS servers for about 600 bridges in TxDOT's Austin District.

Findings for Bridges:

1. **National Bridge Inventory** – The U.S Department of Transportation's Federal Highway Administration (FHWA) requires that TxDOT comply with their requirements providing inspection data for bridges throughout the state every two years. These data are aggregated into a National Bridge Inventory (NBI) layer. The data specifications (both spatial and attributes) for collecting the NBI data in compliance with FHWA are likely not sufficient for TxDOT's management of its bridge assets. A bulk overhaul of TxDOTs bridge data system may allow for the semi-automated creation of a better attributed bridge inventory dataset. Additional detail is contained in the TxDOT AssetWise system.

2. **Flood Inundation Mapping with Missing Bridges** – Most flood inundation mapping libraries currently being produced from 'bare-earth' terrain models have the bridge deck data removed. When using these inundation libraries, a 'false positive' occurs that indicates that the road with the bridge is being flooded. To solve this problem, there should be a modeling surface and a mapping surface.
    a. Modeling Surface – the hydro-enforced terrain model where it is ensured that water flows downstream. Typically bridges and culverts are removed. This is typically the surface used with the creation of flood inundation limits from the National Weather Service's "height above nearest drainage" (HAND) methodology and the Federal Emergency Management Agency's Base Level Engineering (BLE) models.
    b. Mapping Surface - Adding the bridge deck data back into the flood inundation surfaces would better indicate when a bridge was subject to flooding.

3. **Graphical Dissemination of Flood Data** – The challenge with reporting real-time and predictive flood warning data on a transportation system is to provide locally meaningful results over a large spatial area. Hydrologic engines (such as the National Water Model) determine hydrographs that report flood flow rates as a function of time. We learned that emergency management personnel do noy find these hydrographs very helpful during a crisis. Rather,

TxDOT staff expressed interest in providing contextual information that related flooded elevation and depth relative to their managed infrastructure. Conveying the information concisely in a graphical method is necessary.

4. **2-Dimensional Rating Curves** – Flood depth and limit predictions are based on a 1-dimensional rating curve that establishes a discharge as a function of flood depth. The base assumption is that the flow rate is constant and steady. Flood depths and prediction limits are based on this steady flow rating curve. The RQ-30 gauges can measure velocity (and by association acceleration) of the water flow at any point in time. It is possible that a flow rate can be determined from both depth and acceleration, therefore, creating a 2-Dimesnional flow estimate.

Recommendations for Bridges:

1. **Bridge Data Extraction** – Develop a methodology to extract all bridge data across the entire State of Texas. This includes creating the data in compliance with the prescribed schema and coordinating with TxDOT GIS staff to develop a more robust bridge database as compared to the current NBI requirements.

2. **Bridge Warning Service** – Expand the real-time and forecasted bridge flood warning service across the State of Texas. This includes an 18-hour 'look ahead' of the prediction. This may be a geospatial point service with a cross section and predictive stage vs. time graph rendered at ask.

3. **Healed Flood Inundation Maps** – Take the bridge deck digital elevation model (DEM) data that is programmatically extracted from the classified LiDAR with TX-Bridge and add it to the 'bare-earth' DEM to create a 'healed' terrain model. Use these composite surfaces for create a revised flood inundation map that better represents when the bridge are subject to overtopping flood inundation.

4. **Culverts and Low Water Crossings** – Leverage the TX-Bridge code to utilize LiDAR data to create point flooding predictions at culvert and low water crossings (expanding beyond the bridge extraction).

5. **Error Limits –** Determine a method to compute and display the limits of the assumed error in the flood depth at bridges for the current and forecasted times. This may include items such as the (1) hydrologic flow rate confidence, (2) assumption of a steady flow rating curve and (3) hydraulic modeling for the determination of the rating curve.

Accomplishments for Roads:

1. Workflows were developed for computing length and depth of flooded roads from several sources of flood inundation information including hydraulic simulations of historical floods, gauged streamflow and water levels, and forecasted streamflow. To visualize results in a map, a classification was adopted of linear road segments by depth range implemented in the FIMAN-T

system of the North Carolina Department of Transportation, where roads are color coded as follows:

- 0 to 0.5 feet of water depth, yellow
- 0.5 - 2 feet, orange
- 2 - 5 feet, red
- > 5 feet, purple

Maps of flooded roads using this color scheme were tested in exercises held with the Beaumont District and Austin District where the results were well received.

2. A prototype 2D dataset for the extent and centerlines road system of the Austin District was purchased for this project from the Ecopia company of Montreal, Canada. This is presently being converted to 3D by combining it with TNRIS LIDAR data. A successful result at the scale of individual roads has been obtained and will be further extended across the Austin District as during the remaining months of the project. The Ecopia dataset maps 38,000 miles of roads in the Austin District compared to 18,000 miles in the TxDOT Roadway Inventory. That is a substantial expansion of the knowledge of the road connectivity of Texas.

Findings for Roads:

Accurate portrayal of road flooding requires at least three high quality datasets:

1. **Road lines.** We found linework from the TxDOT Roadway Inventory to be horizontally inaccurate in places, which tends to result in an overprediction of road flooding, for example where the road line is offset and runs parallel to the road in the adjacent drainage ditch. The ditch, and the offending road line on top of it, may be flooded while the actual road may be fine.
2. **Elevation data.** We use digital elevation models (DEMs) and LiDAR to determine the elevations of 2-dimensional road lines in order to determine flood depth. We found that DEMs with 3-meter horizontal resolution are not precise enough, with local smoothing resulting in depression of road surfaces which are often elevated from the surrounding terrain. This results in an overprediction of road flooding. We suggest using a DEM with at least a 1-meter horizontal resolution, and we have demonstrated how to derive this DEM from LiDAR data available from TNRIS for the State.
3. **Flood inundation**. Flood mapping will be most accurate at locations where water level is measured with gauges. For other locations, we can use modeled streamflow estimates from the National Weather Service via their National Water Model (NWM) products. There is some uncertainty in the results of these models, and several NWM products are available as ensembles where each ensemble member represents one possible forecast outcome. We have demonstrated that forecast skill can be improved with data assimilation, which is described in another section of this report.

Recommendations for Roads

We must utilize a horizontally and vertically accurate representation of road lines to estimate road flooding. While we have explored ways of obtaining these road lines from commercial vendors such as

Ecopia or deriving road lines in-house via machine learning, either approach still requires extensive quality control and the assignment of pertinent attributes to each line such as road name. The Austin case study for the 2D/3D roads may be extended later across Texas.

While the color scheme for road flooding was well-received at district exercises, more collaboration with stakeholders is necessary to finalize the end products for road flooding, particularly with respects to these areas:

- **What temporal views are desired?** NWM includes several products, from near-real-time estimates of current streamflow conditions, to 15-hr, 10-day, and 30-day ensemble forecasts. There are thousands of possible ways these data could be temporally sliced. We need feedback from TxDOT on the most important slice(s) in order to provide actionable intelligence without information overload.
- **What summaries are desired?** To show summary tables, road lines need attributes for grouping, such as district, county, and some measure of road type or importance. Summary maps could also be produced which symbolize districts or maintenance sections by flooded road impact such as forecasted day-miles of flooding.
- **What level of detail is acceptable for forecasts?** The flooded road color scheme includes depth ranges as small as 0.5 feet, which may be beyond the precision supported by streamflow forecasts. A more reasonable approach for forecasts may be to show extent, but not depth, of road flooding.

Forecast System

Accomplishments

- Using the KISTERS Datasphere, cohesive integration of multiple data sources was achieved with a high level of automation. Both historic and live data pipelines were set up and commissioned in Datasphere. The ingested products include the majority of the water products provided by NOAA or its subsidiaries, the NWM reanalysis, and gauges owned and managed by LCRA and other river authorities.
- Data processing pipelines were built, and broadcasting bridge cross-section visualizations were made available to external software. The data was made available through REST API endpoints, a CLI application (datasphere-cli), and a web application (Datasphere), providing flexibility and covering basic and expert-level use cases.
- A Data Assimilation study was performed on the Llano River watershed using the 4DVAR method to prove the concept of estimating effective rainfall on the subcatchment areas above the most upstream gauge. This is a vast improvement over the nudging method, which is generally used, including in the National Water Model (NWM).

Findings

- Ingesting the water products provided by NOAA, USGS, or local river authorities requires continuous support and maintenance to keep all the data pipelines and ETLs operational. Datasphere's capabilities to ingest, process, and broadcast raster or scalar timeseries in a coherent and standardized format creates the foundation for building additional services. These services include data validation and alarming capabilities, data assimilation, and forecast adjustments.

- Data availability and quality might suffer during flood events, especially if the gauge is submerged. The Data Assimilation method has been prepared for these events. Automating model building based on the currently available and validated gauge data makes the data assimilation and forecasting products more robust, especially in critical timeframes during flood events.
- The lead time of the NWM products results in lag, which might delay response to the flood event. The data assimilation method implemented by KISTERS, using 4DVAR, significantly reduces lead time. Assuming that the gauges are online, the lead time can be reduced to 1-5 minutes, with results comparable or even better than the NWM in some cases.
- Since the result of the data assimilation is used to initialize flows in the catchment area, it opens up possibilities for forecasts using more advanced routing methods or multiple forecast ensembles.
- The double trapezoid cross-sections, which are used in the NWM as well, turned out to be a rough estimation of the channel's cross-section.
- Multiple data assimilation models can be built from the hydrofabric and assimilating streamflow gauges from multiple sources at a local (HUC8-HUC10) scale. This task can be fully automated.

Recommendations

- The background services built during Streamflow II Phase 1 lay the foundation to build and commission more advanced analytics and adjusted forecasts. Multiple smaller models and adjusted forecasts should be built and commissions on a HUC8-HUC10 scale.
- Multiple local models require the automated assessment of model performance. The model performance assessment metrics developed in Uncertainty Assessment should be run simultaneously with the operational data assimilation and adjusted forecasts. This would provide context to the forecast, helping decision-makers with information about the reliability of the forecasts.
- The data pipelines should be maintained continuously, for example, decommissioning the legacy USGS water data endpoint in the foreseeable future, which is based on the rdb format, could inadvertently break some existing services.

Uncertainty Assessment

This task focused on the evaluation of measurements and flood forecasting models. This analysis involves various spatial scales; from the gauge scale, at which measurements of stage and velocity are collected, to the river network scale, at which flood forecasting models run. Measurements of stage and velocity are fundamental to improve the performance of such hydrological models and improve our understanding of river hydraulics mechanisms such as hysteresis. Additionally, observations can be used in Data Assimilation schemes to improve the predictions of flood forecasting models and flood predictability.

Accomplishments

- performed an error analysis of the National Water Model (NWM) and of its patterns in space and time
- established an operation Data Assimilation method that operates on the Kisters system at watershed scale. The assimilation method has a domain of influence upstream of the discharge measurements. This is a significant advantage over the nudging applied in the current version of the NWM, because most of the concern points and low water crossings have no discharge gauge upstream to them
- developed a scalable and solution architecture utilizing KISTERS' cloud-based services to perform data assimilation runs dynamically, based on the currently available discharge measurements
- showed the potential of using other Data Assimilation methods at network scale
- investigated from data and models the hysteresis behavior detected in many streams in the network
- theoretically-derived the k-factor used at the gauges to adjust surface velocity to mean velocity.

Findings

- the performance of the NWM varies spatially across the State of Texas
- the NWM was found to have greater errors in areas that experienced higher precipitation, and on average, to underestimate discharge during the time period analyzed
- the assessment of similarity between the NWM and observed annual peak streamflow distributions showed that the NWM was able to capture the annual peak flow in less than 44% of the locations
- no spatial bias was observed over the state of Texas, suggesting that the NWM does not preferentially overperforms or underperforms in specific areas
- based on the proof of concept of Data Assimilation using the 4D VAR approach on the Llano river basin, the dynamic approach to the discharge measurements makes the solution robust and less sensitive to temporary data unavailability and it automatically adapts to the currently available gauges, making fully autonomous updating the models
- the Data Assimilation approach via Kalman Filtering showed that it significantly improves estimates of both depth and discharge at the downstream holdout site. By incorporating data assimilation, the model achieves a substantial reduction in RMSE—approximately 46.2% for depth and 56.2% for discharge
- the analysis of RQ-30 stage and discharge data revealed previously unobserved hysteresis behavior in which the discharge and velocity are larger on the rising limb of the hydrograph
- an analysis of hysteresis based on the Saint-Venant equations suggested that the pattern observed at the gauges is real and this finding opens the door to more accurate estimation of discharge through the development of 'dynamic rating curves' that account for this behavior
- the theoretically-derived the k-factor used at the gauges showed promise in improving discharge estimates produced by RQ-30 gauges. Because this k-factor can be derived from known values of channel surface roughness—a property that can be estimated directly from material properties—it can potentially be applied to new gauge sites without the need for calibration to manual discharge measurements.

Recommendations

- expand current error analysis to full observable period

- quantify uncertainty associated with flood forecasting at the river network and river reach scales
- communicating uncertainty information to emergency managers by integrating uncertainty bounds into the flood information system we have developed.

Response Exercises

Accomplishments

The project team has conducted two large-scale flood emergency response exercises with TxDOT Districts: in February 2021 in the Beaumont District, and in January 2022 in the Austin District. Both exercises were deemed successful based on the attendance, engagement, and findings during the 5-hour exercise. Each exercise had about TxDOT participants and produced several hundred witten comments related to the review of the current products and improvement recommendations. The following tasks were accomplished:

- Identify flooded roads with prototype methodology.
- Identify and display bridge status based on water height.
- The use and need for spatial information by both the EOC and Maintenance groups.
- Fostered idea sharing and enhanced communications between the EOC and Maintenance groups via the formal Homeland Security Exercise and Evaluation Program (HSEEP) format.

Findings:

Bridge Warnings – Found the symbology and the cross-section of the bridge (with water depth to low chord) helpful and informative. Would like to see them expanded to low water crossings.

Flooded Roads – Found the spatial display of flooded roads (current and predicted) to be helpful and informative. Would like to see them expanded to both on-system and off-system roads.

Situational Awareness – Found the spatial display of bridge status and flooded roads helpful and informative. Would like to include some additional layers to help with the overall situational awareness for both the Maintenance Sections and District (low water crossings, off-system roads, etc.). Also, would like to have access to the map in the field for improved communication between the Maintenance Section staff and the EOC staff.

Alerts and Reporting – During the exercise, there was discussion about the need to have either spatial or tabular alerts highlighting changes in flooding situations (increased flooding, receding water levels, etc.). Also, the idea of a tabular report of flooded roads / bridges to help with work orders and response by field personnel.

Recommendations

Based on the findings from the two exercises (Beaumont & Austin) the Project Team will focus on development of the following:

Bridge Warnings – Work on presentation of additional data and improved symbology

Flooded Roads – Work on designing a prototype Flooded Roads Methodology

Low Water Crossings – Work on incorporating a way to highlight flooded low water crossings.

The exercises also highlighted a few items which are solely within TxDOT's environment.

- **Allow use of mobile devices** in the field to improve information sharing between EOC and field personnel.
- Include **sharing capabilities** in all existing and future TxDOT spatial platforms to improve effective and efficient information sharing between staff.

Conclusions

- The advent of the National Water Model is transformative for flood emergency response in Texas. It produces flood discharge forecasts on about 100,000 stream reaches covering 102,000 miles of streams and rivers in Texas. These streams impact about 25,000 bridges and 21,000 bridge-class culverts stored in the National Bridge Inventory (NBI) and a much larger number of smaller bridges, culverts and low water crossings not included in the NBI.
- In October 2023, the National Weather Service is going to begin releasing real-time flood inundation mapping across about half of Texas, covering all of 12 TxDOT Districts and part of 6 other Districts. This is the first part of a national rollout of real-time flood inundation mapping what will be complete for the US in 2024. TxDOT's work on linking this inundation mapping to flood impact on the road transportation system leads the country.
- TxDOT wants to move from a "reactive response" in which their field staff are deployed to flooded roads after the water is already on them to a "proactive response" in which advance forecasting knowledge and observed flood gauge data are used to guide staff deployment and flood emergency response operations.
- The use of web map services has proved to be remarkably effective in allowing TxDOT personnel to visualize and react to flood risks. The flood emergency response exercises have focused the need to prepare such map services for bridge warnings and flooded roads.
- The RQ-30 stream gauge program has produced a new method for gauge calibration based on two discharge measurements with an Acoustic Doppler Current Profiler – one measurement with the water within the stream channel and a second with the water in the floodplain. It has been found that the adjustment between the measured surface water velocity and the mean velocity across the cross-section is then sufficiently sound that subsequent ADCP measurements show reasonable error from the RQ-30 discharge values. This reduces the cost and manpower needed to operate the gauges.
- A short-coming of the NWS inundation mapping is that it is built on bare-earth elevation models that have no bridges in them. As a consequence, a very high proportion of the roads shown to be flooded are actually false positives. A method for correcting this problem has been developed in this project through geospatial description of the bridge extent and elevation The

inclusion of this information in the flood inundation mapping is needed. This innovation is being scaled out so that it can be applied to all Texas bridges identified in LIDAR areal mapping of the state.