



**THE UNIVERSITY OF TEXAS AT AUSTIN
CENTER FOR TRANSPORTATION RESEARCH**

Technical Memorandum 5B, Evaluate Streamflow Measurement at TxDOT Bridges

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Road and Bridge Flooding

1. Introduction

Assessment of flood impact on roads and bridges can be done from two perspectives – a long-term risk perspective where the probability of flooding in any year is evaluated, and a short-term or real-time perspective where the likelihood of flooding during a current flood event is determined. In either case, the basic problem is the same – how high will the flood waters rise and will they inundate a road or impact the supporting beams above the low chord elevation of a bridge? Several billions of dollars have been invested in the US through the FEMA floodplain mapping process in determining long-term flood risk, primarily for building infrastructure. The road transportation system has not been a primary focus of that effort, and indeed, in the process of constructing bare-earth digital elevation models used for FEMA floodplain mapping, bridges are removed from the terrain dataset. It follows from this reasoning that the first step in quantifying flood risk on the road and bridge system from either the short-term or the long-term perspective is to “get the roads and bridges right”. This requires constructing a 2D and 3D geospatial representation of the road and bridge system, which is a focus of this report.

The main geographic datasets used at TxDOT to describe the road and bridge system are the TxDOT Roadway Inventory and the National Bridge Inventory. The TxDOT Roadway Inventory is a line dataset located approximately along the road centerline for the principal roads and streets of the state. This dataset is linearly referenced so that distance along the road is recorded along with the (x,y) location of points on the road line. The National Bridge Inventory is a point dataset containing the latitude and longitude of a representative point near the bridge. These two datasets each have about 120 tabular attributes to describe a road line or a bridge point. These GIS data are used to report to the federal government the characteristics and condition of the state’s road and bridge system.

Flooding depends on the vertical or z-dimension of information – when the water level is above the road or bridge level, flood inundation occurs. Since current TxDOT GIS data are described only in the (x,y) or horizontal coordinate system, this project has begun the development of a new road and bridge dataset for TxDOT that will eventually describe roads and bridges more completely in 2D and 3D. That is a very large goal which will take years to complete, so what is reported here is a point of departure rather than a complete solution. We have, however, been able to proceed sufficiently far in the Austin District to be able to show what a more complete solution could look like, and in the case of bridges we have been able to develop a procedure called TxBridge, which can describe bridges in a simplified form across Texas.

1.1. Definitions

When we measure something with a ruler, we establish a zero mark at the point of origin of the object and then measure the distance along the object from that point of origin. A **datum** is a reference point, line or surface from which measurements are made. Datums are of two kinds. A **geodetic datum** is a reference surface defined by a geoid, or surface of constant gravitational potential (Committee on FEMA Flood Maps, 2009). Geodetic datums are established by gravitational surveys over large areas and are regional or even national in scope. A **local datum** is a point or line used for measurements at a particular location such as a stream gauge or a bridge, or along a line, such as a stream reach or a road segment. In this report, the term **elevation** refers to vertical measurements relative to a geodetic datum, and the term

height refers to measurements above a local datum. More specifically, the term **water surface elevation** refers to the height of a water surface above geodetic datum, and **stage height** refers to the height above a local datum, such as the minimum channel elevation, or a stream gauge datum, generally located a little below the stream bed.

One way of illustrating these definitions is to compare them with the more generally used terms from fluid mechanics, as shown in Figure 1.1, where $h = z + y$, in which h is the water surface elevation above geodetic datum, z is the minimum channel bed elevation above geodetic datum, and y is the stage height of the water surface above the minimum channel elevation, sometimes called hydraulic head (Texas Department of Transportation, 2019, p. 6-7)

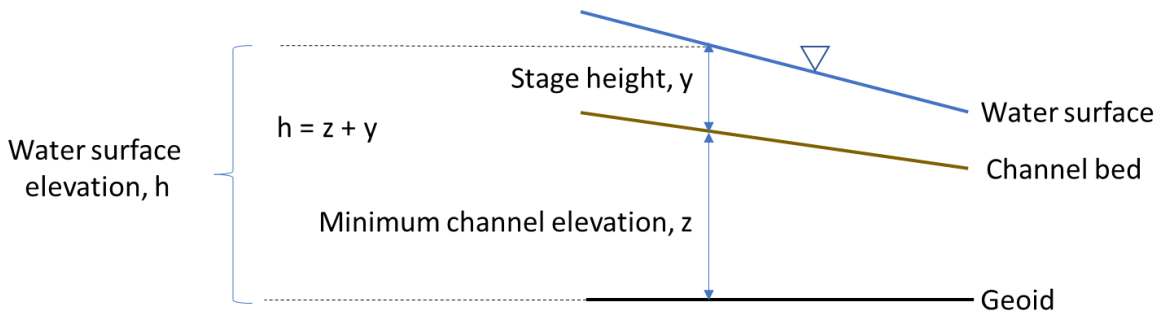


Figure 1.1 Water surface elevation and stage height

The reason for emphasizing these definitions is that very often a particular water level is associated with both a stage height and a water surface elevation. It is possible that stage heights from two or even three local datums will be defined at a particular location. For example, the same water surface elevation on a river reach at a bridge with a stream gauge on it could have a **stream stage height** that refers to the average height of water above the channel bed along the stream reach, a **stream gauge height**, which is the height above a local stream gauge datum, and a **bridge stage height** which refers to the height of water above the minimum channel elevation at the bridge. Similarly for roads, a **road stage height** refers to the height of the water above the minimum elevation along the centerline of a road, and a **road gauge height** refers to the height above the zero point of a gauge board erected by the side of a road, such as at a low water crossing

A **rating curve** is a function or table that relates the stage height to the discharge. It follows that rating curves based on local datums can be defined for stream reaches, for stream gauges, for bridges and culverts, and for roads and low water crossings. However, the rating curve that relates discharge to water surface elevation above geodetic datum is unique at a particular location on a stream reach or a road.

1.2. Flood Inundation Map Services

In October 2023, the National Weather Service is planning to begin deployment of real-time flood inundation mapping services to about half of Texas, as shown in Figure 1.2. This will provide full coverage for 12 TxDOT Districts and partial coverage of 6 Districts. The National Weather Service also provides precipitation map services. The USGS provides streamflow data, including from 80 RQ-30 radar gauges supported by this project, which can be accessed as a query able map service. To these can be added a bridge warning service, a flooded roads service, and an asset inventory service, all supported and

maintained by TxDOT. As shown in Figure 1.3, the collection of all these map services constitutes the Flood Assessment System for TxDOT (FAST). The main focus of this report is on the technical basis of the bridge warning service and the flooded road service.

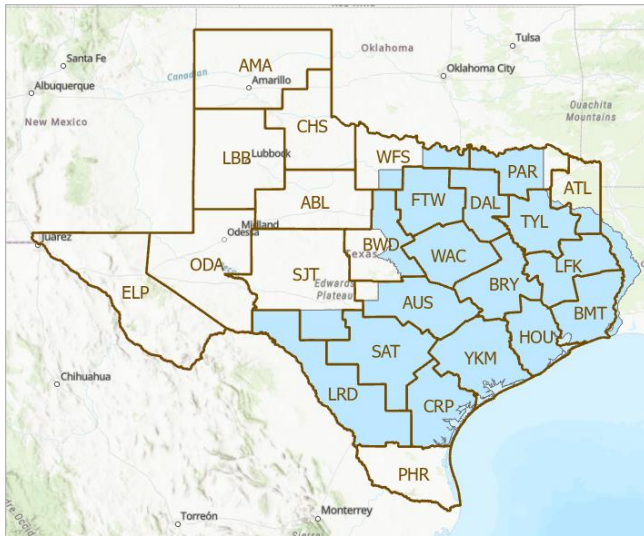


Figure 1.2 Deployment in 2023 of National Weather Service real-time flood inundation map services in Texas

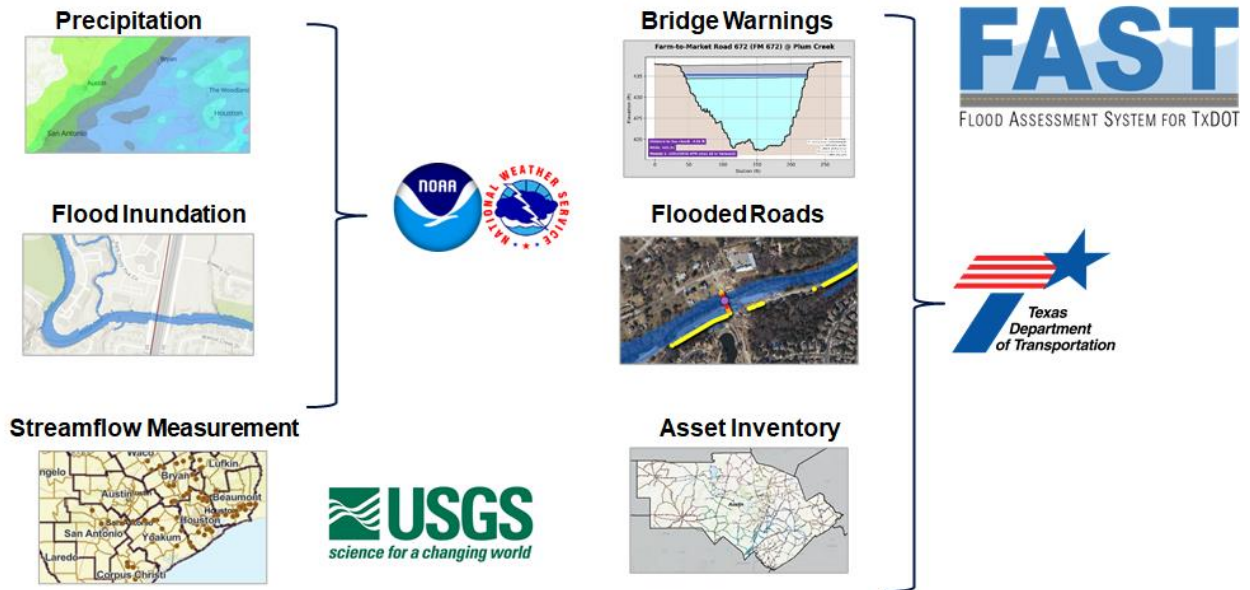


Figure 1.3 Map services in the Flood Assessment System for TxDOT (FAST)

Following this introductory chapter, the report contains three main sections: Chapter 2 deals with bridge representation and flooding, Chapter 3 deals with road representation and flooding of low water crossings, and Chapter 4 deals with road flood mapping. Conclusions are presented in Chapter 5.

2. Bridge Flooding

2.1. Overview

The TxDOT standard specifications define a bridge as: “A structure, including supports, erected over a depression or an obstruction (e.g., water, a highway, or a railway) having a roadway or track for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 ft. between faces of abutments, spring lines of arches, or extreme ends of the openings for multiple box culverts” (Texas Department of Transportation, 2014, p.6).

As of December 2022, the public highway system in Texas included over 57,000 bridges. These comprise two fundamental bridge types: (a) span bridges, and (b) bridge-class culverts. As shown in Figure 2.1, **span bridges** are characterized by a bridge deck supported at discrete points along its length. By contrast, a culvert is supported by a continuous bottom slab. A **bridge-class culvert** is any culvert which spans at least 20 ft. Span bridges are designed so that the **low chord** or lowest elevation of the supporting beams is at or above the water surface elevation of a flood.

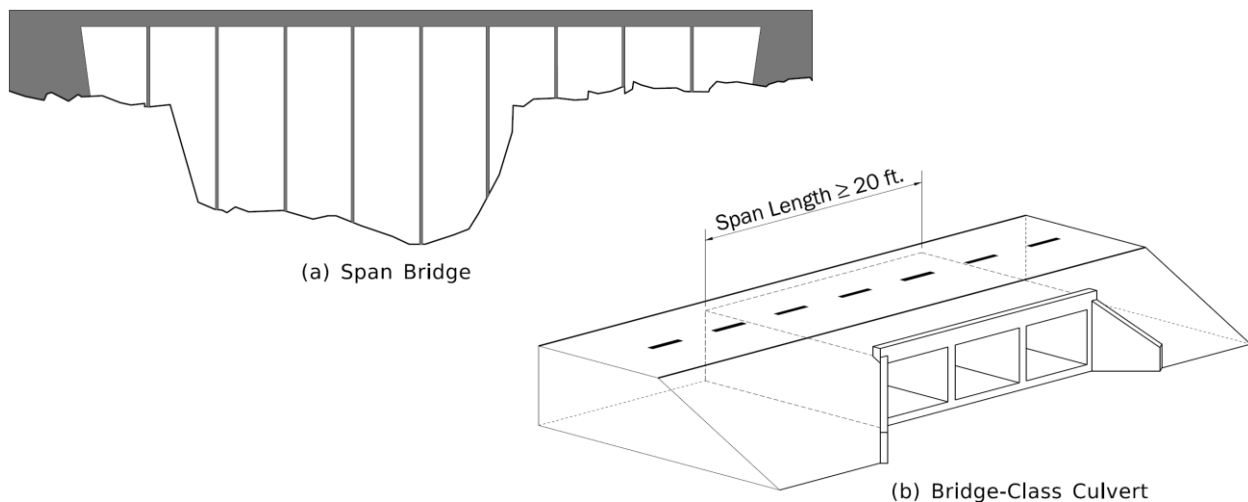


Figure 2.1. Fundamental bridge types: (a) Span Bridge, and (b) Bridge-Class Culvert

Bridges owned and maintained by the State are designated **on-system**. Many bridges on the public highway system are owned and maintained by local governments; these are designated **off-system**. The State performs routine inspections for all public highway bridges, both on-system and off-system. Thus, TxDOT maintains a detailed National Bridge Inventory (NBI) record for each bridge on the public highway system in Texas. To that end, each bridge is issued a permanent and unique 15-digit NBI number, where:

DD-CCC-0-CCCC-SS-JJJ is the NBI number format, and:

DD = TxDOT District ID number

CCC = County ID number

0 = zero

CCCC = control number

SS = section number

JJJ = job number

If an NBI number includes a letter, it very likely represents an off-system bridge – and vice versa.

Texas has more bridges on its highway network than any other state in the nation. As shown in Figure 2.2, this includes nearly 25,000 span bridges over water (12,799 on-system; 12,129 off-system). It also includes some 21,000 bridge-class culverts (13,763 on-system; 7,249 off-system). The remaining 11,209 structures are **grade crossings** (i.e., span bridges where a highway crosses another lane of traffic rather than a waterway). TxDOT maintains its bridge information in a data system called AssetWise. This inventory is evolving through time as new bridges are constructed and old bridges are taken out of service.

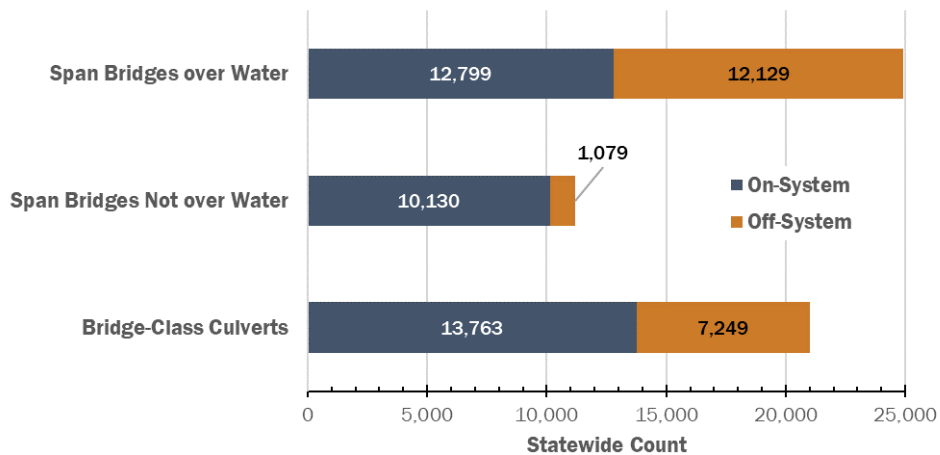


Figure 2.2. Texas highway bridge inventory breakdown (Data queried from AssetWise on 12/91/2022)

The dataset for Texas bridges is publicly accessible through the TxDOT Open Data Portal <https://gis-txdot.opendata.arcgis.com/search?q=bridge> where the link just given contains also a Bridge Coding Guide and the Bridge Data Dictionary. The Bridge Coding Guide describes in detail the categories of information in the National Bridge Inventory and how they are classified. The Bridge Data Dictionary gives the attribute names for the corresponding fields in the bridge GIS dataset. For example, a particularly critical descriptor of span bridges is the Service Type Under Bridge, Item 42.B in the National Bridge Inventory description, which has the values 0-9, as shown in Table 2.1. This is specified as SUBSTRUC_MAJR_SPAN_BELOW in the attributes of the publicly accessible GIS bridge dataset. The values of this attribute between 5 and 9 identify bridges over water.

Code	Description
1	Highway, with or without pedestrian
2	Railroad
3	Pedestrian exclusively
4	Highway-railroad
5	Waterway
6	Highway-waterway
7	Railroad-waterway
8	Highway-waterway-railroad
9	Relief for waterway
0	Other

Table 2.1. Classification codes for Service Type Under Bridge

2.2. Characterizing Bridges

To develop a statewide flood forecast system for transportation infrastructure in Texas, the hydraulic modeling must represent tens of thousands of bridges over hundreds of thousands of acres.

The following criteria are usually sufficient to define a span bridge in a hydraulic model:

- centerline and width of bridge deck;
- high chord of bridge (*i.e.*, top of deck or top of rail);
- low chord (*i.e.*, bottom elevation of beams or girders); and
- centerline and shape of intermediate supports (*i.e.*, columns or piers); and
- shape of spill-through abutments.

These criteria are usually sufficient to define a culvert in a hydraulic model:

- number, shape, and size of barrels;
- material and end treatments;
- culvert length; and
- upstream and downstream invert elevations.

The analyst usually has three options for obtaining bridge (or culvert) information:

- review as-built construction plans;
- review documentation and coding from the National Bridge Inventory (NBI); and/or
- field measurement.

Unfortunately, the bridge/culvert criteria necessary for hydraulic modeling are not available in a format that can be digitally queried in bulk. In a best-case scenario (ready access to complete and legible construction plans for every bridge in the NBI database), a full-time engineer would need roughly five years to gather the statewide bridge data needed for hydraulic modeling. This best-case scenario still fails

to account for culverts spanning less than 20 ft., which are not inventoried in a systematic way by TxDOT.

For an initial phase at statewide bridge characterization, a certain amount of accuracy must be traded for automation; the inventory of bridge and culvert data can be expanded and refined over time. As a starting point:

- Culverts may be omitted from the initial phase of hydraulic modeling.
- LiDAR point cloud data – the field data from which DEMs are derived – can identify the top surface of a bridge, including elevation, width, and orientation. This process can be automated through advanced computing.
- Bridge thickness (*i.e.*, the combined thickness of bridge deck and girders) can be estimated using approximate rules of thumb based on bridge type and bridge length.
- Intermediate supports (*i.e.*, columns or piers) may be omitted from the initial phase of hydraulic modeling.

Channel profile measurements are another consideration for hydraulic modeling. For span bridges over water, bridge inspectors measure the channel profile during each routine inspection (usually every 24 months). Measured channel profiles are documented in portable document format (PDF) inspection reports which are saved to the State’s bridge inventory system, AssetWise. Measurements are recorded in both tabular and graphical format; however, this data is not digitized or geo-referenced. While channel profile measurements are useful for hydraulic modeling, it is not feasible to work with the existing measurements at this time.

2.3. Bridge Thickness

LIDAR point clouds can be used to describe bridge deck elevation. An important criterion for bridge safety during flooding is that flood waters should not reach the low chord elevation, or bottom of the girders supporting the bridge deck. As shown in Figure 2.3, bridge thickness is defined as the sum of girder depth and deck thickness. The height of the bridge rail is not included in this estimate, a simplification that is necessary for an initial phase of statewide bridge characterization for regional hydraulic analysis. The philosophy behind this approach to characterizing bridge thickness is two-fold:

1. Bridge thickness depends on what type of girder or beam is used for the main span. This information is coded in AssetWise under NBI Item 43.1.3 (see Table 2.2)
2. In general, longer bridge spans require deeper girders to support structural loads.

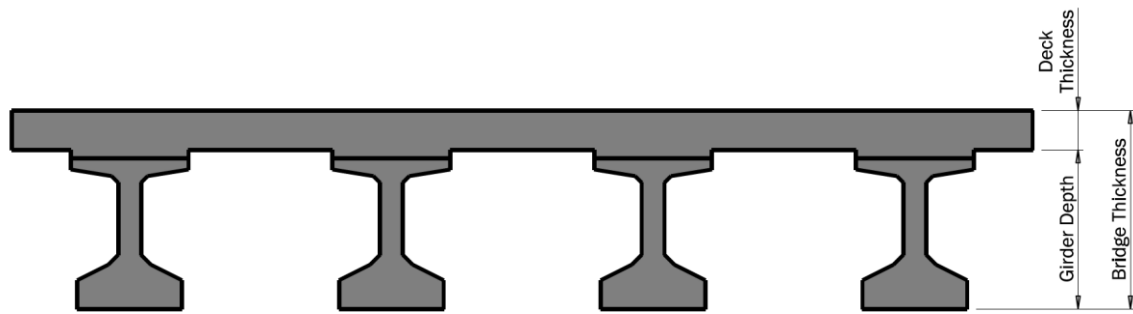


Figure 2.3 Bridge Thickness as the sum of girder depth and deck thickness

Code	Description	Code	Description	Code	Description
1	WS I-Beam	31	PS Conc. Girder-Multiple	67	Whipple Truss
2	WS Plate Girder-Multiple	32	PS Conc. Girder-w/Floor System	68	Bedstead Truss
3	WS Plate Gird., Var. Depth-Mult.	33	PS Conc. Box Girder-Multiple	71	Parker Truss
4	WS Plate Girder w/Floor System	34	PS Conc. Box Gird.-Sing. or Spread	72	Camelback Truss
5	WS Box Girder-Multiple	35	PS Conc. Slab&Gird.-Pan Formed	73	Pennsylvania Truss
6	WS Box Girder-Single or Spread	36	PS Conc. Slab-Full Depth	74	K Truss
8	WS Orthotropic Plate Girder	37	PS Conc. Slab-Partial Depth	75	Warren Truss
9	WS Other	38	PS Conc.-U-beam	76	Bowstring Truss
11	Steel I-Beam	39	Other Prestressed Concrete	77	Lenticular Truss
12	Plate Girder-Multiple	41	Timber Stringers-Multiple	78	Whipple Truss
13	Plate Girder, Var. Depth-Mult.	42	Timber Girder w/Floor System	79	Pegram Truss
14	Plate Girder w/Floor System	43	Timber Truss	81	Howe Truss
15	Steel Box Girder-Multiple	49	Other Timber	82	Post Truss
16	Steel Box Gird.-Single or Spread	51	Metal Arch	83	King Post or Waddell "A" Truss
17	Steel Channel Beam	52	Other Metal	84	Queen Post Truss
18	Steel Orthotropic Plate Girder	53	Masonry Arch	85	Bollman Truss
19	Other Steel	54	Movable, Vertical Lift	86	Fink Truss
21	Concrete Girder – Tee Beam	55	Movable, Bascule	87	Fink-Stearns Struss
22	Conc. Gird., Var. Depth-Tee Bm.	56	Movable, Horizontal Swing	88	Kellog Truss
23	Conc. Box Girder-Multiple	57	Movable, Other	89	Pratt-Greiner Truss
24	Conc. Box Gird.-Single or Spread	59	Other thn MetalTruss or other Met.	91	Continuous Truss
25	Conc. Slab&Gird.-Pan Formed	61	Pratt Truss	92	Wichert Continuous Truss
26	Concrete Flat Slab	62	Pratt Truss, Half-Hip	93	Vierendell Truss
27	Conc. Slab-Variable Depth	63	Warren Truss	97	Other Truss
28	Conc. Arch, Open Spandrel	64	Warren Quadrangular Truss	98	Other Truss
29	Other Concrete	65	Baltimore Truss		
30	Segmental Box Girder	66	K Truss		

Table 2.2. Coding reference for NBI Item 43.1.3: Type of beam or girder for main span (BEAMTYPE)

The coding reference for NBI Item 43.1.3 (Table 2.2) can seem overwhelming; very few engineers or hydrologists are familiar with all 79 bridge types. Figure 2.4 is included here to illustrate which bridge

types are most common in Texas for span bridges over water. Note that just seven coding values for Item 43.1.3 account for over 90% of the span bridges over water in Texas.

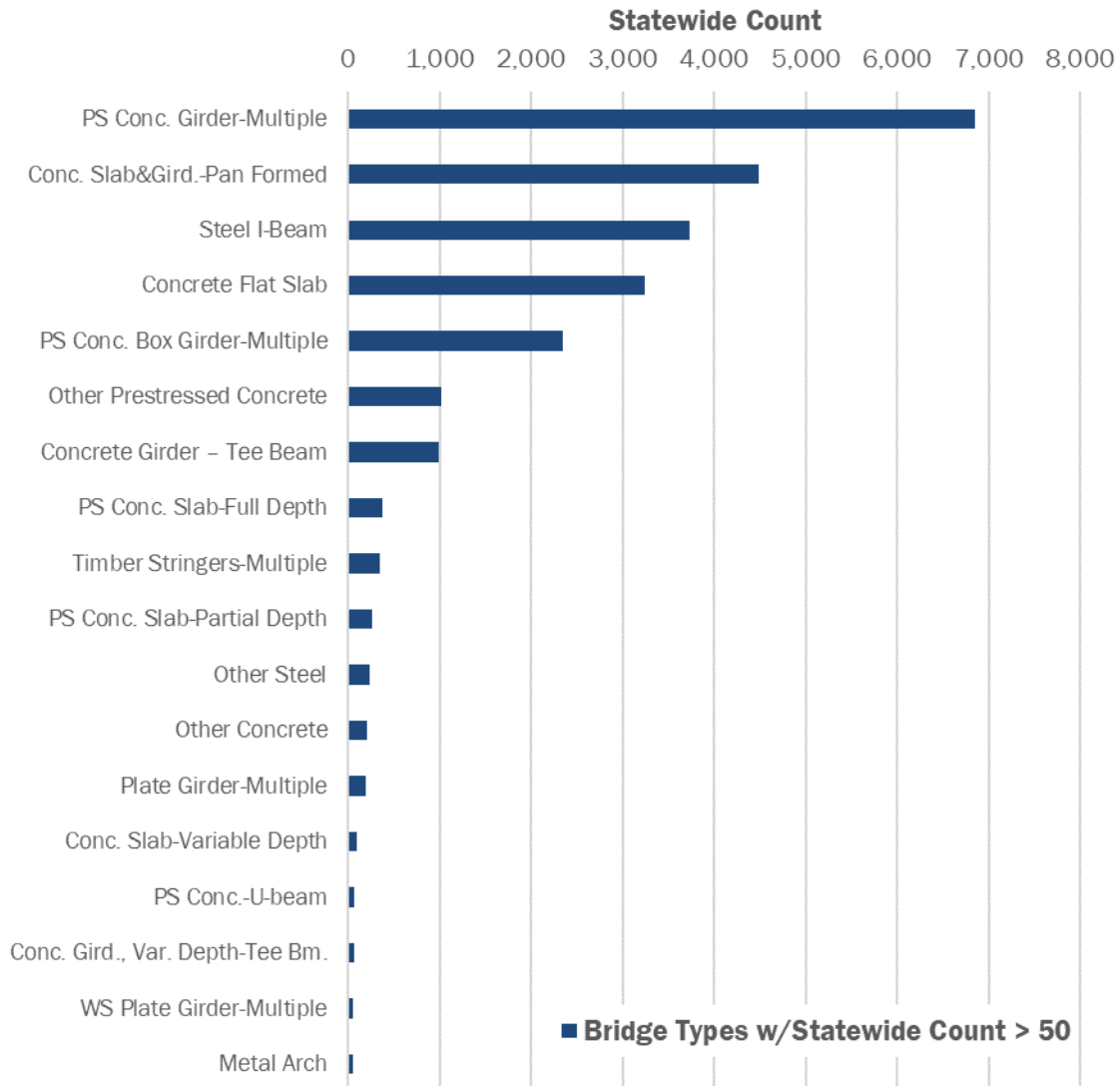


Figure 2.4 Main span beam/girder type for span bridges over water in Texas.

Several sources of data were evaluated to develop the rules of thumb that relate bridge thickness to main span type and length.

- TxDOT has long maintained [standard drawings for common bridge types](#). Current and historic bridge standards help us to characterize bridge thickness for the most common bridge types.
- [TxDOT's Bridge Division](#) also issues span length recommendations for commonly used girder classes (e.g., [I-girders](#), [slab beams](#), and [box beams](#)). For a given type of girder, a span table indicates the maximum span length that can be achieved with each available size of girder. AASHTO also provides minimum beam depths in its LRFD Bridge Design Standards.

- TxDOT employees can query AssetWise to view the distribution of actual span lengths for each girder type currently in-service. TxDOT employees can also retrieve construction plans, which are archived electronically in AssetWise, and manually check bridge thickness on a case-by-case basis.

The resulting rules relating Bridge Thickness to span length and type are shown in Table 2.3.

Main Span Girder Type	Bridge Thickness
1 - 19	0.48 × NBI Item 48
21 - 22	If NBI Item 48 ≤ 35' → 22" Else If NBI Item 48 ≤ 40' → 28" Else (NBI Item 48 > 40') → 36"
23 - 24	If NBI Item 48 ≤ 35' → 22" Else If NBI Item 48 ≤ 40' → 28" Else (NBI Item 48 > 40') → 36"
25	If NBI Item 48 ≤ 65' → 25" Else If NBI Item 48 ≤ 80' → 33"
26	28"
27	28"
28	36"
29	48"
30	0.28 × NBI Item 48
31 - 32	If NBI Item 48 ≤ 70' → 38" Else If NBI Item 48 ≤ 80' → 44" Else If NBI Item 48 ≤ 95' → 50" Else If NBI Item 48 ≤ 105' → 56" Else If NBI Item 48 ≤ 125' → 64" Else If NBI Item 48 ≤ 135' → 72" Else (NBI Item 48 > 135') → 80"
33 - 34	If NBI Item 48 ≤ 65' → 25" Else If NBI Item 48 ≤ 80' → 33" Else (NBI Item 48 > 80') → 39"
35	If NBI Item 48 ≤ 30' → 24" Else (NBI Item 48 > 30') → 33"
36 - 37	If NBI Item 48 ≤ 40' → 19" Else (NBI Item 48 > 40') → 22"
38	If NBI Item 48 ≤ 105' → 50" Else (NBI Item 48 > 105') → 64"
39	0.54 × NBI Item 48
41	28"
42	28"
43 - 98	48"

Table 2.3. Coding rules for estimating bridge thickness

The rules of thumb were developed based on a review of bridge standards and other design guides, then checked using AssetWise queries and spot-checked against construction plans. This approach worked better for concrete bridges than for steel bridges. Indeed, the same “ballpark” figure is suggested for all

truss bridges, regardless of span length. It bears repeating; these rules of thumb are only intended for an initial phase of statewide bridge characterization for regional hydraulic analysis. This rubric may be refined with additional research, and individual bridge thicknesses will likely need to be updated over time by local personnel.

2.4. TX-Bridge Overview

A simplified characterization of each bridge’s geometry can be developed by analyzing classified LiDAR point clouds. From these publicly accessible datasets, a polygon of the horizontal (plan view) limits of each bridge deck can be extracted. We shall refer to this a **bridge hull**, as shown in Figure 2.5.

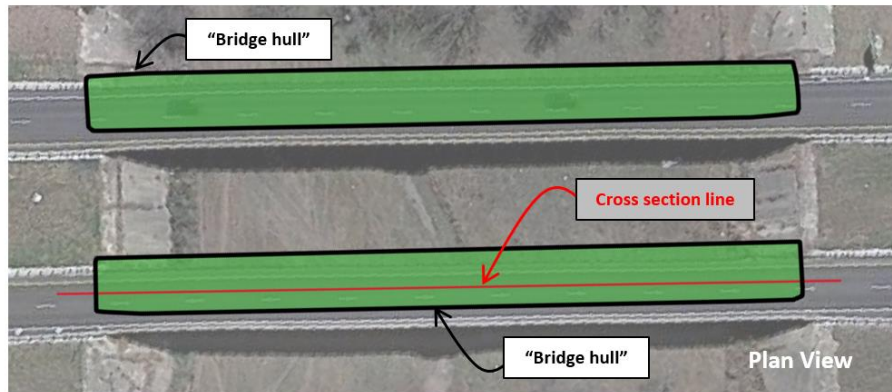


Figure 2.5 Example bridge hulls

Within this polygon, a cross section can be made along the transportation feature (such as a road, rail, or footpath). Along this transect, a cross section (profile view) of the ground below the bridge and the deck elevation of the bridge are sampled. Offsetting the bridge deck by a uniform thickness determined from the methods described in previous sections, a **bridge envelope** is produced (Figure 2.6). This cross section is a simplified view of the bridge that does not contain piers, bents or deck railings.

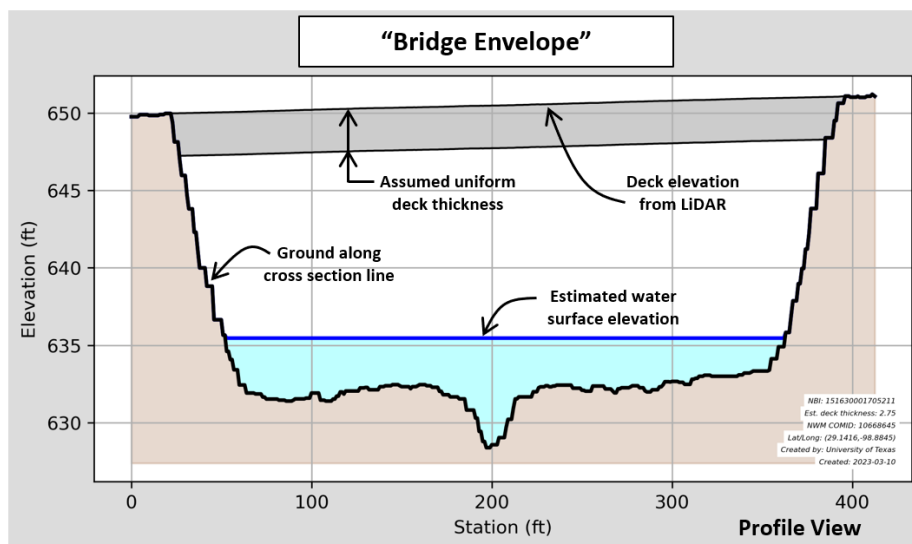


Figure 2.6 Example bridge envelope as a simplified representation of conveyance area under a bridge

TX-bridge (pronounced as “Texas Bridge”) is a software repository designed to extract and derive geospatial bridge hulls and envelopes of bridges from LiDAR points classified as ‘bridge’. TX-bridge was created using open-source tools and is written in Python. It is developed and maintained by Andy Carter at the University of Texas’ Center for Water and the Environment. The code is available on GitHub at <http://github.com/andycarter-pe/tx-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 gaged and un-gaged bridge structures. Specifically, it was built to conflate bridges to the National Water Center’s National Water Model (NWM) hydrofabric.

The user supplies a polygon shapefile of the area of interest and a cloud optimized point cloud where the three-dimensional points describing bridge decks have been classified. From these data, bridge points are extracted. Clusters of these bridge points are spatially grouped and a polygon is determined around each cluster creating a “bridge hull”.

With the polygon “bridge hulls” the user provides a vector line data of transportation elements within the area of interest. These are typically centerlines of roadways and railroads. TX-bridge assumes that these transportation lines are from the crowd sourced OpenStreetMap but could be from other sources such as municipal or state geospatial repositories. On each “bridge hull” polygon, a programmatic attempt to determine the “major axis” is made. The “major axis” is typically the longest transportation line feature that intersects a buffered “major hull” polygon.

From all the points classified as ‘bridge’ within a given “bridge hull”, a digital elevation model (DEM) of the bridge deck is created as a GeoTIFF. With a user supplied stream network drawn from upstream to downstream, “major axis” lines crossing streams are adjusted to be left-to-right looking downstream in standard hydraulic notation.

For each bridge, a cross section is created. Within TX-bridge, this is described as the “bridge envelope”. Using the “major axis” as a horizontal alignment transect, a cross section of the bare-earth ground below the bridge is determined. TX-bridge defaults to using the USGS National Map’s 3DEP Elevation web coverage service to fetch the bare-earth ground profile. The “bridge-hull” DEM is utilized to get the top of the bridge deck for this cross section. Each bridge is conflated to the nearest point within the National Bridge Inventory (NBI) dataset. For Texas, the NBI data was extended to include an estimation of uniform bridge thickness based on a Texas Department of Transportation (TxDOT) provided rubric which is a function of bridge deck type and length of the main span.

To make flood predictions at bridges over rivers, it is necessary to know the flow rate at the bridge and a way to determine the expected water surface as a function of the flow rate. For TX-bridge, it is assumed that flow rates for both current and predicted flows are broadcasted from the National Weather Service’s National Water Model. Where a bridge crosses a NWM stream reach, the stream’s unique identifier is assigned to the bridge so that a flow rate can be determined. A rating curve relating flow to depth is assigned to each bridge is needed. Currently, TX-bridge is using a synthetic rating curve determined using a “Height Above Nearest Drainage” (HAND) calculation made on 3-meter terrain across Texas. This could be superseded and replaced with more detailed hydraulic modeling in the future to provide a more detailed water surface prediction.

2.5. Creating Cloud Optimized Point Clouds

There is contiguous point cloud availability across the State of Texas collected by various vendors over the last 10 years. This contiguous coverage is comprised of fifty-nine individual collections. All LiDAR tiles for the fifty-nine collections are currently stored at the Texas Advanced Computing Center (TACC).

For example, Travis and Bexar counties were flown in early 2021, as shown in Figure 2.7. This collection is 3,953 square miles (about the area of Connecticut) and covers 1.5% of the state. It is provided as 3,673 individual tiles. Per modern LiDAR specifications, bridge deck data are classified with a value of 17. For TX-bridge, it is desired to have one file that contains all the points within this collection that are classified as ‘bridge’.

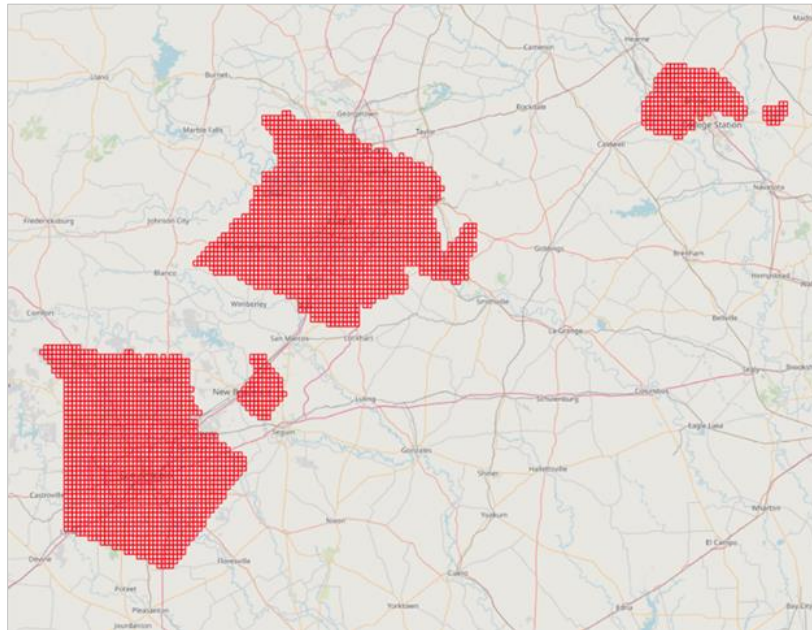


Figure 2.7 Polygons of the LiDAR tiles comprising the “Bexar & Travis Counties” collection

TX-bridge contains code that allows for the creation of a single file containing just the bridge deck point cloud data. The elected file format for this single file is the “Cloud Optimized Point Cloud” (COPC). This is an open-source format published in 2021.

Creation of the bridge deck COPC requires four steps. Given the file count (3,673 files) and the aggregate data size (837 Gb), it is recommended that the creation of the COPC per collection be performed in parallel on a high-performance computer (HPC) such as the TACC. The first step to creating a collection’s COPC is to extract just the bridge points from each tile. Second, each tile’s bridge points are reprojected to a uniform coordinate reference system. Third, using LASTools, these reprojected tiles are merged into a single point cloud (LAS) file. Finally, a COPC file is created from the single LAS file utilizing the open-source Point Data Abstraction Library (PDAL), Figure 2.8.

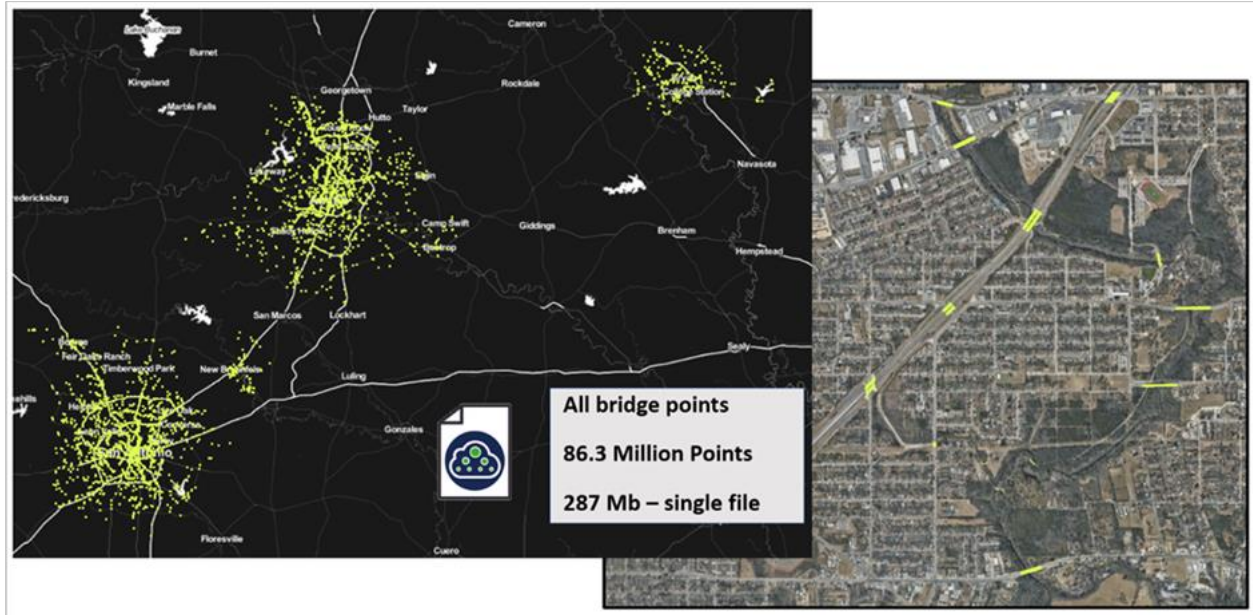


Figure 2.8 Cloud Optimized Point Cloud (COPC) created from the “Bexar & Travis Counties” collection for the points classified as bridge [Classification = 17]

2.6. Polygonising Point Cloud Groups by Classification

Assuming there is one COPC describing all the bridge classified points within a given area-of-interest, a method was determined to create a polygon representing each bridge's limits. This is accomplished by utilizing a density-based spatial clustering of applications with noise (DBSCAN) algorithm. This algorithm groups together points that are tightly packed together. TX-bridge groups the points into clusters based solely on the horizontal (X,Y) dimensions and disregards the vertical (Z) dimension, Figure 2.9.

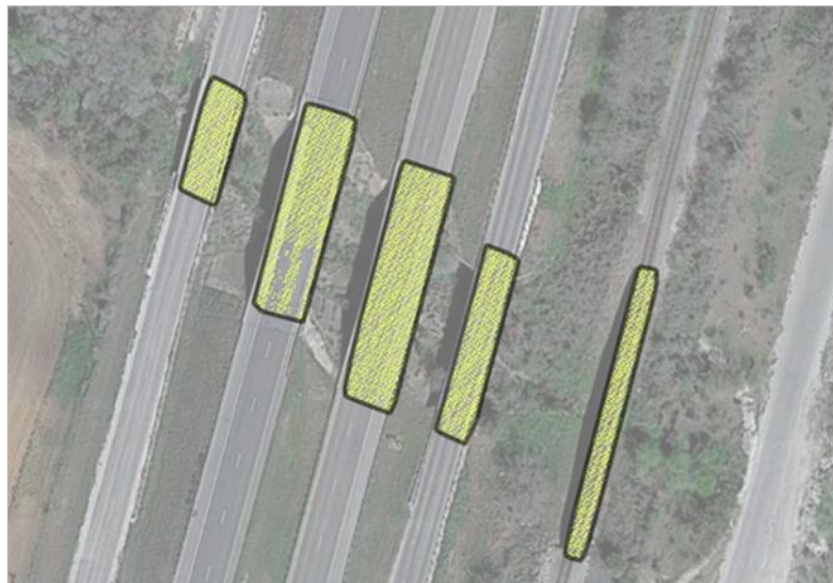


Figure 2.9 Bridge hull polygons determined from clusters of LiDAR points classified as 'bridge'

Typical point spacing for modern LIDAR has a point on average every 0.7 square meters. The clustering algorithm requires an ‘epsilon’ parameter which represents the maximum distance that a point can be from a cluster to still be considered in the group. In the TX-bridge code, this distance defaults to 2.5 meters but can be manually reset if the collection’s density varies from the expected 0.7 point per square meter density. The other parameter is a count of points that are needed to anoint a point within the cluster as a core point. This is hard coded to 4 within the TX-bridge code.

Once a cluster is ordained, a polygon of the bridge limits is determined by creating a convex hull around each cluster. This is a quick calculation and is accurate on bridge point clusters of straight and prismatic bridges. On curved bridges and bridges with complex non-prismatic geometry, a convex hull tends to overestimate the “bridge hull” limits. While not currently incorporated into the TX-bridge polygonization routine, it is anticipated that “bridge hull” polygons will need to consider recalculations of optimized concave hulls per point cloud grouping to derive better polygons for complex bridge geometries.

A “major axis” line is determined for each “bridge hull” polygon, Figure 2.10. This is a horizontal alignment of the longest transportation line that intersects the “bridge hull”. It is possible that more than one transportation line crosses a “bridge hull” line and is common for grade separation bridges. For example, the bridges in Figure 2.10 intersect the lines for both Interstate 35 and East 2nd Street. The longest is the Interstate 35 line and is therefore ordained as the “major axis” line for each bridge.



Figure 2.10 ‘Major Axis’ determined for bridge hulls using OpenStreetMap transportation linework

Where bridges cross streams, it is desired that the “major axis” be aligned such that it is in proper hydraulic direction. This means that the major axis is described to be “left-to-right” looking in the downstream direction. To make this determination, the high-resolution National Hydrograph Dataset (NHD) from the United States Geological Survey (USGS) was downloaded for the entire State of Texas. The NHD dataset is provided as a vector data set typically drawn as upstream-to-downstream. TX-bridge determines if a “major axis” line crosses a NHD streamline. If it does, a cross product of the intersection of the streamline and “major axis” is made. If the cross product is a positive value, then the “major axis” is flipped to conform to standard hydraulic alignment.

If a bridge does not cross a streamline, then it is not possible to align the “major axis” line to be left-to-right in the downstream direction. In this case, the direction of the OpenStreetMap line is retained as direction, Figure 2.11.

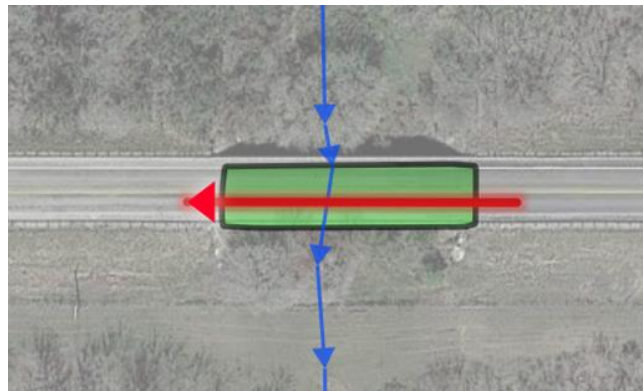


Figure 2.11 ‘Major Axis’ oriented to be ‘left-to-right’ looking in a downstream direction using the National Hydrograph Dataset stream vector dataset

It is necessary to create a digital elevation model (DEM) of the bridge deck for each “bridge hull”. This is accomplished in TX-bridge by creating a GeoTIFF raster from the bridge classified points within that “bridge hull”. The TX-bridge code defaults to build a DEM with a grid resolution of 0.3 meters. Typically, a point on the bridge deck is not available at this small density. Gaps are filled in with standard interpolation. The bridge deck DEM is clipped to the “bridge hull”, Figure 2.12.

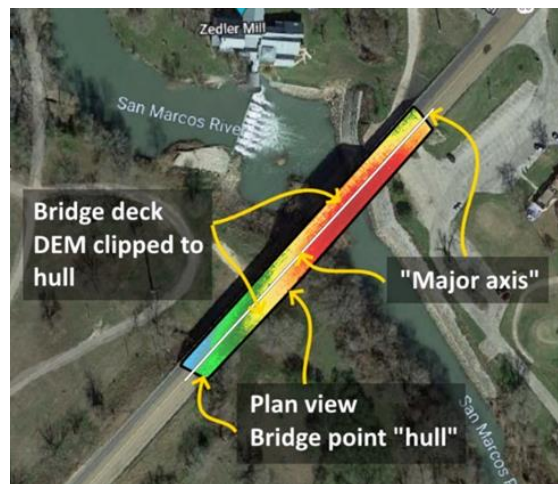


Figure 2.12 Digital Elevation Model (DEM) created from LiDAR bridge classified points within the limits of the ‘bridge hull’

2.7. Analysis of Stream Channels

In 2019, the Texas Water Development Board (TWDB) commissioned the creation of a state-wide seamless terrain dataset across the State of Texas. The goal was to supersede and replace the data served by the United States Geological Survey (USGS) which in general provided terrain elevations on a gridded 10-meter resolution. The TWDB desired that the new elevation surface be updated to a 3-meter resolution. The creation of this new 3-meter terrain was contracted to a firm named “Fathom” based in

Bristol, England. Fathom aggregated air-borne acquired LiDAR datasets to create a digital elevation model (DEM) for the entire state. This data set is referred to as the **3m Fathom DEM** and can be accessed at: <https://web.corral.tacc.utexas.edu/nfiedata/fathom3m/>

Synthetic rating curves are determined from hydraulic modeling and relate the flow of a stream to its water level or stage. It is used to estimate flooding limits and depth for given discharges when direct measurements are not available. The accuracy of a synthetic rating curve is sensitive to the resolution of the hydraulic model's channel geometry. Therefore, as the underlying terrain resolution increases, it is assumed that the accuracy of the synthetic rating curve will improve.

Hydrofabric is a term that refers to a digital dataset containing a network of connected representations of rivers, lakes and catchments used to create a representation of a hydrologic model. The National Oceanic and Atmospheric Administration's (NOAA) National Water Center (NWC) maintains the National Water Model (NWM) hydrofabric which provides a national-scale stream network consisting of more than 2.7 million reaches for the continental United States (CONUS). Each reach is assigned a unique numeric value noted as 'feature_id'. Geospatially, the location of the NWM hydrofabric is based on the National Hydrography Dataset – Medium Resolution (NHD-MR). Generally, the synthetic rating curves and hydrofabric of the NWM were derived from the USGS's 10-meter terrain data.

It was determined that a hydrofabric and corresponding synthetic rating curves derived from the 3m Fathom DEM terrain would likely provide a better estimate of flood limits and depth than those provided in the National Water Model. From the 3m Fathom DEM a new hydrofabric was determined utilizing the higher resolution data. This was accomplished by deploying the Flood Inundation Mapping version 3 (FIM 3) software created by the NWS. <https://github.com/NOAA-OWP/inundation-mapping/tree/dev-fim3>. The Fathom 3m hydrofabric more closely follows the lowest point along the streambed (thalweg) when compared to the NWM hydrofabric.

Each of the Fathom 3m stream segments has a unique numeric value which is called a Fathom Segment identifier (FATSGTID). For each FATSGTID, a synthetic rating curve was calculated on the 3m Fathom DEM utilizing a Height Above Nearest Drainage (HAND) based hydraulic simulation. Stream flows are computed and broadcasted by NOAA using the NWM hydrofabric. So, the NWM hydrofabric is used as a hydrologic (flow) basis and the Fathom 3m hydrofabric is utilized as a hydraulic (floodplain mapping) basis, Figure 2.13.



Figure 2.13 Comparison on the National Water Model and Fathom 3m Hydrofabric (N 28.971°, W 98.451°)

As an example, let's assume that it is desired to determine the maximum flooding depth under Bensdale Road where it crosses the Atascosa River in Pleasanton, Texas for the next 18 hours. The NWM stream under the bridge has a 'feature_id' of '10827668', Figure 2.14.

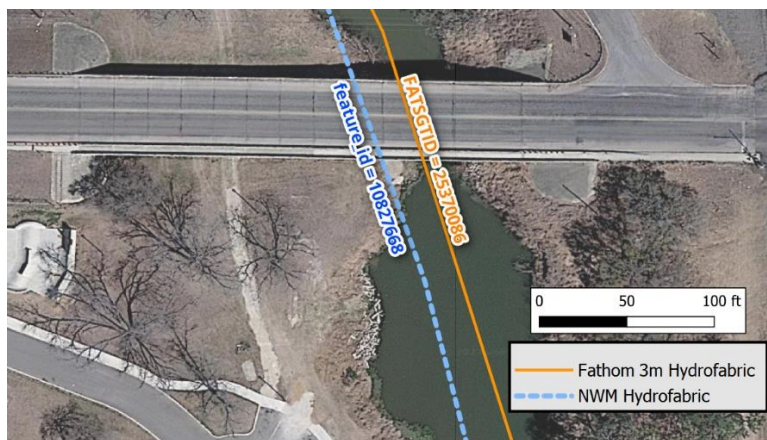


Figure 2.14 Bensdale Road over the Atascosa River in Pleasanton, Texas (N 29.9720°, W 98.4818°) – National Water Model and Fathom hydrofabric streams

For this example, the short-range forecast shows that the maximum flow anticipated is 420 cubic feet per second (cfs) on this NWM reach. The FATSGTID that crosses the bridge is '25370086'. Looking at the HAND synthetic rating curve derived from the Fathom 3m data, this corresponds to 8 feet of depth, Figure 2.15.

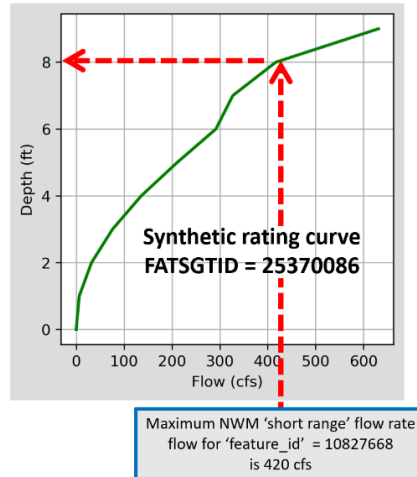


Figure 2.15 Synthetic rating curve from FATSGTID 25370086 derived from Fathom 3m terrain

The minimum channel under the bridge was determined to be at an elevation of 340.9. For the 420 cfs predicted flow rate, a maximum water surface elevation under the bridge is assumed to be 348.9 feet, Figure 2.16.

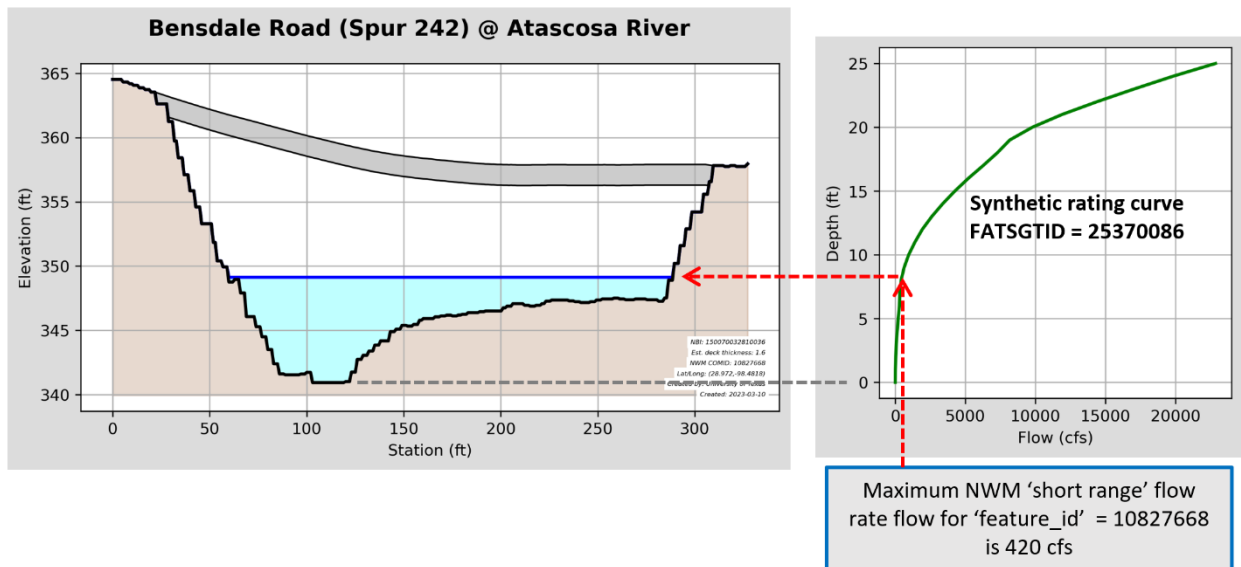


Figure 2.16 Flood depth example at Bensdale Road over the Atascosa River in Pleasanton, Texas (N 29.9720°, W 98.4818°)

2.8. 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 traverses one of these streams, it is possible to extrapolate the current and predictive water surface on each of these bridge envelopes.

The KISTERS Bridge Viewer Engine and Map Services are running in the Datasphere cloud system and using data from the NOAA Office of Water Prediction National Water Prediction Service RESTFUL API and the Bridge Geometry Database created by the University of Texas. Every hour, the Bridge Viewer Engine calls the National Water Prediction Service RESTFUL API for each bridge defined in the Bridge Geometry Database and generates a preview image with accurate current and forecast levels, Figure 2.17. Once a preview is selected, the engine calls the RESTFUL API on-demand and generates a larger interactive view of the bridge with the most current levels. Both preview and interactive bridge images may be imbedded in other applications and views with basic https calls by National Bridge Inventory Asset Number.

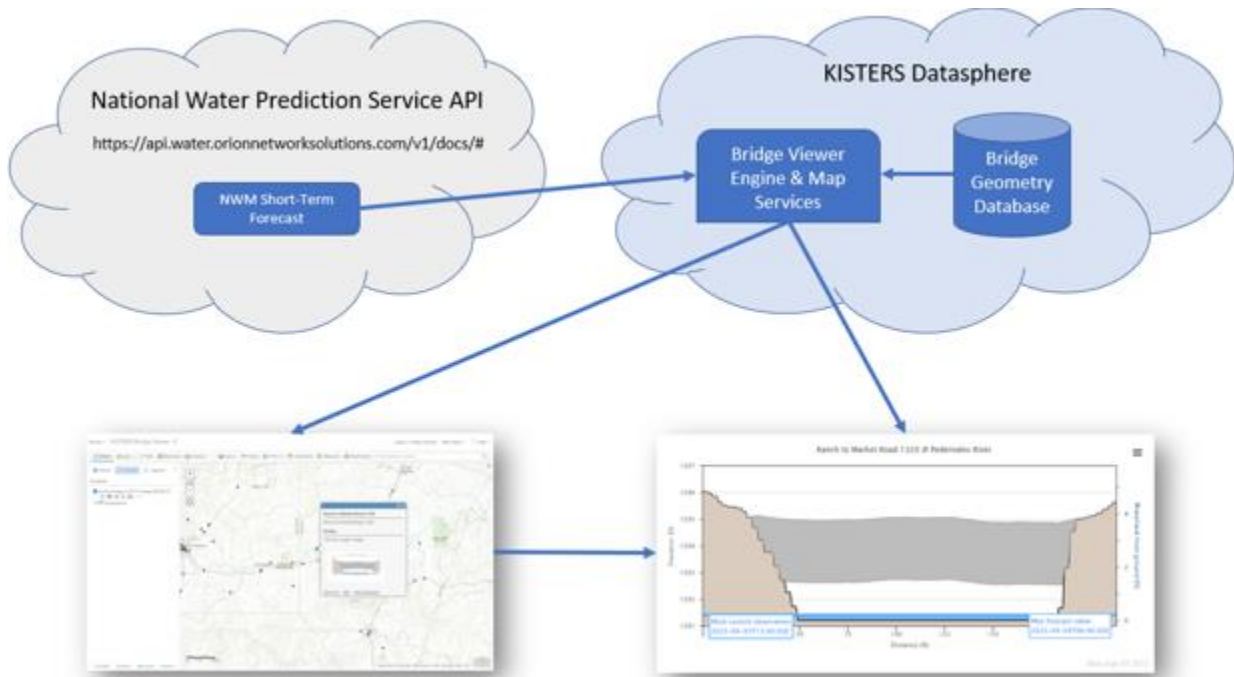


Figure 2.17 Bridge warning service is based on the KISTERS Datasphere which translates the discharge from the National Water Prediction Service into a stage height and bridge warning graphic.

Where a bridge crosses a NWM stream, that bridge’s geospatial data (bridge hull) is attributed with that stream’s NWM unique identifier (feature_id). A hydraulic simulation was used to pre-compute the flow rate versus depth relationship (synthetic rating curve) for each one of these reaches. Currently, synthetic rating curves are determined for the entire NWM domain using a height above nearest drainage (HAND) method. HAND synthetic rating curves provide an estimate of depth at a cross section based relative to the lowest elevation of that cross section. Once a NWM is known at each bridge, a pre-computed synthetic rating curve can be assigned.

After combining a ‘bridge envelope’ with a ‘synthetic rating curve’ one only needs a hydrologic discharge rate to determine a water surface elevation at any given cross section, Figure 2.18.

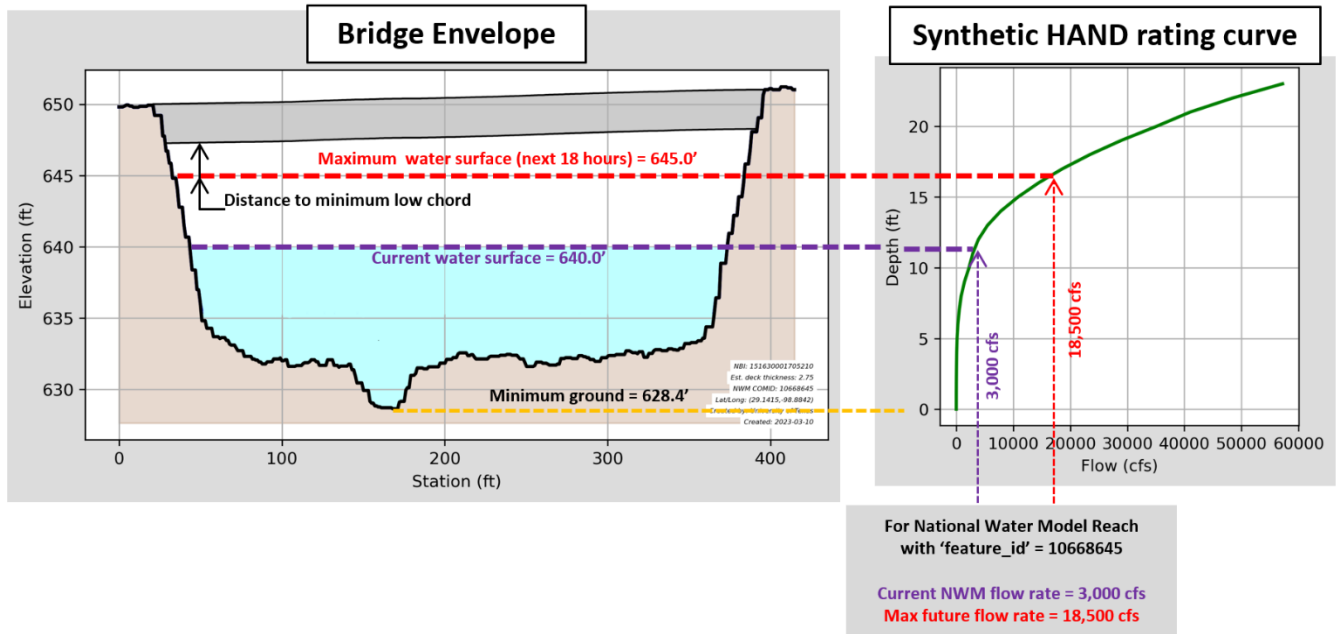


Figure 2.18 Water surface elevation and distance to minimum low chord estimated from National Water Model reach flows at a bridge envelope.

At each bridge location, a continuously operating service can ingest the current and predictive flows at each bridge location from the National Water Model. At each ‘bridge envelope’ a calculation can be made to determine the distance that the water surface is from the minimum low chord elevation. At a regional scale, each bridge envelope is better represented at a point.

Bridge envelopes and corresponding synthetic rating curves were determined at over 500 bridges with the Austin maintenance district. To provide a real time and predictive assessment of these bridges from an emergency management perspective, each point can change colors to indicate the risk and potential of flood waters threatening the low chord of the bridge.

For example, a red point might indicate that the flood waters are predicted to be between 0.5 and 2.0 feet from the low chord requiring potential maintenance action. A purple point shows where flood waters are predicted to overtop the bridge.

An operational service of this sample set was demonstrated to TxDOT (Figure 2.19) and is currently live at <https://ut-austin.maps.arcgis.com/apps/instant/basic/index.html?appid=bda0cc1d37e2490ca8c806d0ae2d3ce0>

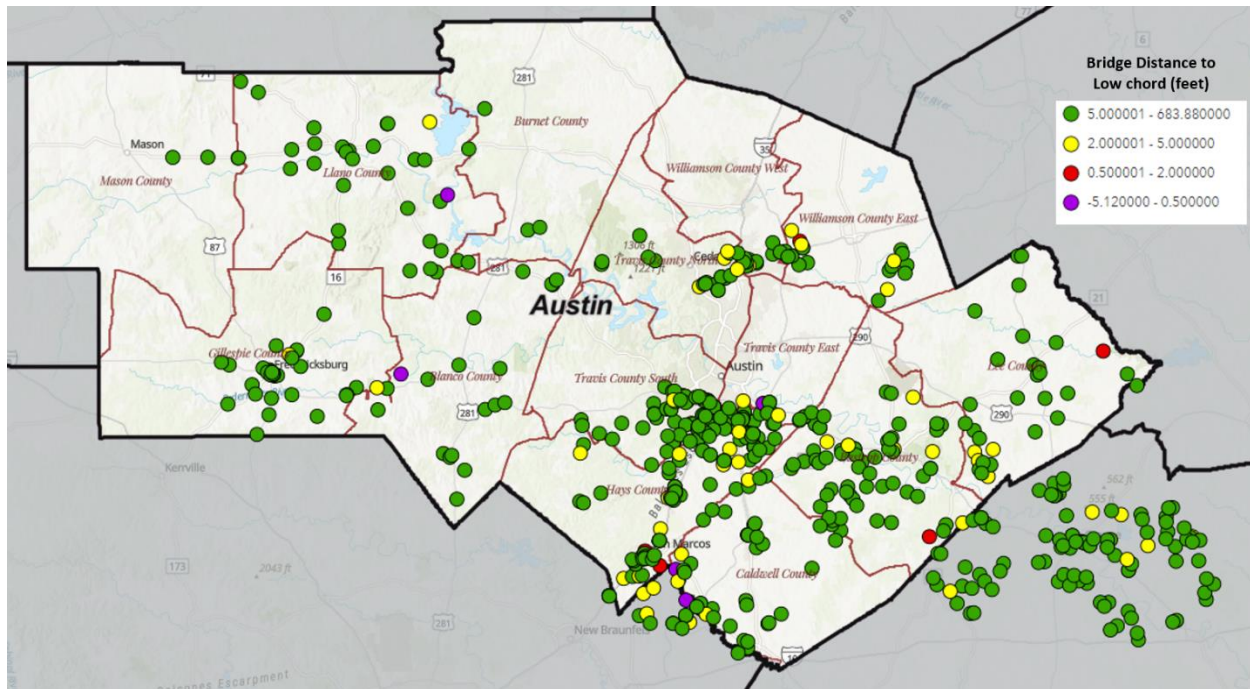


Figure 2.19 Flood warning service showing estimated distance between water surface elevation and minimum low chord at 500+ bridge envelopes

2.9. Taxonomy of Bridge Attributes

As each bridge is characterized in Tx-Bridge a set of 37 attributes is created, which are listed individually in Appendix A and illustrated in Figure 2.20. These can be summarized in five attribute types:

- **Geometry** – a sequence of coordinate values defining the geometry of a line;
- **Descriptive** – text values describing the bridge, its associated stream and road
- **Location** – information showing where the bridge is located on a map
- **Elevation** – elevation of various bridge and channel characteristics
- **Comparison** – measures that define how closely a computed bridge characteristic matches a known value

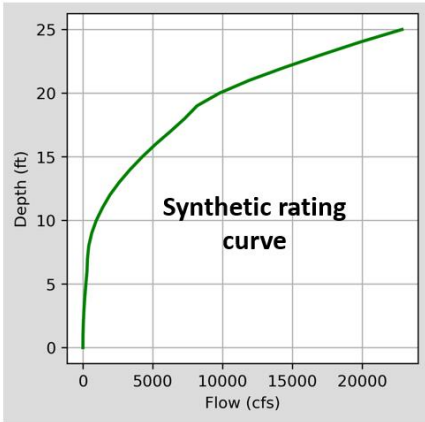
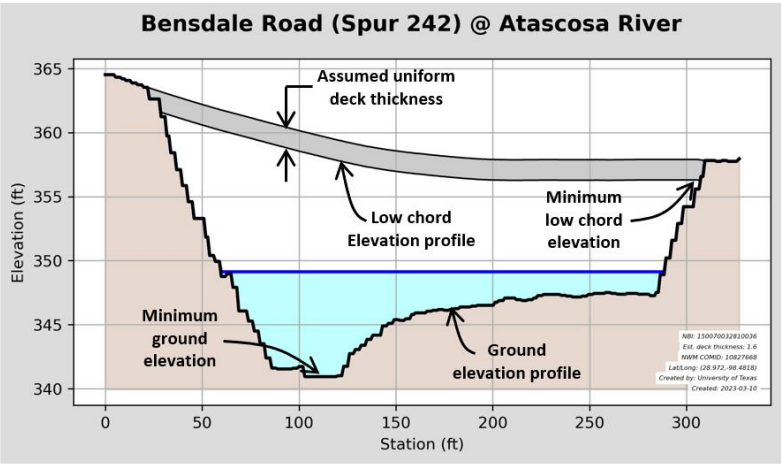
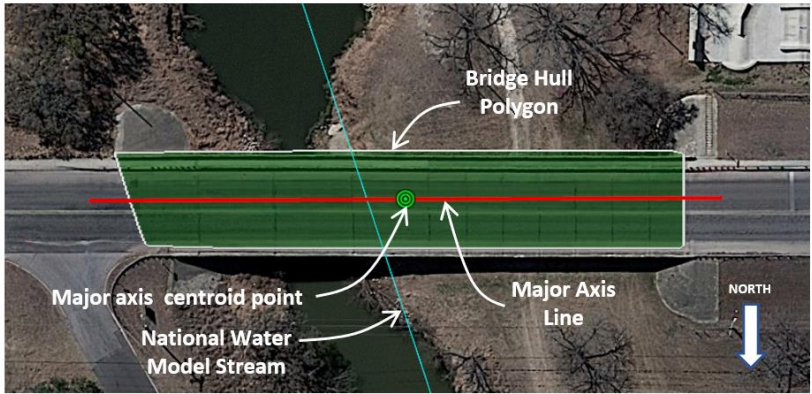


Figure 2.20 Summary of information contained in the bridge data specification

3. Flooding of Low Water Crossings

During a flood emergency response exercise that the Streamflow project team conducted with the Austin District of TxDOT in January 2023, significant concern was expressed by the Maintenance staff about the need for better information on flooding at low water crossings. This concern had earlier prompted the Austin District to commission a study of priority low water crossings (RPS Klotz Associates, 2017). That study identified 153 priority low water crossings in the Austin District, and identified and prioritized 20 of these locations as candidates for a recommended “High Water Decision System” conceived of as including warning signs, solar powered flashing beacons and field equipment that would automatically sense high water conditions at these locations. The Streamflow research team developed a process for rapid field assessment of low water crossings and applied it in the Austin District, as reported in Report P6B2 (Thies et al., 2022), surveying most of the 20 highest priority low water crossings and presenting the resulting data in an ArcGIS Storymap¹.

In this Chapter, the flooding of low water crossings is examined using one of these low water crossings, labeled 20B in the Storymap. This low water crossing is located on FM 150 at Onion Creek, as shown in Figure 3.1. It happens that there is also a USGS gauging station, Onion Creek near Driftwood, Tx, located nearby, which provides objective data for flood frequency analysis of flood discharge and water surface elevation. This low water crossing is a structure maintained by the San Marcos Maintenance Section of the Austin District. Frequent flooding at this location and the high traffic volume on FM 150 have prompted TxDOT to work towards increasing the culvert capacity of this low water crossing, and a HEC-RAS hydraulic engineering analysis has been carried out at this location examining various culvert capacity alternatives.



Figure 3.1. Low water crossing on FM 150 at Onion Creek near Driftwood, Texas showing the high water mark for a flood event inundating this road.

¹ <https://ut-austin.maps.arcgis.com/apps/MapSeries/index.html?appid=30acdecc9e5d4bae8568dc6a0047caab>

3.1. Description of a Low Water Crossing

This low water crossing is located on FM 150 West where it crosses Onion Creek, just south of Driftwood, Texas. Descriptive attributes from the TxDOT Roadway Inventory and the National Hydrography Dataset are summarized in Table 3.1. This highway is owned and maintained by TxDOT as part of the On-System roads, and is classified as level 5, a major collector, in a 7-level road classified system where level 7 is an Interstate Highway. This reach has a COMID of 5780099 in the National Hydrography Dataset and feature-id of 5780099 in the National Water Model Hydrofabric.

Source	Attribute	Value	Explanation
Road Characteristics			
TxDOT Roadway Inventory	MAINT_DIS	14	Austin
TxDOT Roadway Inventory	MNT_SEC	6	San Marcos
TxDOT Roadway Inventory	RIA_RTE_ID	RM0150-KG	Route ID
TxDOT Roadway Inventory	GID	1631232125	Geometry ID
TxDOT Roadway Inventory	DFO	9.15	Distance from origin
TxDOT Roadway Inventory	HWY	RM0150	Highway name
TxDOT Roadway Inventory	RB_WID	20	Road bed width (ft)
TxDOT Roadway Inventory	RDWAY_MAINT_AGCY	1	TxDOT maintenance
TxDOT Roadway Inventory	F_SYSTEM	5	Major collector
Stream Characteristics			
NHDPlusMR	HUC8	12090205	Watershed
NHDPlusMR	COMID	5780099	Stream ID
NHDPlusMR	GNIS_NAME	Onion Creek	Stream name
NHDPlusMR	REACHCODE	12090205000390	Reach code
NHDPlusMR	Measure	81.68	% dist. along reach
NHDPlusMR	TotDASqKm	320.91	Drainage area (Km2)
NHDPlusMR	SLOPE	0.002494	Stream slope
NHDPlusMR	QE_MA	53.155	Mean ann flow cfs
NHDPlusMR	VE_MA	1.2915	Mean velocity fps
National Water Model	feature-id	5780099	NWM reach ID

Table 3.1. Stream and road attributes for this low water crossing.

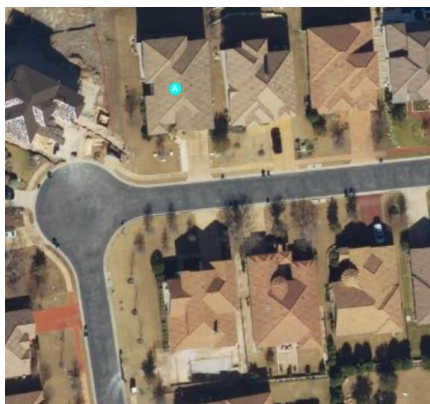
The physical layout of the culvert pipes is shown in Figure 3.2. Water flows from left to right in the picture. The pipe conveyance is corrugated metal of elliptical shape with width 50” and height 36”. Some of the corrugated metal is eroded away to a concrete surface. There are four pipes. The TxDOT staff gauge is at elevation 872.79 ft. The Crossing Type is low bridge slab crossing with culvert.



Figure 3.2. Low water crossing pipes and geographic location

3.2. Ecopia Road Representation

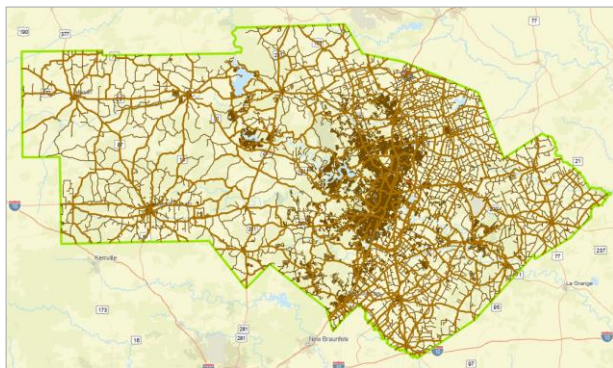
In the Beaumont flood emergency response exercise in January 2022, it was found that some road lines from the Texas Roadway Inventory were not near the centerline of the actual highway – in some instances they ran along the edge of the road, and in some smaller roads, they were not on the road surface at all. This prompted a search for a better description of roadway extent and centerline positioning. The resulting search led to the acquisition of Ecopia roadway polygons and road centerlines, Figure 3.3



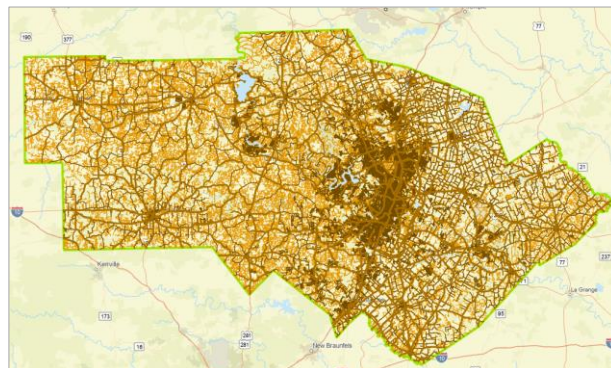
(a) Hexagon 6'' aerial imagery



(b) Ecopia road polygon and centerline



(c) 18,000 miles TxDOT Roadway Inventory



(d) 38,000 miles Ecopia Road coverage

Figure 3.3. Ecopia road coverage in TxDOT the Austin District

Ecopia AI <https://www.ecopiatech.com> is a company based in Toronto, Canada, which uses artificial intelligence to interpret aerial imagery and classify land cover into more than 20 categories, including roads and bridges. TxDOT RTI purchased the road and bridge polygon data and road centerlines for the Austin District for use in this Streamflow research project. In this instance, the imagery being interpreted is the Hexagon 6” aerial imagery purchased by TNRIS and licensed by TxDOT to which the Streamflow research team has access by being a TxDOT contractor. A comparison of the Hexagon imagery with the Ecopia interpretation is shown in Figures 3.3 (a) and (b). In general, it was found that the road polygon data are a remarkably good representation of actual road extent. There were some instances of roads under trees where the interpretation was faulty and a few cases where truss bridges with elevated superstructures were interpreted incorrectly, but in general these instances were few and the Ecopia data were found very suitable for use in this project. The separate classification of two classes of road features with bridges separated from roads was found to be accurate in some cases but entirely missing bridges in others, and it is apparent that the LIDAR-based bridge identification process described in Chapter 2 works more effectively than the Ecopia bridge interpretation algorithm.

The coverage of the Ecopia road dataset is remarkable. As shown in Figure 3.3 (c) and (d), the TxDOT Roadway Inventory maps 18,000 miles of roads in the Austin District, of which 4400 miles are on-System roads. The Ecopia road coverage is 38,000 miles, much of which is smaller roads in rural areas but some additional coverage also exists in urban areas, perhaps because of recent construction of roads and subdivisions. It is apparent that the “eye in the sky” of automated interpretation of aerial imagery is a very effective way of identifying the extent of a road network. The TxDOT Roadway Inventory was overlaid on the Ecopia road coverage, and it was found that 1600 miles or 9% of the 18,000 miles in the TxDOT Roadway Inventory in the Austin District have road lines not located on the Ecopia pavement surface, almost all of these being for the off-System roads.

3.3. Road Inundation

The road extent of FM 150 near the Onion Creek low water crossing is shown in Figure 3.4. Part (a) shows 6-inch Hexagon aerial imagery and Part (b) shows the Ecopia roadway polygon and centerline. As in Figure 3.3, the agreement between the aerial imagery and the Ecopia polygon is good, and the centerline is located in the middle of the road.

A **Road Ribbon** is a Polygon of the road extent which encompasses the LIDAR points at ground elevation. Part (c) shows the Road Ribbon with the LIDAR point cloud data for the road polygon obtained from TNRIS LIDAR coverage, with an overview on the upper image and a zoomed in view below that. Part (d) shows a Triangulated Irregular Network view of the LIDAR point cloud, which was built from an ArcGIS Terrain dataset that comprised the road polygon, LIDAR points and centerline, using the ArcGIS Terrain to Tin function. Part (e) shows a 1m Digital Elevation Model for the “road ribbon” which was resampled from a 3m DEM created by the Fathom firm for Texas.

A depth of flooding of 5 ft at this low water crossing corresponds to the water surface elevation of 877.79 ft because the TxDOT staff gauge has its base at 872.79 ft above geodetic datum. Figure 3.5 (a) shows the depth of flooding with the water surface elevation and three profiles of the road centerline elevation, one derived from the TIN surface model, a second derived from a 1m DEM developed from the TIN, and a third derived from the 3m Fathom DEM used in developing the flood inundation maps in Texas. It can be seen that the difference between the TIN and 1m DEM developed from the TIN is very small, but the

3m Fathom DEM underestimates the road centerline elevation significantly. This occurs because the road elevation across the road profile is influenced by low road elevations in the ditches next to the road and the 3m cells are large when compared to a normal road line width of 12 ft. It is concluded that either a TIN formed from LIDAR points on the road ribbon or a 1m DEM derived from that TIN be used to represent road surface elevation.



(a) Hexagon 6" aerial photogrammetry



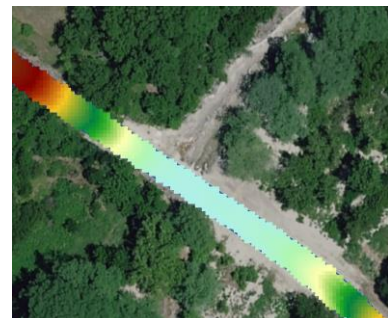
(b) Ecopia centerline and road polygon



(c) LIDAR Point Cloud



(d) Triangulated Irregular Network (TIN)



(e) 1m Digital Elevation Model

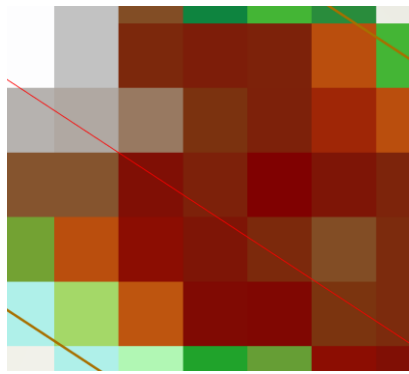
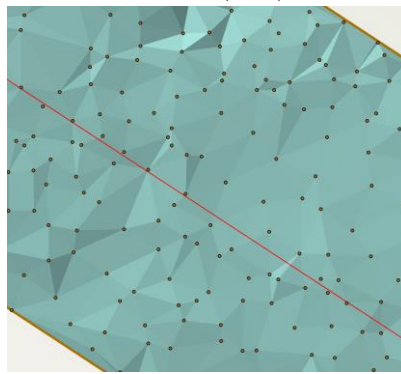
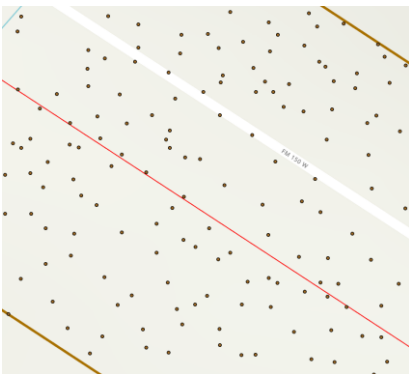
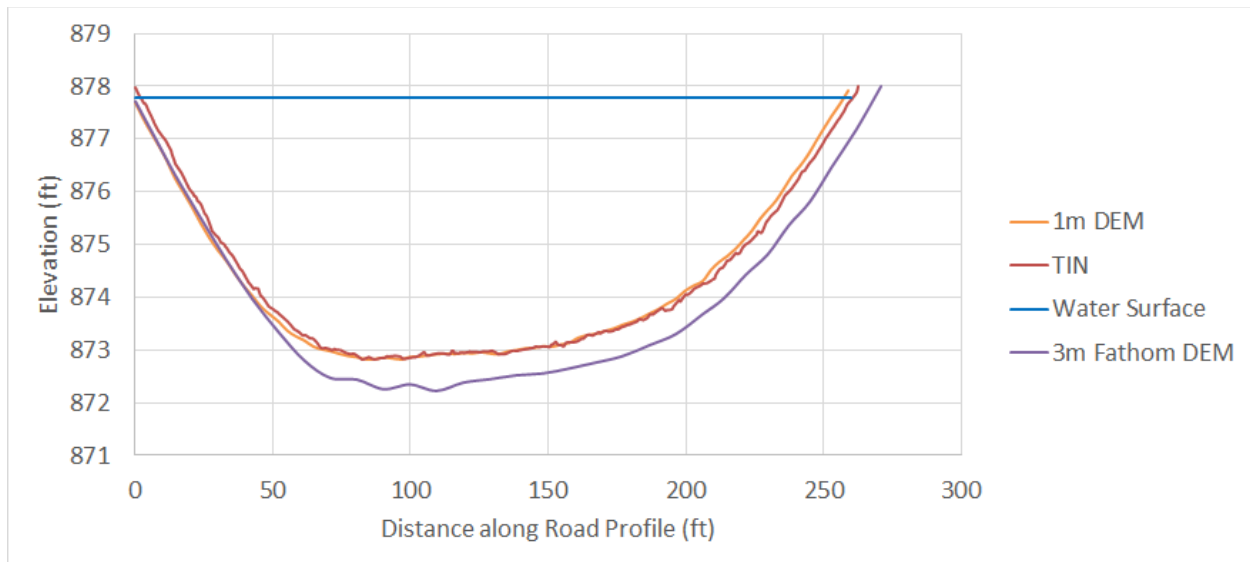
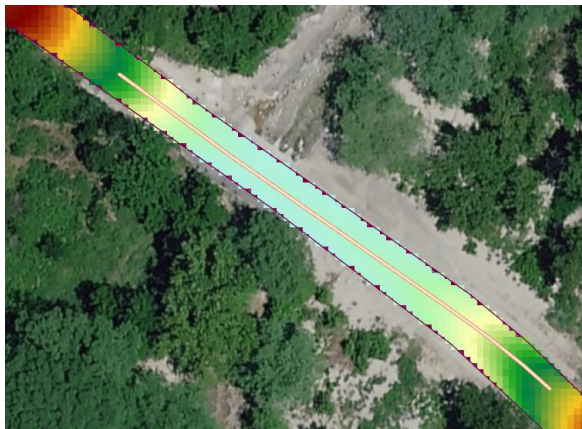


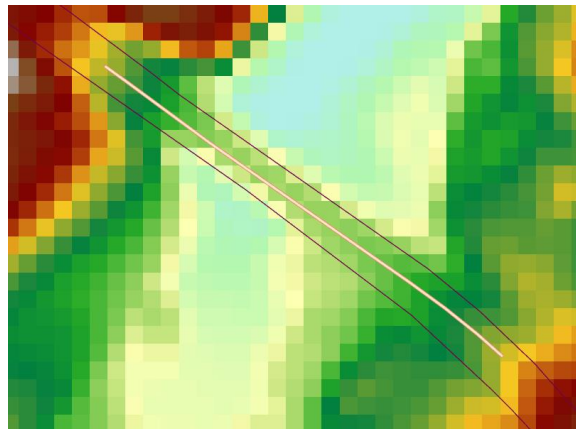
Figure 3.4. Geospatial representations of the “road ribbon” at the low water crossing



(a) Water surface and road elevation profiles



(b) 1m DEM derived from road LIDAR points



(c) 3m Fathom DEM for Texas

Figure 3.5. Water inundation along the road centerline

3.4. Discharge and Water Surface Elevation

The National Water Model continually computes and forecasts streamflow discharge in 2.7 million stream reaches of the continental United States, of which this low water crossing lies on Onion Creek, whose stream centerline is labeled in the National Water Model as feature-id 5780099. To determine flood inundation at the low water crossing, it is necessary to have a rating curve that relates discharge and water surface elevation. The TxDOT Austin District has built a 1-D HEC-RAS model for this reach of Onion Creek, as shown in the Figure 3.6. This rating curve is taken from the design model for increased culvert capacity, so the current flow conveyance is not exactly as shown in Figure 3.2 but the difference is not important for the analysis presented here. Where HEC-RAS models are not available, a usable culvert

rating curve can be determined by using the HY-8 culvert hydraulic analysis program (Federal Highway Administration (2023)).

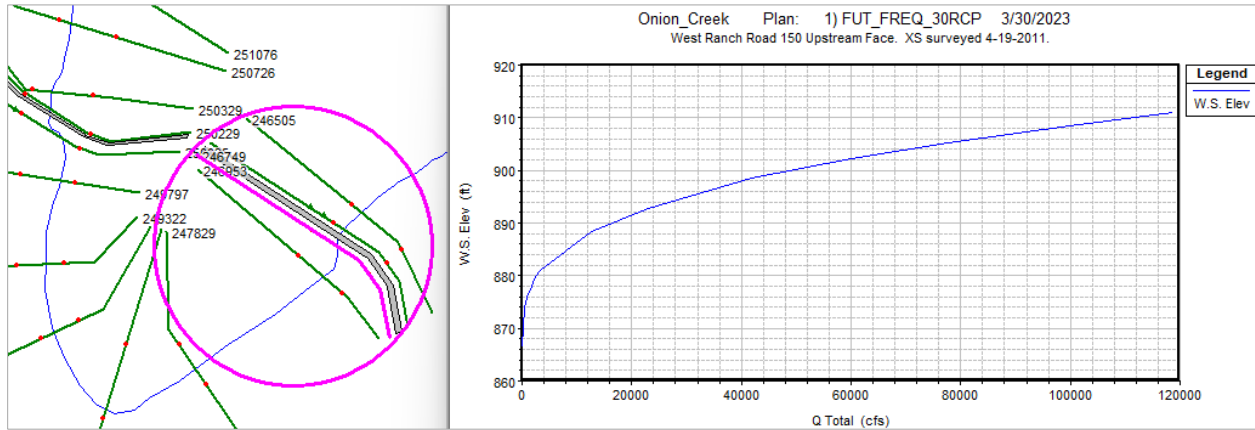


Figure 3.6. Rating curve for cross-section 246749 located just upstream of low water crossing. Source of data: Joseph Goessling and Matt Sanner, TxDOT Austin District

As each new version of the National Water Model is developed, a reanalysis is carried out, simulating the history of discharge throughout the stream network of the nation for an historical period. For National Water Model version 2.2, this reanalysis covers 42 years, 1979 through 2020. The annual maximum discharge computed in each year has been subjected to a frequency analysis by the National Water Center and the results published as a map service.² The result for reach 5780099 can be seen in Figure 3.7(a). This result can be compared with a standard flood frequency analysis carried out using the USGS Annual Peak data for site 08158700, Onion Creek near Driftwood, Texas. There is a reasonable degree of agreement between the flood frequency curve derived from the National Water Model version 2.2 reanalysis and the observed flood frequency curve at the USGS gauge. This comparison needs to be examined at many other sites before any definitive conclusions can be drawn about its more general validity.

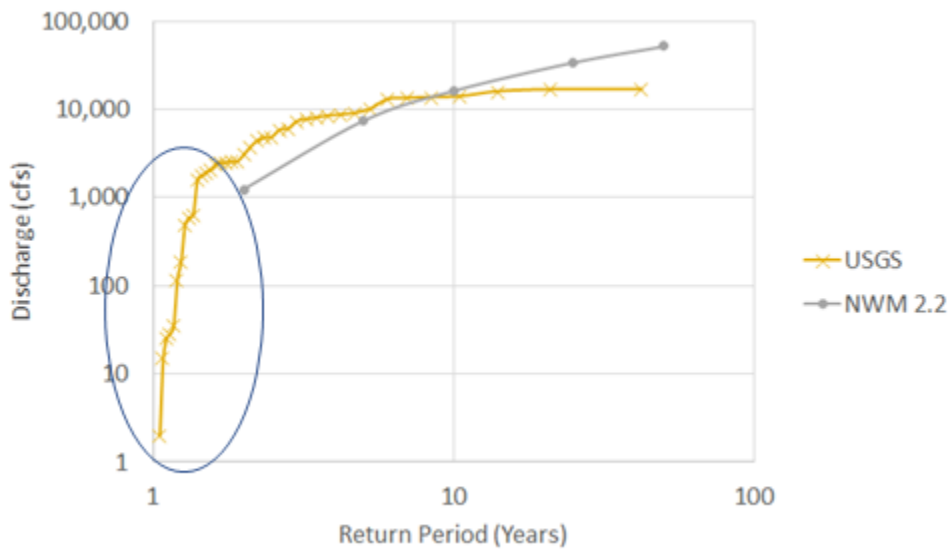
² https://maps.water.noaa.gov/server/rest/services/reference/nwm_flowlines/MapServer

Flowlines - Flowlines

oid	600019
NWM Feature ID	5780099
Name	Onion Creek
Stream Order	3
USGS HUC6	120902
NWM Version	2.2
High Water Threshold (cfs)	3,175.67
2% Streamflow (cfs)	51,621.28
4% Streamflow (cfs)	33,785.24
10% Streamflow (cfs)	16,138.53
20% Streamflow (cfs)	7,326.7
50% Streamflow (cfs)	1,217.22



(a) Frequency analysis results for feature-id 5780099 from National Water Model version 2.2



(b) Flood frequency analysis from National Water Model reanalysis data and USGS observations for station 08158700, Onion Creek near Driftwood, Texas.

Figure 3.7. Flood frequency analysis at the USGS gauge and from National Water Model reanalyses

The local datum of the road stage gauge board at this low water crossing is at elevation 872.79 ft above geodetic datum. If the standard depths of road flooding are added to this, namely 0.5 ft, 2 ft, and 5 ft, the corresponding discharges can be determined from the rating curve in Figure 3.6 and their return periods

estimated from the flood frequency curve in Figure 3.7(b), with results given in Figure 3.8. It is apparent that all the flood map depths occur frequently, with return periods better measured in months rather than years. This is indicated by the blue oval highlighted in Figure 3.7(b).

Depth (ft)	WSE (ft)	Discharge (cfs)	Return Period (Years)	Return Period (months)	Depth Range	
0	872.79	270.42	1.25	14.95		0 - 0.5 ft
0.5	873.29	338.03	1.25	15.06		0.5 - 2 ft
2	874.79	540.85	1.30	15.55		2 - 5 ft
5	877.79	1554.93	1.40	16.79		> 5 ft

Figure 3.8. Return period of standard flood depths at the low water crossing

It can also be noted in Figure 3.7 (a), there is a High Water Threshold at 3175.67 cfs. This corresponds to a 3.2 year return period flow in the NWM 2.2 reanalysis in Region 7 shown in Figure 3.8. In Area 5, a 1.6 year return period to define the High Water Threshold.



Figure 3.8. Regions for defining frequencies of occurrence of High Water Conditions (McCabe and Wolock, 2016)

3.5. Water Velocity

A significant concern at Low Water Crossing is the water velocity over the road. This can be computed for each water surface elevation in a rating table. The inundation length along the road is found by creating a water surface raster at this elevation, subtracting the DEM from it, and isolating all the cells whose depth is greater than 0. This forms an inundation area for the road at this depth, as shown in

Figure 3.9. Using the ArcGIS function Zonal Statistics by Table for the flooded cells along the road centerline, the number of flooded cells, n , and the sum of the water depths, d at these cells can be combined with the cell width, w , to compute the flow area, A , and then the velocity V , using the discharge Q coming from the rating table.

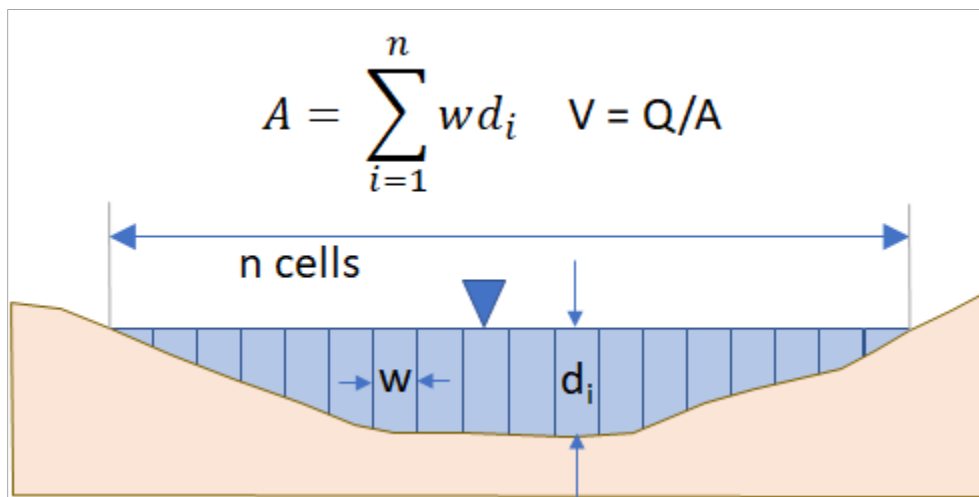
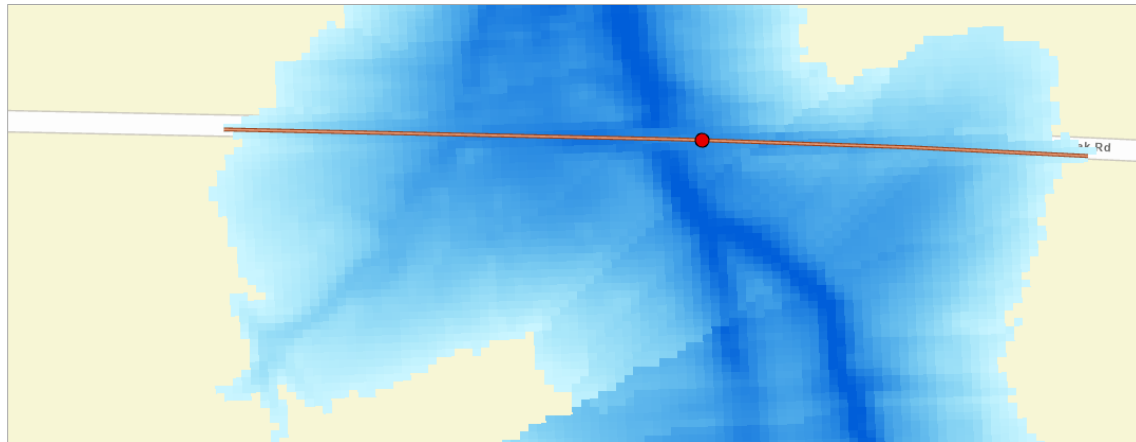


Figure 3.9. Computation of water velocity at a low water crossing

4. Road Flooding

This section describes concepts and approaches for depicting flooded roads information in support of an online mapping application with implementation examples for ArcGIS. The application's objective is to support Texas Department of Transportation (TxDOT) personnel from those in the field to those coordinating operations, before, during, and/or after flood events. The intended audience for this section is TxDOT personnel with at least some familiarity with TxDOT's geospatial data assets. The scope of this section is limited to the display of flood inundation along roads. It does not cover the depiction of flooding at key locations such as bridges or low water crossings.

4.1. Data Sources and Assumptions

This methodology assumes that there is a source of flood inundation information and a representation of roads, both of which are compatible with geographic information systems (GIS) software. Correcting or identifying errors with either type of data source is beyond the scope of this section.

The extent of flood inundation is difficult to map in real-time from direct observation. Instead, the typical practice is to compute flood inundation from other readily available data, such as measured or calculated values of streamflow or water level in river reaches. Streamflow can be converted to water level using rating curves which can be derived using publicly available data sources. The water level can then be compared to local topography to produce a dataset representing flood inundation (also known as flood depth). These flood inundation datasets are typically stored as raster data in GIS, which is a grid of cells where each cell is attributed with the flood depth value at that location.

Crucial to the accuracy of the flood inundation data is the underlying topography data. Currently, widely available elevation data for the nation is typically hydroconditioned (also known as hydroflattened), which means some structures such as bridges over water have been removed so that the elevation data can be used to map surface water channels. This presents a problem for mapping flood impact on the road network, since the flood depth at a bridge would appear to be very high when in fact, the actual bridge (which has been removed from the elevation data) could well be above the water surface. In such cases the elevation data need to be "healed" to have road and bridge elevations restored before mapping inundation. In Texas, there is broad coverage of LiDAR-derived elevation data which can be used to heal elevation data. The application of such data to heal terrain is beyond the scope of this section. Rather, this section assumes that one has access to raster inundation data that has been deemed acceptable for use.

Assuming accurate elevation data, the following sources can be used to estimate flood inundation.

National Water Model

Statewide, flood inundation can be derived from the National Water Model (NWM) which predicts streamflow for more than 100,000 river segments in Texas. The model is run by the National Water Center and results are posted online regularly for public consumption. The river network segments are based on the National Hydrography Dataset medium resolution flowlines. These flowlines cover the major surface watercourses, though some smaller watercourses are not included such as ephemeral streams which could convey water during a flood. Still, this is the best source of forecasted streamflow data for the state.

In an exercise conducted with TxDOT's Austin District in January 2023, The University of Texas at Austin (UT) demonstrated that flood inundation could be computed using synthetic rating curves for river reaches in NWM. However, in some cases the result indicated flooding far greater or less than what was expected for the given scenario. While the synthetic rating curve approach used with NWM is simple and can be applied statewide, there are more accurate approaches available. One of these is to use a hydraulic engineering model such as HEC-RAS to computer water level for a given streamflow. The trade-off for this higher accuracy is the increased cost in setting up and executing the model. Therefore, using hydraulic models to derive rating curves may be best suited for the most critical locations in the road network such as bridges, defaulting to NWM synthetic rating curves elsewhere.

The National Water Model is available as several products, providing streamflow estimates for time points from right now up to 30 days out. The products pertinent to Texas include:

- **Analysis and Assimilation** – Estimate of current streamflow conditions. This product is computed hourly (i.e., you can download the latest computed result each hour).
- **Short Range Forecast** – Streamflow forecast out to 18 hours with a streamflow value each hour. This product is computed hourly.
- **Medium Range Forecast** – Streamflow forecast out to 10 days with a streamflow value each hour. This product is computed every six hours.
- **Long Range Forecast** – Streamflow forecast out to 30 days with a streamflow value every six hours. This product is computed every six hours.

With its frequent updates, the short-range forecast is useful during storm events, especially in areas prone to flash flooding. The medium and long-range products would be more useful in planning for upcoming events when there is time to reposition resources to areas predicted to have the greatest flood impact.

Due to the uncertainty in predicting weather events further out in time, the medium and long-range forecast are run with varying inputs to produce several results. Together, these results form an ensemble of possibilities, and they begin to allow one to associate a likelihood of occurrence with a given flood forecast. There are seven ensemble members in the medium range forecast and four with the long-range forecast.

One can add forecasts to the most recent ensemble by including other recent forecast results. For example, since the long-range forecast is run four times per day, with each run producing four ensemble members, one could use all the long-range forecasts throughout the day to accumulate an ensemble consisting of 16 members. One could also treat the short-range forecast as an ensemble by including other recent short-range forecasts. Of course, one can only include as many forecasts in an ensemble as the time coverage allows. For example, one could not include more than 18 short range forecasts since that forecast only goes 18 hours out; a forecast more than 18 hours old would not have an overlapping time period with the most recent forecast. One should also consider that more recent forecasts will likely be driven by more recent and more accurate rainfall data.

If one does not want to consider probabilities, then one could just look at the mean value of forecasted streamflow across all available ensemble members or take the first member only.

Stream Gauges

As part of this TxDOT Streamflow project, the United States Geological Survey (USGS) installed 80 RQ-30 radar gauges which measure water level and streamflow where rivers flow under TxDOT bridges. While few compared to the number of streams in the NWM, these gauges provide actual observations of water level rather than estimated values and are far more accurate than the NWM.

Aside from the gauges installed for TxDOT, there are additional USGS gauges or gauges from other networks available from which streamflow or water level information can be obtained. For those reporting only streamflow, a rating curve must be used to convert the streamflow to water level. Still, the result will likely be more accurate than that computed by the NWM alone.

In a flood mapping application, data from stream gauges can be used in lieu of NWM calculations where those stream gauges exist to show current conditions, defaulting to NWM where gauges are not installed. Current observations from gauges can also be assimilated into forecasts to improve forecast accuracy, which is one avenue of research being conducted at UT, though that process is beyond the scope of this section.

Flood Inundation in Flat Areas

For areas with flat topography like those along the coast, flooding due to local rainwater ponding can be as significant as or greater than overbank flow from rivers. Since NWM and stream gauges only indicate water levels in rivers, one may need to use additional sources of flood inundation. For example, one could run a “rain on grid” simulation for several design storms using a coupled hydrologic and hydraulic model. When an actual storm is forecasted, one can select the best matching design storm given the forecasted rainfall totals and storm duration and see what flood inundation is likely to occur.

Linear features representing road segments (in GIS terms, “polyline”) are available from several sources such as TxDOT and OpenStreetMap. These segments are typically drawn down the centerline of roads. They depict road network connectivity but do not visually indicate road width. To include road width and map the actual extent of the road surface, one can use product derived from imagery, such as polygonised roads from the commercial vendor Ecopia.

The methodology in this section is agnostic as to the source of road location data. It assumes the roads are in a GIS-compatible format, and that the roads are associated with whatever attributes are of concern to TxDOT (e.g., road name, road type, district, county). The roads are assumed to be spatially accurate. Inaccuracies in road location would result in incorrect assessments of flood inundation when the two datasets are overlain.

4.2. Designing the Output

This section describes alternatives for displaying flooded roads in a mapping application. It considers data availability and accuracy, user perspective, and technological limitations.

Spatial Representation

There are several ways of depicting roads in GIS: lines representing connectivity and centerlines, polygons representing road extent, or a grid of cells coded as a road. The right choice depends on the data's accuracy and resolution and the technological capabilities available. For example, one could use a road grid or portions of road polygons to indicate exactly which portions across a given road are flooded,

such as the road shoulder or only the first of three eastbound lanes. However, for ungauged areas or areas without a good hydraulic model, the uncertainties in flood mapping may not warrant the portrayal of accuracy the user would assume with a road grid or polygons. If the elevation data are coarser than a foot or two in horizontal resolution (also known as grid cell size), then it is possible that grid cells that span both a road and the adjacent drainage ditch could be incorrectly classified as road but also show inundation. Regarding technology, within TxDOT a grid of roads would be published as an ArcGIS image service, which is of a different nature than vector-based services (for polylines and polygons) and would require a license beyond the basic ArcGIS for Server license. Considering these challenges, the authors suggest starting with a polyline depiction of roads, and moving toward polygon or grid representations once the data accuracy is deemed sufficient and the technological resources are available.

Another technological issue is the rendering of features in the final Web application (such as TxERA, but beyond the scope of this section). In testing with ArcGIS Online, the authors found that very short road segments are not always drawn at various scales. This is a limitation of ArcGIS Online, but if the final Web application has a similar limitation, then a different approach from polyline, or some sort of clustering at coarse scales, may be required.

There are also several ways of depicting flooding on roads. One could show the estimated flood depth value at every location along the road; however, such detail may prevent a user from quickly assessing impact. To simplify the information content for the end user, one can bin the flood depth values into meaningful categories and then use colors for each category when drawing roads on a map. For example, consider the National Weather Service (NWS) Advanced Hydrologic Prediction Service (AHPS) (<https://www.drought.gov/data-maps-tools/advanced-hydrologic-prediction-service-ahps-river-gauge-data>), which color codes stream gauges based on flood severity. Without knowing any streamflow values, the end user can assess within seconds which areas of the nation have rivers at flood stage. (This idea of simplified display also lends itself to the polyline depiction of roads described above, rather than a polygon or grid representation.)

In exercises given to TxDOT for the Streamflow II project, the authors used the color scheme in Figure for depicting flooding on roads, which bins depth values into the following ranges. The color scheme seemed well-received. These ranges and colors were inspired by those used in the FIMAN-T system in North Carolina.

- 0 to 0.5 feet - slight risk to normal vehicular traffic
- 0.5 to 2 feet - possible risk to specialized vehicles that may be required to traverse the road
- 2 to 5 feet - elevated risk to specialized vehicles
- Greater than 5 feet - likely requires boat to access

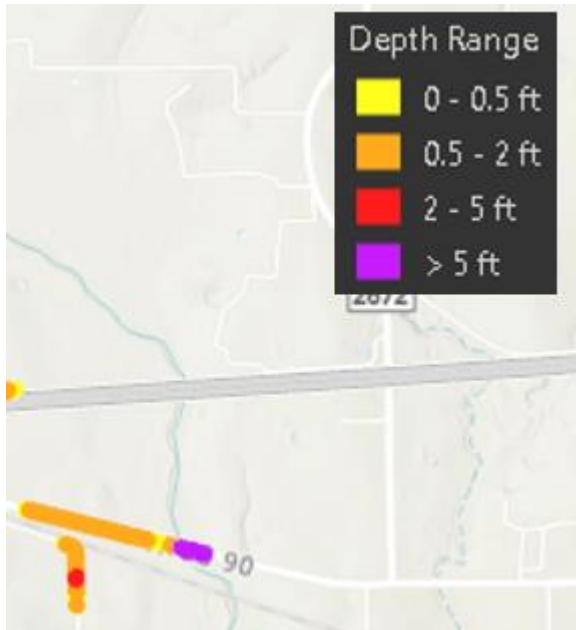


Figure 4.1. Road symbology showing flood categories by depth range for an example flood

When visualizing roads by these categories, one must decide over what length of road to apply the category. Options include:

- Color each portion in each depth range individually. This is the most accurate approach but can lead to very short segments of alternating colors when the depth values are close to the point where one bin ends and another begins. Also, the short segments may not display at certain scales in ArcGIS Online.
- Color the entire segment of road (e.g., from one road intersection to the next) based on the worst inundation along the road. This results in longer segments, which may reduce the information that the end user needs to digest and may improve drawing performance. This approach is useful if the user only wants to know the worst inundation on the road, as in, “What kind of vehicle am I going to need to get from point A to point B.” However, if the user wants to know the flood severity along each portion of the road, as in, “Which address points along this road can evacuate safely without assistance from emergency responders,” then this approach may not show the required detail.
- Split roads into specified lengths, and color code each segment based on max severity along each segment. This is like the above approach, except roads are partitioned by length rather than intersection-to-intersection. This is the approach used by the FIMAN-T system in North Carolina and so is included here for completeness. However, when inquiring with the consultant who developed FIMAN-T, they could not provide justification for the use of the 50-foot segments. As of this writing, FIMAN-T is focused on inundation at select gauge locations. This local scale around gauges may work with 50-foot segments but may be too cumbersome for a statewide implementation.

The intent of the depth range bins is to categorize roads based on impact to the transportation network, specifically as to traversal of the road by vehicle category. A more accurate assessment of this kind of

impact would be flood hazard level, which is a combination of flood depth and water velocity. A low flood depth with high water velocity could be just as dangerous as a higher flood depth with lower velocity. Computing accurate water velocity across the road requires hydraulic modeling. Until such modeling becomes ubiquitous across the state, the simpler approach of showing flood depth may be more practical. However, this does not preclude one from indicating flood hazard level at critical locations where hydraulic models do exist, such as certain bridges or low water crossings. Displaying flood data for those features is beyond the scope of this section.

The authors recommend color coding each portion of the road based on flood depth range as this provides a balance of detail and simple display. The authors are currently investigating how to overcome technological issues in displaying short road segments.

Temporal Representation

Due to the number of forecast products and time steps in NWM, there are dozens of ways of viewing flooded road information temporally. For example, one could look at values at each time step, or the maximum flooding predicted across all time steps in a given forecast, or the mean prediction across all ensemble members, or the mean of all the maximums across each time steps in all ensemble members, mean minimum, and so on. One may want to visualize data based on “how soon is the road going to be impacted,” or “when will the maximum impact be,” or for post-event inspection, “When is a flooded road not going to be flooded anymore.” Whatever temporal view is chosen will have a significant impact on how processing of the data is handled and the computational load, as well as how complex or busy the user interface will appear to the end user.

Choosing to include information about when a given segment of road will be flooded or when its status will change from flooded to “not flooded” could have a great impact on how the system is designed. At a minimum, supporting this functionality requires an attribute identifying a given road segment. This attribute could then be used to group information about status changes between flood and not flooded. Note that an attribute like road name is likely not granular enough. For example, “I-10” crosses the entire state, and so reporting that I-10 is flooded may be helpful to someone near Beaumont during a tropical storm but not to someone in El Paso at that same time. The GID attribute in the TxDOT Roadway Inventory may be a better fit from a granularity perspective, though those IDs may not mean much to someone viewing a summary table of closures.

Furthermore, one must consider what happens when a single segment of road, which may logically be a single feature in the roadway inventory, has two distinct areas of flooding during a given event. Should each area of flooding be treated as a separate event, or should the entire segment be considered? Over time, a single large stretch of flooded road could evolve into several smaller isolated stretches as floodwaters recede, which makes treating each distinct area as its own event complicated. The authors recommend summarizing information about onset or termination of flooding across the entire road segment rather than by each distinct area of flooding. Ideally, each segment would be a single feature in the road dataset, have its own unique identifier, and have a label that the end user could use to identify the road and its location.

Attributes of Interest

Prior to any processing for flooded roads estimates, the GIS dataset representing roads should be attributed so that each road segment can be identified and so that summaries of flooded roads can be

computed. For example, if knowing when a road segment will be flooded or when flood water will recede is required, since a single segment of road could have several pockets of flooding along it, the road needs a unique identifier to tie all the pockets together. The road will also need a name or label such as “Smith Road” to help the user identify it and convey its location to other personnel.

To support a summary table that shows total length of flooding in each TxDOT district according to road type (Interstate, highway, county road, etc.), the roads dataset will need attributes such as District Identifier and Road Type for grouping, and Road Length for computing statistics.

When the user clicks to view attributes for a single flooded road segment in the map, they may want to see details such as date and time represented by the flooded road, depth class for the flooded road segment, e.g., “2 to 5 feet”, date when flooding began for the overall road segment (including this and any other parts of the segment that are flooded during this forecast), and date when flooding is predicted to end for the overall road segment. Computing and assigning these attributes would be part of the flooded roads workflow.

4.3. Caching Results

Computing flooded roads statewide in real-time from gauges and forecasts can be a heavy task. Therefore, the authors recommend precomputing flooded roads for a variety of water conditions and storing those results in a database. This cache of results can then be searched to find the closest match for a given water condition described in a forecast or represented by a given stream gauge reading. The water condition for which the cache was computed may not exactly match the forecast or current observation, but there is always some uncertainty in the inundation anyway, and so the key is to use enough scenarios when building the cache such that all possible flood scenarios are reasonably represented the subset stored in the cache. For flooding based on overbank flow from streams, the authors suggest selecting water levels in the stream at half-foot increments (e.g., a 10-ft flood, a 10.5-foot flood, an 11-foot flood), and using inundation associated with that water level to estimate flooded roads.

Feature and Scenario Identifiers

Two attributes are key for relating a flooded road segment in the cache to a flood scenario: a scenario identifier and a feature identifier. The feature identifier represents the feature associated with the water data relevant to a given road. For streamflow forecasted from NWM, each stream segment includes the local catchment that drains to that stream. The logical choice for feature identifier in this case is the unique ID of the catchment that the road segment lies within. For water level from a stream gauge, one would select roads near the gauge and assign as the feature identifier the unique ID for the gauge. For a rain on grid simulation, the feature identifier would represent the entire model domain.

One could use a generic name like `Feature_Id` for the feature identifier attribute, though there is also merit in using a name such as `Catchment_Id` to make the relationship between the road and the relevant water feature more obvious.

The scenario identifier, named `Scenario_Id`, identifies the precomputed flood scenario at the given feature. Examples of flood scenarios include the flood associated with a particular water level in the stream, or the flood associated with a particular stream discharge. `Scenario_Id` could be any arbitrary identifier. Though it may be convenient to encode intelligence into the identifier, for example by using the water depth in the stream in centimeters for the identifier, e.g., 65, the authors generally do not

recommend using Scenario_Id as the only place where such intelligence is encoded. One may find it useful to keep a separate table listing the scenario identifiers for each feature along with the associated stream water level and discharge.

When a water value is obtained for a current flood situation, for example a water level reading at a gauge, the cache is searched for any road segments that have the feature identifier of the gauge and whose flood scenario is the closest match to the actual water level reading. This is where encoding intelligence into Scenario_Id can be convenient, since finding the closest match would simply mean converting the water level to a stream depth in centimeters and then comparing to the Scenario_Ids. If arbitrary IDs are used instead, then an extra step is required in which the water value is matched with Scenario_Id, for example by using a lookup table with columns for feature identifier, scenario identifier, and water level. Note that the water level could instead be stored as a column in the cache, eliminating the need for a separate lookup table. However, the authors recommend against this, as there could be multiple types of features in the cache such as road lines, low water crossing points, and bridge polygons, all of which could reuse a single scenario lookup table.

It is the combination of desired feature identifier and scenario identifier that selects road segments from the cache. Therefore, scenario identifiers only need to be unique for a given feature such as a stream gauge. It does not matter if the same scenario identifier is used for different features.

Flooding Description

The flooded road features need an attribute to store a representation of the degree of flooding on the road. As a simple example just to illustrate the concept, a Flood_Severity attribute could store text descriptions such as “Minor Flood” or “Major Flood.” A more useful attribute might be Depth_Class, which stores a code indicating the range of depth values over the road. Some example codes and values are shown in Table 4.1.

Code	Depth range
1	0 - 0.5 ft
2	0.5 - 2 ft
3	2 - 5 ft
4	> 5 ft

Table 4.1. Depth Class codes and associated depth ranges

Once retrieved from the cache, a flooded road segment needs the usual attributes for the road such as road identifier, name, and district identifier. These could be stored directly in the cache as attributes of each flooded road segment. If this causes problems with storage space, one could instead just store identifiers for the road, water feature, and flood scenario in the cache, and store the other road attributes in a separate lookup table indexed by road identifier. This saves space but requires an extra step of joining those attributes to the flooded roads when retrieving them from the cache. For simplicity, the authors recommend storing the attributes directly on the road segments until disk space becomes an issue.

Cache Maintenance

The flooded roads cache requires updates with changes to the road network such as the addition of a new road or corrections to the GIS representation of an existing road. The cache also requires updates when

flood scenarios change, which would happen if a more accurate hydraulic model became available for computing flood inundation in a given region. In these cases, the cached features for the affected roads and scenarios would need to be overwritten.

Having attributes such as road identifier, water feature identifier, and district identifier on cached features makes it easy to filter for just the roads that need to be replaced with updates. The water feature identifier also enables the cache to store results associated with multiple sources of water data such as stream gauge observations and National Water Model forecasts, as long as feature identifiers are globally unique across all the included water data sources.

To support maintenance provenance, one could add a table with attributes for road identifier, feature identifier, date of cache edit, reason or purpose of the edit, and person who performed the edit.

4.4. Example Implementation: Maximum Flooding for a Given Forecast

The following example shows how flooded roads could be displayed for the maximum flood predicted from a National Water Model forecast. The example demonstrates the author's recommendations from previous sections, namely, that flooded roads are depicted as line segments color coded by depth range, and that flooded roads are precomputed for a variety of flood scenarios.

This example assumes the following:

- ArcGIS is used for GIS processing and map service display of flooded roads.
- The projection of the online map in which roads will be displayed is EPSG:3857 (Web Mercator).
- Forecasts will come from the National Water Model (NWM), which predicts streamflow for river segments. Each river segment is associated with a local catchment that drains to that segment.
- We have a set of precomputed flood depth grids named by catchmentId_scenarioId.tif, all located in a single folder. How those grids are generated is beyond the scope of this section.
- Depth grids are expressed in 1/10th of a foot (NAVD 88). Example: a value of 165 means 16.5 ft.
- An external application will provide a table of requested flood scenarios, for example by converting forecasted streamflow to water depth and finding the nearest precomputed flood scenario matching that depth.
- The reader is familiar with ArcGIS. For example, if the instructions say, “Use the Make Feature Layer tool...” it is assumed that the user knows to open the Geoprocessing pane, search for the Make Feature Layer tool, and run the tool.

For simplicity, this example works on a local copy of TxDOT data. It does not prescribe how data should be managed at TxDOT or which production databases should be used. The intent is to demonstrate the geoprocessing methodology rather than the data management scheme.

Prepare Base Data

The result of this section includes two feature class and a table:

- Roads (Roads_Prj), in the right projection with only necessary fields.
- An empty copy of roads (FloodedRoadCache), where we will build the cache of flooded roads for all possible scenarios.

- An empty table of requested scenarios (RequestedScenarios), where we will load requested scenarios from an external source at run time. This enables quick selection of desired scenarios from the cache.

The procedure to prepare base data is:

1. Download the TxDOT Roadway Inventory from <https://gis-txdot.opendata.arcgis.com/datasets/TXDOT::txdot-roadway-inventory/about>
Save the geodatabase as **Roadway_Inventory.gdb**.
2. Edit the metadata summary for **Roadway_Inventory.gdb** to indicate the download date.
3. Use the Make Feature Layer tool to make a layer from the roads in **Roadway_Inventory.gdb**.
The query expression below was provided by Michael Chamberlain of TxDOT and is intended to filter out unwanted road lines like those representing median centerlines.
 - a. Expression:

```
RDBD_ID IN ('GS', 'RG', 'AG', 'BG', 'LG', 'MG', 'PG', 'SG', 'XG', 'YG', 'TG')
OR (RDBD_ID = 'KG' And (MED_TYPE = 0 Or HWY_DES1 NOT IN (0, 3, 4, 5)))
OR HSYS IN ('LS', 'CR')
```
 - b. Fields:
 - i. OBJECTID
 - ii. SHAPE
 - iii. GID
 - iv. HSYS
 - v. HNUM
 - vi. HSUF
 - vii. STE_NAM
 - viii. DI
 - ix. CO
 - x. MAINT_DIS
 - xi. MNT_SEC
 - xii. F_SYSTEM
4. Use the **Copy Features** tool to copy the roads to a new, temporary feature class. This is necessary because the Project tool does not honor definition queries.
5. Use the **Project** tool to project the roads copy to EPSG 3857, with **Preserve Shape** checked and a maximum offset of **one foot**. Save as **Roads_Prj**. Using the same coordinate system as the online map improves drawing efficiency.
6. Add a label field to **Roads_Prj**. This will serve as a human-friendly label for each road.
 - a. name: Label
 - b. type: Text
 - c. length: 50
7. Calculate **Label** using a Python expression.
 - a. Label =

```
make_label(!HSYS!, !HNUM!, !HSUF!, !STE_NAM!)
```
 - b. Code Block:

```
def make_label(hsys, hnum, hsuf, ste_name):
```

```

if hsys is None:
    hsys = ''
if hnum is None:
    hnum = ''
if hsuf is None:
    hsuf = ''
if ste_name is None:
    ste_name = ''
if ste_name:
    return ste_name
elif hnum.isnumeric():
    hnum = str(int(hnum))
    if hnum == '0':
        return hsys
    else:
        return (hsys + ' ' + hnum + ' ' + hsuf).strip()
elif hnum:
    return hnum
else:
    return hsys

```

8. Use the **Delete Field** tool to delete these unneeded fields in **Roads_Prj**.
 - a. HSYS
 - b. HNUM
 - c. HSUF
 - d. STE_NAM
9. In the geodatabase containing **Roads_Prj**, create a **coded value domain** for the depth classes.
 - a. Name: Depth_Class
 - b. Description: Describes severity of flooding on road
 - c. Type: Short Integer
 - d. Codes and descriptions:
 - 1: 0 - 0.5 ft
 - 2: 0.5 - 2 ft
 - 3: 2 - 5 ft
 - 4: > 5 ft
10. To **Roads_Prj**, add a **Catchment_Id** field of type **Long**.
11. Add a **Scenario_Id** field of type **Short**.
12. Add a **Depth_Class** field of type **Short**. Assign it the **Depth_Class domain**.
13. Use the **Create Feature Class** tool with **Roads_Prj** as the template to create a polyline feature class named **FloodedRoadsCache** with the same projection as **Roads_Prj** and set Has M to **Yes**.
14. Repeat the previous step to create a feature class named **FloodedRoads**. This will store the flooded roads that are extracted from the cache and displayed in the map service as new water forecasts are obtained.
15. To **FloodedRoads**, add a field named **Datetime** of type Date.
16. In the same geodatabase as **FloodedRoadsCache**, create a table named **RequestedScenarios** with these fields:
 - a. Catchment_Id of type Long
 - b. Scenario_Id of type Short

- c. Datetime of type Date

Compute Flooded Segments for the Cache

With the input roads prepared, the next step is to intersect the roads with the flood depth grids to determine which road segments are flooded. For each water feature of interest such as an NWM stream segment, there are several flood depth grids representing the various flood scenarios. With so many grids to process, one should iterate through the grids using ArcGIS ModelBuilder or a Python script. This example demonstrates the procedure in ModelBuilder.

When working manually in Pro, set the map projection to match the depth grids. This avoids possible quirks in the software during raster calculations.

To compute flooded road segments:

1. In an ArcGIS Pro project, in the Catalog pane, expand Toolboxes. Right-click your project toolbox and click **New > Model**.
2. Set the model name.
 - a. Click **Properties**.
 - b. For Name, enter **ComputeCache**.
 - c. For Label, enter **Compute Flooded Roads Cache from Depth Grids**.
 - d. Click **OK**.
 - e. Click **Save**.
3. Add **Roads_Prj** and **FloodedRoadsCache** to the model.
4. Add an iterator to loop through all rasters.
 - a. Click **Iterators > Iterate Raster**.
 - b. Double-click the iterator in the model to set its properties.
 - c. Set the Workspace to be the folder storing the depth grids.
 - d. Select **TIF** as the Raster Format.
 - e. Click **OK**.
5. Parse the water feature identifier from each raster filename.
 - a. Click **Utilities > Calculate Value**.
 - b. Double-click **Calculate Value**.
 - c. Enter this Expression and click **OK**. If you do not know what the percent signs mean in the expression, search online for ModelBuilder inline variable substitution. In this case, the expression is parsing the raster filename as output from the Iterate Rasters tool.
`'%Name%'.split('_')[0]`
 - d. Right-click **Calculate Value** and click **Rename**.
 - e. Rename it to **Parse Feature ID**.
 - f. Right-click the output Value and click **Rename**.
 - g. Rename it to **FeatureId**.
 - h. Drag **Name** to Parse Feature ID and set it as a **Precondition**.
6. Parse the scenario feature identifier from each raster filename.
 - a. Click **Utilities > Calculate Value**.
 - b. Double-click **Calculate Value**.

- c. Enter this Expression and click **OK**:
`'%Name%' .split('_')[1]`
 - d. Right-click **Calculate Value** and click **Rename**.
 - e. Rename it to **Parse Scenario ID**.
 - f. Right-click the output Value and click **Rename**.
 - g. Rename it to **FeatureId**.
 - h. Drag **Name** to Parse Scenario ID and set it as a **Precondition**.
7. Use the **Reclassify** tool on each depth raster to categorize by depth range.
 - a. In the Geoprocessing pane, search for the **Reclassify (Spatial Analyst Tools)** tool and add it to the model.
 - b. Drag the green output from the Iterate Rasters tool onto the Reclassify tool and set it as the **Input raster**. The green output shows the full path and filename of one of the rasters in the folder as an example of what will be returned from the iterator.
 - c. Drag the outputs of both of the Calculate Value tools onto the Reclassify tool and set them as **Preconditions**. This ensures that the IDs are parsed before subsequent tools are run.
 - d. Double-click **Reclassify** to set its properties.
 - e. Click **Classify**. Set the number of classes to **4** and click **OK**.
 - f. Assuming that each grid value is the water depth in tenths of a foot, revise the start and end values as follows:
 - i. 0 to 5 (i.e., zero to half of a foot)
 - ii. 5 to 20
 - iii. 20 to 50
 - iv. 50 to 9999
 - g. Optionally, choose an output raster workspace and name.
 - h. Be sure to check the start and end values before clicking OK. ModelBuilder may adjust start or end values based on raster statistics as it validates inputs; if it does, change it back.
 8. Use the **Raster to Polygon** tool to convert the reclassified grid to polygon, with **Simplify polygons** unchecked. At this point, we assume you know how to find a geoprocessing tool, add it to a model, connect inputs, and set tool parameters. Optionally for this tool, instead of specifying an output workspace on disk, you can use “in_memory” to use the in-memory workspace, which should improve performance.
 9. Use the **Intersect** tool to intersect Roads_Prj with the new polygons, keeping all attributes except feature IDs. You can use in_memory for this output workspace as well.
 10. Use the **Delete Field** tool to delete **ID** (an attribute added during grid processing).
 11. Use **Logical > If Data Exists** as a precondition to the Delete Field tool to skip scenarios that do not result in any flooded roads, i.e., the intersect result is empty.
 12. Use the **Append** tool to add results in **FloodedRoadsCache**. If this is not the first time you have run this workflow, you may want to delete existing features in FloodedRoadsCache.
 - a. Use the Field Map to map fields from the appending input to the cache.
 - b. In the field map, map gridcode to Depth_Class.
 13. Use the **Calculate Field** tool to set the **Catchment_Id** in the cache equal to the %FeatureId% inline variable.

14. Use the **Calculate Field** tool to set the **Scenario_Id** in the cache equal to the %ScenarioId% inline variable.
15. Set model parameters.
 - a. Right-click Roads_Prj and click **Parameter**.
 - b. Repeat for the depth grids folder and FloodedRoadsCache.
16. Save the model.

You can now run the model. ModelBuilder is convenient for rapidly testing a geoprocessing workflow. However, you may want to export the model to a Python script if you want more control over the workflow.

When the workflow finishes, you should have a FloodedRoadsCache populated with flooded roads for all flood scenarios around all features of interest.

4.5. Extract Scenarios

Current or forecasted flooded roads are published as a map service, e.g., a hosted feature layer in AGOL or a map service on ArcGIS Server. The section assumes you have already published such a service and just need to update it with the latest requested scenarios.

An external application will provide a table of requested scenarios. For example, KISTERS Datasphere ingests NWM forecasts, translates forecasted streamflow to water depth and finds the nearest precomputed flood scenario matching that depth, and generates a CSV table of these scenarios with columns for catchment identifier (the water feature identifier), scenario identifier, and datetime. Once the table is retrieved, the procedure to extract flooded roads is:

1. Use the CSV table to overwrite the **RequestedScenarios** table.
2. Use the **Make Query Table** tool on **FloodedRoadsCache** and **RequestedScenarios**.
 - a. Set the fields to include all fields from **FloodedRoadsCache** and **Datetime** from **RequestedScenarios**.
 - b. Use this query:


```
FloodedRoadCache.Catchment_Id = RequestedScenarios.Catchment_Id And
FloodedRoadCache.Scenario_Id = RequestedScenarios.Scenario_Id
```
 - c. Use **FloodedRoadCache.OBJECTID** as the Key Field.
3. Delete all features in **FloodedRoads**.
4. Append from the query table into FloodedRoads, using a field map to reconcile schema differences.

After you run this workflow for the first time, you can publish the result as an ArcGIS map service. Then you can implement the scenario extraction workflow as a Python script that is run hourly to retrieve the latest flood scenarios and update the service accordingly. Setting up a map service is beyond the scope of this section.

5. Conclusions

This report summarizes the progress in characterizing road and bridge flooding as part of the TxDOT research project 0-7095, “Evaluate Streamflow Measurement at TxDOT Bridges”, being conducted from September 2020 to August 2023 as part of the Research and Technology Implementation program. Insights arising from this research can be summarized as follows.

(1) Road Flood Inundation and Bridge Warnings. Two emergency response exercises have been conducted by the Streamflow research project, one in the Beaumont District in February 2022, and the second in the Austin District in January 2023, with participation of about 40 TxDOT Maintenance staff in each case. During these exercises, various web map services to provide assessment and forecasting of flood conditions were evaluated. The highest priority items consistently identified by the Maintenance staff were map services depicting road flooding and warning of high-water levels at bridges. These map services and others arising from the National Weather Service, and stream gauge measurement from the USGS, are being assembled in a real-time Flood Assessment System for TxDOT (FAST).

(2) Existing GIS Data for Roads and Bridges. There are two standard GIS datasets used by TxDOT to describe its road and bridge assets – a line dataset called the TxDOT Roadway Inventory, and a point dataset called the National Bridge Inventory. Both of these datasets are defined using (x,y) coordinates only, and their features contain no elevation information, either in the geometry or tabular attributes. Elevation plays a critical role in flooding – by definition, a road or bridge floods when the surrounding water surface elevation exceeds the elevation of the road surface or bridge deck. The Streamflow research team has reluctantly come to the conclusion that the goals of the project cannot be achieved with TxDOT’s current GIS description of roads and bridges, and a new geospatial description of these assets is needed in 2D and 3D.

(3) Tx-Bridge. The Texas Natural Resources Information System (TNRIS) has now acquired state-wide coverage of land surface terrain elevation in the form of LIDAR point clouds from a series of about sixty airborne LIDAR measurement projects covering various areas of the state, and some updating of LIDAR measurement is carried out annually. Bridges are separately classified as part of the LIDAR data interpretation that follows data collection. All the LIDAR datasets have been transferred to the Texas Advanced Computing Center (TACC). An open-source computer code called Tx-Bridge has been developed in this project which isolates a LIDAR point cloud for each bridge deck, and surrounds it with a bounding polygon defining its horizontal spatial extent. A standardized taxonomy of 37 bridge attributes is computed in Tx-Bridge. These attributes are described in Appendix A.

(4) State-wide Bridge Polygon Dataset. This Bridge Polygon and its associated LIDAR point cloud are sufficiently accurate to describe the extent and elevation of a bridge, and the Tx-Bridge process is scalable at the TACC so that it will be able to be executed state-wide in Texas. The TxDOT GIS program and Bridge Division are ingesting the Bridge Polygons for the LIDAR data collections analyzed to date, and checking them for quality assurance and accuracy with a goal of creating an enterprise level state-wide Bridge Polygon dataset for TxDOT. It is anticipated that this process will continue until the Bridge Polygon coverage of the state is complete.

(5) NWS Flood Inundation Mapping. The National Weather Service plans to deploy real-time flood inundation map services covering about half of Texas during 2023. This will completely or partially cover 18 TxDOT Districts. Standard flood inundation mapping is carried out on bare-earth digital elevation models with all bridges removed, so in this condition it will appear that many roads are flooded when in fact they have bridges that are still safely carrying traffic. NWS intends to use the Bridge Polygons and LIDAR point clouds arising from this project to adjust their inundation mapping to reflect correct bridge extent and elevation in Texas.

(6) Bridge Envelope. Besides the polygon of horizontal bridge extent, Tx-Bridge also produces a vertical Bridge Envelope depicting an elevation view of the bridge drawn along a transect line following the centerline of the bridge. This envelope has the bridge deck as its upper bounding line and the stream channel cross-section forming the sides and bottom of the envelope. The stream channel cross-section is defined from the bare-earth elevation model used in doing flood inundation mapping. In this project, that data is drawn from a seamless 3m Digital Elevation Model developed for Texas by the Fathom company for the Texas Water Development Board. The bridge deck has a thickness estimating the difference between the bridge deck and low chord elevation defined by a set of rules relating bridge thickness to type and length of the main span of the bridge. The Bridge Polygon and associated Bridge Envelope together form a Simple Bridge Model providing an elementary plan and elevation view of each bridge.

(7) Bridge Warnings. The KISTERS Datasphere is used to ingest discharge forecasts from the NOAA National Water Prediction Service, convert them into stage heights at bridges and produce a standardized graphic that shows the current and forecast water level superimposed on the bridge envelope. A web map service incorporating these real-time bridge warnings has been produced and is running as an operational prototype for several hundred bridges, mostly in the Austin District.

(8) Road Polygons and Centerlines. Similar to the bridge polygon and LIDAR point cloud dataset, a description of the road pavement surface extent and elevation is required to depict flood inundation accurately. For the TxDOT Austin District, RTI purchased a road polygon and centerline dataset from the Ecopia corporation. These data were derived by artificial intelligence interpretation of Hexagon 6” aerial imagery used by TxDOT as a standard state-wide imagery service. These polygons and centerlines have been found to very well represent the location and spatial extent of the road pavement surface. The length of road coverage provided by the Ecopia dataset is 38,000 miles in the Austin District compared to 18,000 miles in the TxDOT Roadway Inventory.

(9) Road Ribbon. A Road Ribbon is a combination of a bounding polygon of the road pavement extent and the LIDAR point cloud defining the elevation of the pavement surface within that polygon. LIDAR point clouds are not normally classified to show the road surfaces as they are for bridges, but if a bounding road polygon is available, it can be used to select the LIDAR ground elevation points on the road pavement. These LIDAR points, together with the road polygon and centerline can be combined into a Terrain dataset for the road surface and transformed into a Triangulated Irregular Network, or TIN, to describe the road elevation surface. The road and bridge data for the Austin District are being analyzed to develop a template for a comprehensive 2D and 3D geospatial dataset describing road and bridge extent and elevation. It is recommended that road surface elevations be derived from a TIN surface or 1m DEM surface developed directly from the LIDAR points in the road ribbon. The underlying 3m Fathom

DEM used in creating flood inundation mapping may be biased low on the road surface and result in greater flooded road depths than are actually occurring.

(10) Low Water Crossings. During the Austin flood emergency response exercise, the Maintenance personnel made it clear that flood risk at low water crossings is a serious concern. Early in the Streamflow project, a procedure for Rapid Field Assessment of Low Water Crossings was developed and field data collected for 17 high priority low water crossings in the Austin District. One of these low water crossings, on FM 150 at Onion Creek, has been studied carefully to provide a framework for a larger scale characterization. This includes computation of the flow through culvert pipes at the low water crossing and flood frequency analysis for discharge and water surface elevation to provide a context for expected flood levels that may occur during real-time events. It is shown that for the standard flood inundations for roads of 0.5, 2, and 5 feet, the corresponding flood return periods vary between 14 and 17 months. Hence, it can be concluded that low water crossings flood frequently with return periods better measured in months rather than years.

(11) Road Flooding. Mapping flooded roads is achieved by quantifying the depth of inundation on the road centerline. Accurate road elevation data is crucial for estimating flood inundation. Flood inundation is based on forecast water levels derived from the National Water Model for all rivers, or from USGS or TxDOT stream gauges at select locations. To support flooded roads display as individual road segments and as summary tables, the following types of attributes should be included in the roads dataset:

- Unique identifier
- Human-friendly name
- Attributes for grouping and summaries, e.g., District, County, Road Importance, On- or Off-System
- Attributes for statistics, such as road length and number of address points.

(12) Flooded Road Maps. The authors recommend displaying flooded roads as lines color coded by these depth ranges:

- 0 to 0.5 feet
- 0.5 to 2 feet
- 2 to 5 feet
- Greater than 5 feet

Once flooded roads have been computed, the following attributes may be useful for display:

- Date and time represented by the flooded road
- Depth class for the flooded road segment, e.g., “2 to 5 feet”.
- Date when flooding began for the overall road segment (including this and any other parts of the segment that are flooded during this forecast).
- Date when flooding is predicted to end for the overall road segment.

There are dozens of ways of displaying flood roads information over time. The authors would like to work with TxDOT to determine the best approach that balances information needs, complexity of the end user interface, and complexity of computational setup.

6. Acknowledgements

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7. References

Committee on FEMA Flood Maps (2009), Mapping the zone: improving flood map accuracy, Chapter 3, Elevation and Height, National Academies Press.

Federal Highway Administration (2023), HY-8 Culvert Hydraulic Analysis Program, <https://www.fhwa.dot.gov/engineering/hydraulics/software/hy8/>

McCabe, G. J., & Wolock, D. M. (2016). Variability and trends in runoff efficiency in the conterminous United States. *JAWRA Journal of the American Water Resources Association*, 52(5), 1046-1055.

RPS Klotz Associates (2017), "Low Water Crossing Study", prepared for Austin District, TxDOT, Project 0121.072.004, 208 p.
<https://www.caee.utexas.edu/prof/maidment/StreamflowII/Documents/Final%20Report%20WA%204%20Low%20Water%20Crossing%200227017.pdf>

Texas Department of Transportation (2014), "Standard Specifications for Construction and Maintenance of Highways, Streets, and Bridges", Adopted by the Texas Department of Transportation, 1 Nov 2014.

Texas Department of Transportation (2019), "Hydraulic Design Manual", p.6-7, September 2019

Thies, C., H. Evans, A. Carter, D. Maidment (2022), "Rapid Assessment Survey for Culvert Crossings", Report P6B2, Project RTI 0-7095, Texas Department of Transportation, 8 p.
<https://www.caee.utexas.edu/prof/maidment/StreamflowII/Documents/ProjectP6B2Project07095.pdf>

8. Appendix A: Tx-Bridge Data Description

The goal of the TX-Bridge scripts is to create geospatial data that describes a simplified geometry of bridges extracted from airborne acquired LiDAR point clouds. Plan view (aerial) geometric descriptions include the **major axis line** and the **bridge hull polygon**. The spatial description also includes profile view (cross section) information necessary to render a **bridge envelope**. In addition to geometric descriptions, TX-Bridge also determines text and numeric values for each bridge.

Data for bridges processed by TX-Bridge are conveyed in a GeoJSON format. GeoJSON is an open standard and extensible format for representing geographical features and their non-spatial attributes. It is an extension of JavaScript Object Notation (JSON).

The current version of GeoJSON created from TX-Bridge (April 2023) contains thirty-seven (37) attributes. Each of these attributes are individually described below for a sample bridge.

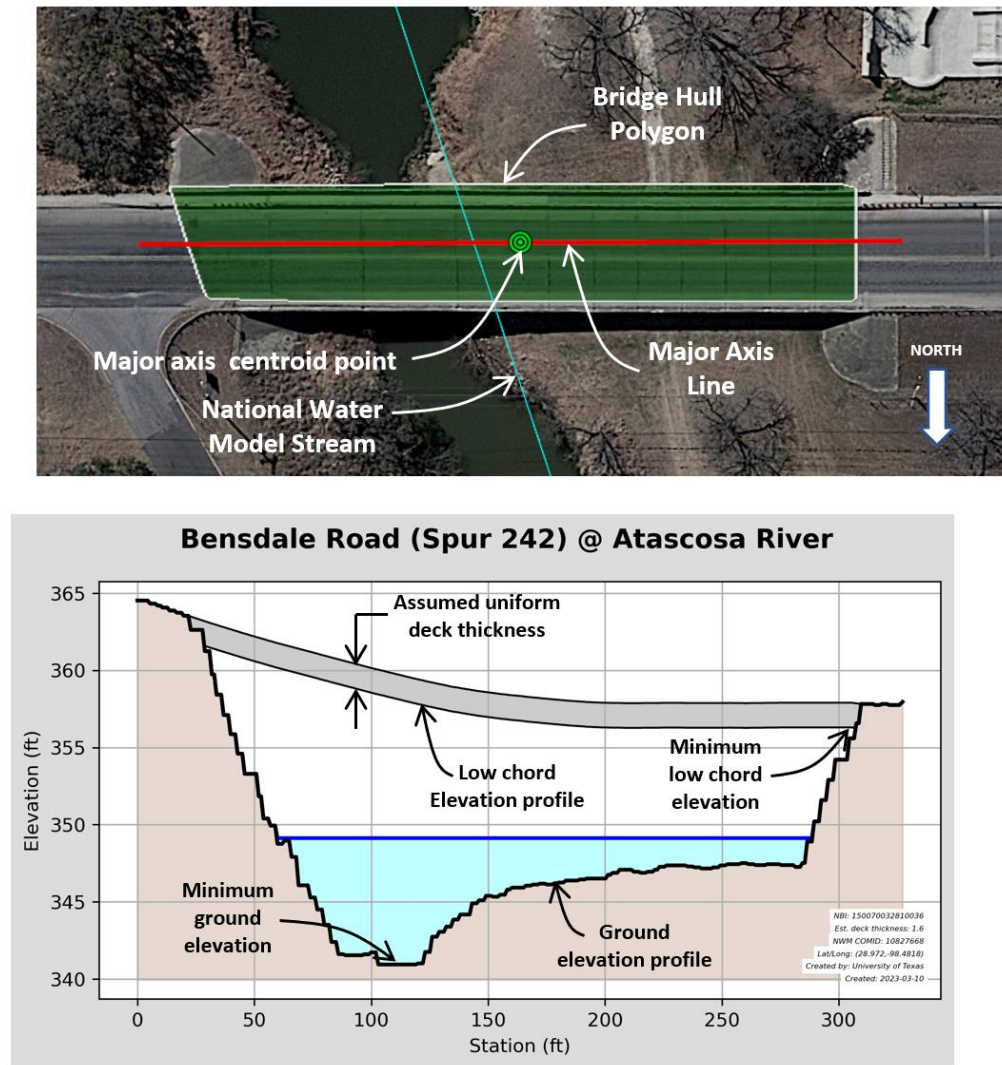


Figure A.1 Example bridge for data description; Bensdale Road over the Atascosa River in Pleasanton, Texas (N 28.972°, W 98.482°)

1) Geometry

Attribute Number	1
Name	geometry
Alias	major axis line geometry
Type Details	well-known text (WKT) (Linestring)
Description	Geospatial description of the major axis line along the bridge described as "Well-known text". From an input vector data set, this represents the longest road segment that intersects the bridge hull polygon. This line is typically extended past to the limits of the bridge hull polygon at a pre-determined distance. Units are specified GeoJSON coordinate reference system.
Example	MultiLineString ((2134341.91 13537716.31, 2134332.14 13537716.39, 2134017.35 13537718.96, 2134014.67 13537718.98))



Note: This horizontal alignment consists of four (4) pairs of X,Y coordinates in the EPSG:2278 coordinate reference system (Texas South Central – US Survey foot) . This feature is 327.25 feet long.

Figure A.2 Major axis line geometry

2) hull_len

Attribute Number	2
Name	hull_len
Alias	length of the hull
Type Details	float
Description	length of the bridge; this is length of the major axis line "geometry" clipped to the "hull_wkt" polygon. Units are specified in GeoJSON coordinate reference system.
Example	286.19



Figure A.3 Bridge length

3) avg_width

Attribute Number	3
Name	avg_width
Alias	average width
Type Details	float
Description	The average width of the "hull_wkt" polygon determined by taking the area of the "hull_wkt" and dividing by the "hull_len"
Example	49.81



Figure A.4 Bridge width

4) nhd_name

Attribute Number	4
Name	nhd_name
Alias	National Hydrography Dataset Name
Type Details	string
Description	Name of the nearest National Hydrography Dataset stream to the major axis line. For Example, this can be determined using the USGS web service. https://hydro.nationalmap.gov/arcgis/rest/services/nhd/MapServer/6/query/? -- from "GNIS_NAME"
Example	Atascosa River

Figure A.5 Name of stream in National Hydrography Dataset

5) reachcode

Attribute Number	5
Name	reachcode
Alias	National Hydrography Reach Code
Type Details	string
Description	Reach code of the nearest National Hydrography Dataset stream to the major axis line. For Example, this can be determined using the USGS web service. https://hydro.nationalmap.gov/arcgis/rest/services/nhd/MapServer/6/query/? -- from \"REACHCODE\"
Example	12110110000092



nhd_name = Atascosa River
reachcode = 12110110000092

Figure A.6 Reach Code in National Hydrography Dataset

6) name

Attribute Number	6
Name	name
Alias	transportation feature name
Type Details	string
Description	Transportation (road, railway, etc) name of the major axis line as provided by "name" from an OpenStreetMap vector data
Example	Bensdale Road

Figure A.7 Name of transportation feature (road, railroad)

7) ref_name

Attribute Number	7
Name	ref_name
Alias	transportation reference name
Type Details	string
Description	Transportation (road, railway, etc) of the reference name of the major axis line from OpenStreetMap query "ref" field.
Example	Spur 242



Note: The 'ref_name' can be seen as an alternative road name.

Figure A.8 Reference name for transportation feature

8) file_path

Attribute Number	8
Name	file_path
Alias	file path of major axis line
Type Details	string
Description	Internal filepath to the location of the group of major axis lines computed with TX-bridge from which this specific major axis line was found. [Internal processing attribute]
Example	D:\bridge_south_central_20230310\07_major_axis_names\flip_mjr_axis_w_name_In.shp

Note: For example, this bridge major axis line is just one of 504 'major axis' lines determined for a given LiDAR collection. A shapefile of these 504 bridges was written by TX-bridge to the given path.

Figure A.9 File location for major axis line

9) mjr_ax_idx

Attribute Number	9
Name	mjr_ax_idx
Alias	major axis line index
Type Details	integer
Description	Index of this specific major axis line as located in the "file_path". Used to assist correlation of major axis line with hull polygon. For example, this bridge's index is 238 of the 504 found. [Internal processing attribute]
Example	238

Figure A.10 Major axis line index

10) hull_idx

Attribute Number	10
Name	hull_idx
Alias	major axis hull index
Type Details	integer
Description	Index of the hull polygon for this specific major axis line. Takes the "file_path" and backs out to the "02_shapefile_of_hulls" folder and finds the "class_XX_ar_3857.shp". Used to assist correlation of bridge deck DEM to major axis line. [Internal processing attribute]. For example, this bridge's hull index is 259 of the 553 found. [Internal processing attribute]
Example	259

Note: Multiple bridge hulls are typically extracted across a wide geographical area. These polygons are typically written to a file like D:\bridge_south_central_20230310\02_shapefile_of_hulls\class_17_ar_3857.shp. These polygons are determined from point cloud clusters. There are typically more 'bridge hull' polygons than 'major axis' lines as some polygons don't have a transportation line crossing its boundary.

Figure A.11 Major axis hull index

11) sta

Attribute Number	11
Name	sta
Alias	station
Type Details	list of floats (pythonic list nomenclature)
Description	List of the horizontal station of points along the major axis line alignment. Units are specified GeoJSON coordinate reference system. [used for plotting cross section 'bridge envelope']
Example	[0.0, 1.09, 2.17, 3.26, 4.34, 5.43, 6.52, 7.6, 8.69, 9.77, 10.78, 316.55, 317.55, 318.56, 319.56, 320.56, 321.57, 322.57, 323.57, 324.57, 325.91, 327.25] Edited for brevity... Contains 326 points.

Note: The geometry attribute contains the horizontal geometry which is defined by four (4) plan-view points of intersection. For the profile, line is segmented into 326 points (including the beginning and ending points) where vertical data will be sampled along this transect alignment.

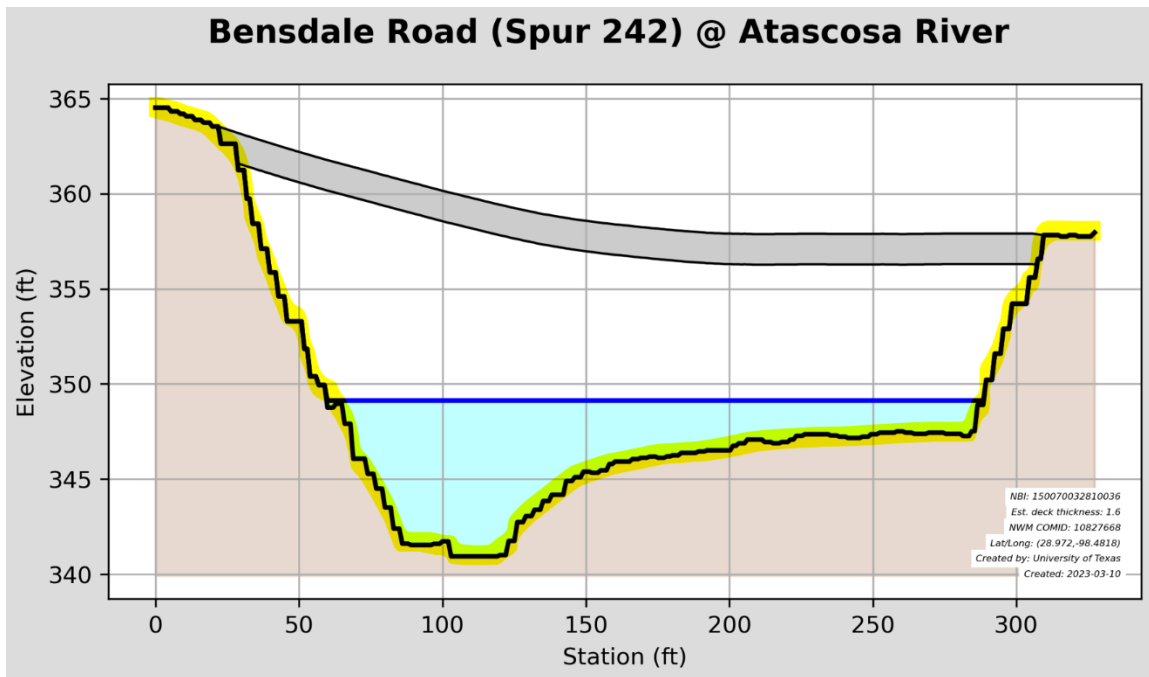
Graphic is a representation of where elevation data will be sampled along the 'major axis' line. It shows an elevation sampling point every 10.9 feet, however, for the example Bensdale Road bridge, the sampling is 10 times (10x) denser at an interval of 1.09 feet.



Figure A.12 Station values for sample points on the major axis line

12) ground_elv

Attribute Number	12
Name	ground_elv
Alias	ground elevation
Type Details	list of floats (pythonic list nomenclature)
Description	List of vertical elevation along station points along the major axis line alignment. Ground data is typically taken from 'bare-earth' terrain data served by the USGS 3DEP WCS web service. [used for plotting cross section 'bridge envelope']
Example	[364.52, 364.52, 364.52, 364.52, 364.52, 364.32, 364.32, 364.32, 364.19, 364.19, 357.75, 357.75, 357.82, 357.82, 357.82, 357.75, 357.75, 357.75, 357.75, 357.95] Edited for brevity... Contains 326 points.

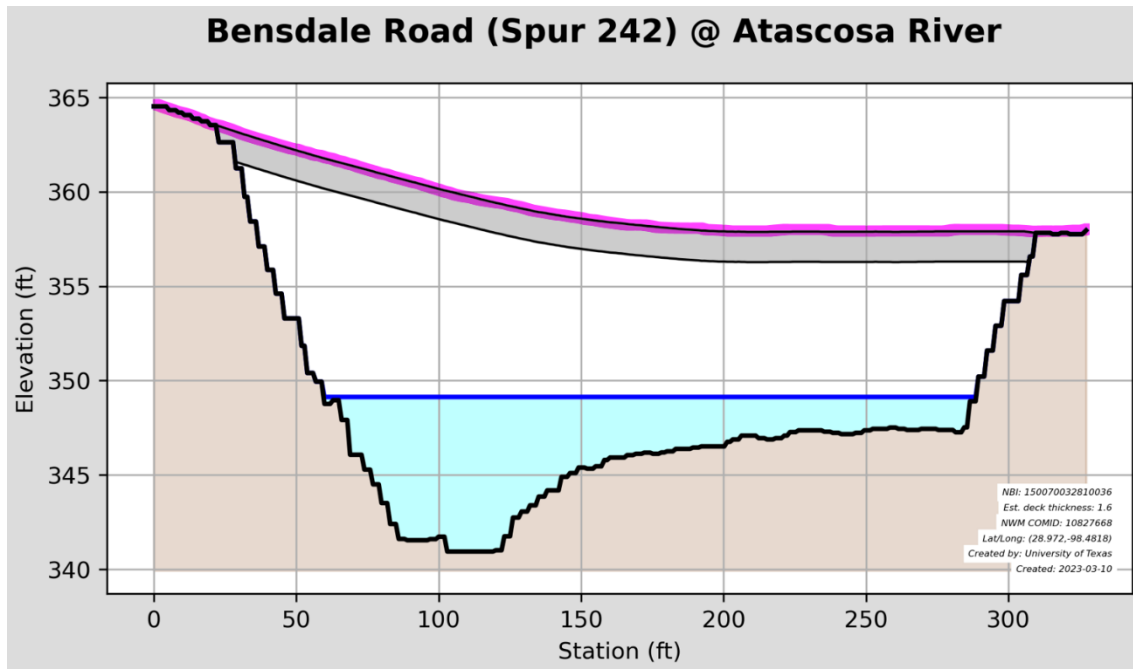


Note: Ground elevation is shown on the bridge envelope highlighted in yellow.

Figure A.13 Ground elevation values on the stream cross-section for sample points on the major axis line

13) deck_elev

Attribute Number	13
Name	deck_elev
Alias	deck elevation
Type Details	list of floats (pythonic list nomenclature)
Description	List of vertical elevation along station points along the major axis line alignment. This is the higher of (1) the deck classified points or (2) the bare earth ground. Samples a ground DEM and a bridge deck DEM for creation. Should have same number of points as the 'sta' list. [used for plotting cross section 'bridge envelope']
Example	[364.52, 364.52, 364.52, 364.52, 364.52, 364.32, 364.32, 364.32, 364.19, 364.19, 364.06, 357.75, 357.75, 357.82, 357.82, 357.82, 357.75, 357.75, 357.75, 357.75, 357.95] Edited for brevity... Contains 326 points.



Note: Deck elevation is shown on the bridge envelope highlighted in purple.

Figure A.14 Bridge deck elevation values on the stream cross-section for sample points on the major axis line

14) latitude

Attribute Number	14
Name	latitude
Alias	latitude
Type Details	string
Description	Latitude of the centroid of the major axis line to four decimal points. In decimal degrees in the EPSG: 4326 projection.
Example	28.9720

Figure A.15 Latitude of the centroid of the major axis line

15) longitude

Attribute Number	15
Name	longitude
Alias	longitude
Type Details	string
Description	Longitude of the centroid of the major axis line to four decimal points. In degrees in the EPSG: 4326 projection
Example	-98.4818



**Lat / Long:
N 28.9720°, W 98.4818°**

Figure A.16 Longitude of the centroid of the major axis line

16) uuid

Attribute Number	16
Name	uuid
Alias	universally unique identifier
Type Details	string
Description	A universally unique identifier automatically generated for each major axis line. Uses uuid version 4.
Example	f06f12b6-f002-43d0-aade-d0edc1a823d3

Note: Each time that TX-Bridge is computed and a bridge is found, it is assigned a unique identifier. These will always be unique for each and every bridge and every execution. It is not unique to bridge, but rather unique to bridge per TX-Bridge execution.

Figure A.17 Universally unique identifier within this collection of bridges

17) feature_id

Attribute Number	17
Name	feature_id
Alias	feature identifier
Type Details	integer
Description	National Water Model stream identifier for the stream crossing the major axis line that highest stream order. If no stream crosses, the identifier of the stream nearest to the major axis line.
Example	10827668



Figure A.18 National Water Model feature-id for stream line passing under the bridge

18) order_

Attribute Number	18
Name	order_
Alias	stream order
Type Details	integer
Description	Strahler stream order of National Water Model "feature_id" that is nearest to the major axis line. If multiple streams cross the major axis line, then this is the highest value.
Example	4

Note: Strahler stream order is a method of classifying the hierarchy of natural channels such as rivers or streams. The order is based on the number and arrangement of tributaries that join the main channel. A stream of the first order has no tributaries. A stream of the second order is formed by the confluence of two or more first-order streams. A stream of the third order is formed by the confluence of two or more second-order streams, and so on.

Figure A.19 Strahler stream order for this National Water Model stream

19) dist_river

Attribute Number	19
Name	dist_river
Alias	distance to river
Type Details	float
Description	Distance to the national water model stream nearest to the major axis line. If zero, then the major axis line crosses the "feature_id" national water model stream
Example	0

Note: For this example, the major axis line crosses national water model stream "10827668". Therefore, the nearest stream to the major axis is 0 feet away.

Figure A.20 Distance (feet) to the nearest National Water Model stream line

20) nbi_asset

Attribute Number	20
Name	nbi_asset
Alias	National Bridge Inventory asset identifier
Type Details	string
Description	Conflated National Bridge Inventory identifier to the major axis line. This is determined from an external point geospatial file which in this case was provided by TxDOT. If "", then none was found within the designated search distance.
Example	150070032810036

Note: It is possible that there is no NBI within the designated search distance of a major axis line. It is also possible that the nearest NBI point to a 'major axis' line is not the same bridge.

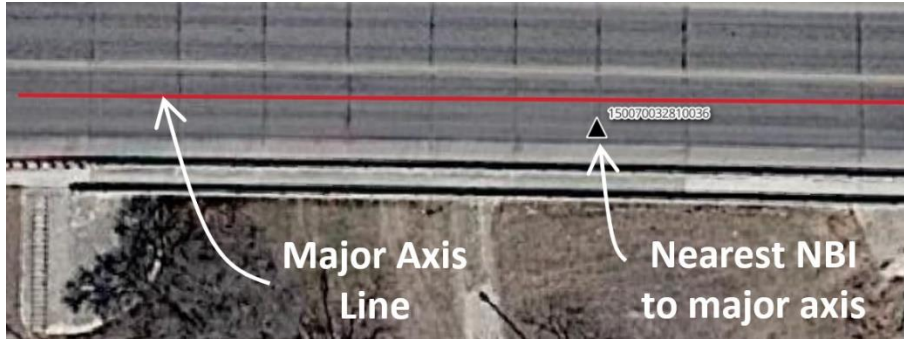


Figure A.21 National Bridge Inventory identifier

21) nbi_thick

Attribute Number	21
Name	nbi_thick
Alias	National Bridge Inventory thickness
Type Details	string (float value at string – can be blank “”)
Description	Estimated uniform thickness of the bridge deck for a given National Bridge Inventory number. This is provided in a rubric computing thickness primarily as a function of bridge type and maximum span length.
Example	1.6

Note: Value is thickness of the bridge deck in feet from the elevation of the travel surface to the low chord of the support structure (such as an I-beam). While a detailed field survey may show that the width is variable, for TX-bridge It is assumed to be uniform.

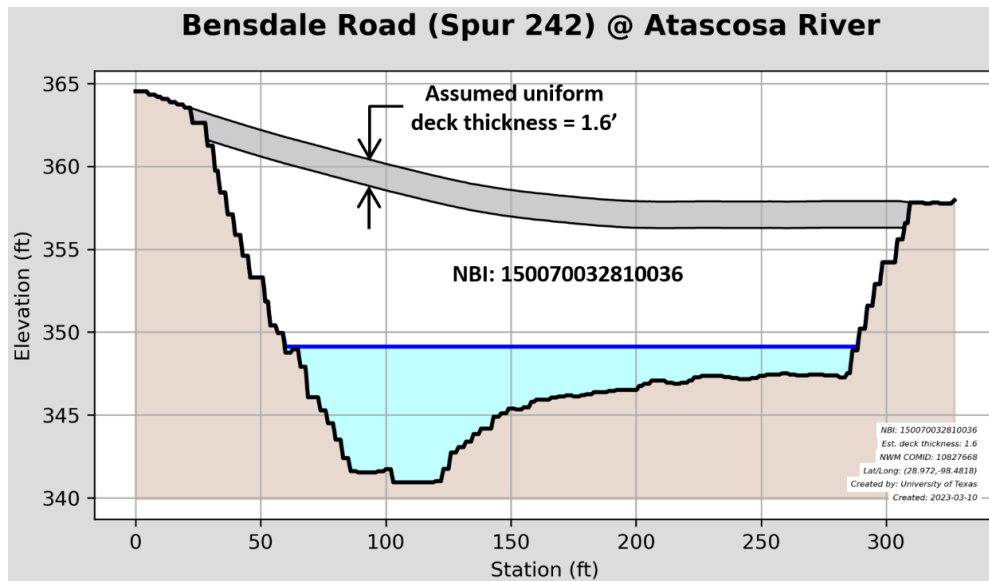


Figure A.22 National Bridge Inventory identifier

22) nbi_dist

Attribute Number	22
Name	nbi_dist
Alias	National Bridge Inventory distance
Type Details	string (float value at string – can be blank "")
Description	Nearest distance of the major axis line to the "nbi_asset" point
Example	5.65

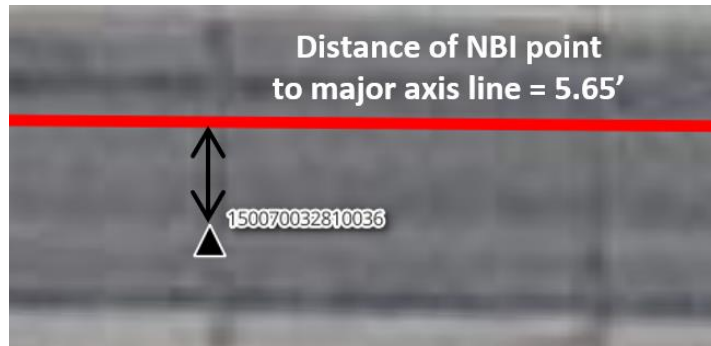


Figure A.23 National Bridge Inventory identifier

23) score

Attribute Number	23
Name	score
Alias	National Bridge Inventory overall conflation score
Type Details	float
Description	Value of the confidence that the major axis has the correct NBI data (0 to 1) 1== highest confidence. This is a composite of various comparison parameters detailed in items 24 thru 27.
Example	0.911

Note: Sample calculation:

	value	weight	value * weight
score_dist	0.972	1.0	0.972
score_span	0.877	2.0	1.754
score_road	0.857	0.2	0.171
score_strm	1.000	0.2	0.200
SUM		3.40	3.10

Score = 0.911 (= 3.10 / 3.40)

The 'score' of how well the NBI that is nearest matches the bridge data extracted from TX-Bridge is a weighted composite calculation. If the 'score_road' and 'score_strm' cannot be determined, then they are removed from the composite score.

Figure A.24 Conflation Index for degree of confidence that the NBI bridge has been correctly identified

24) score_dist

Attribute Number	24
Name	score_dist
Alias	National Bridge Inventory overall conflation score - distance
Type Details	float
Description	Value from 0 to 1 of how close the nbi is to the bridge (0 == father that the max allowed value, 1 == on the major axis. Max allowed distance defaults to 200 units.
Example	0.972

Note: Sample calculation:

nbi_dist = 5.65' (attribute 22)

score_dist = 1 – (5.65 / 200) = 0.972; Minimum value is 0.

Figure A.25 Value of the distance attribute of the NBI conflation index

25) score_span

Attribute Number	25
Name	score_span
Alias	National Bridge Inventory overall conflation score - span
Type Details	float
Description	Value from 0 to 1 comparing the hull_len to the NBI provided bridge length (1 == match, 0 == percent difference greater than 100%)
Example	0.877

The nearest 'NBI' point (150070032810036) has an attribute named 'Structur_1' which is the length in feet of the span of length of the bridge as recorded in the National Bridge Inventory. For this example, the value is 253 feet. The span distance is computed on the major axis line from TX-Bridge (attribute 2) is 286.19.

Sample calculation:

Percent difference of length = $abs(286.19 - 253) / [(286.19 + 253)/2] * 100 = 12.31\%$

Score_span = 1 – 0.123 = 0.877

Figure A.26 Value of the structure length attribute of the NBI conflation index

26) score_road

Attribute Number	26
Name	score_road
Alias	National Bridge Inventory overall conflation score - span
Type Details	float
Description	Value from 0 to 1 of comparing text value of OpenStreetMap road name to NBI road name. Uses the python difflib.SequenceMatcher to compare two strings. A value of 1 is an absolute match.
Example	0.857

Note: Compares both the values of 'name' (attribute 6) and 'ref_name' (attribute 7) to the carrying facility 'Facility_C' of the nearest NBI point (in the TxDOT NBI point shapefile). All values are compared and scored as lower-case strings.

'Facility_C' for NBI 150070032810036 = 'SP 242'

'name' of major axis = 'Bensdale Road'

'ref_name' of major axis = 'Spur 242'

Comparing 'bendsdale road' to 'sp 242' = 0.21

Comparing 'spur 242' to 'sp 242' = **0.857**

Figure A.27 Value of the road name matching attribute of the NBI conflation index

27) score_strm

Attribute Number	27
Name	score_strm
Alias	National Bridge Inventory overall conflation score - stream name
Type Details	float
Description	Value from 0 to 1 comparing text value of ndh_name to the NBI crossing facility name. Uses the python difflib.SequenceMatcher to compare two strings. A value of 1 is an absolute match.
Example	1

Note: Compares both the values of 'nhd_name' (attribute 4) with the name of the feature under the bridge ... 'Feature_In' of the nearest NBI point (in the TxDOT NBI point shapefile). All values are compared and scored as lower-case strings.

'Feature_In' for NBI 150070032810036 = 'ATASCOSA RIVER'

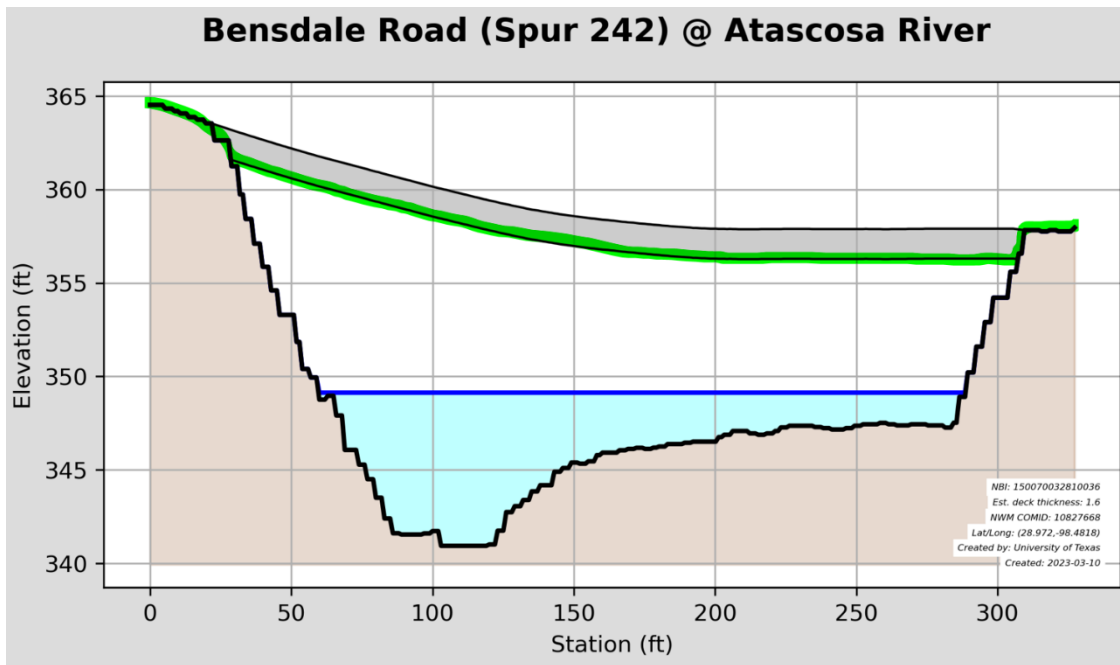
'nhd_name' for TX-Bridge = 'Atascosa River'

Comparing 'atascosa river' to 'atascosa river' = **1.00**

Figure A.28 Value of the stream name matching attribute of the NBI conflation index

28) low_ch_elv

Attribute Number	28
Name	low_ch_elv
Alias	low chord elevation
Type Details	list of floats (pythonic list nomenclature)
Description	List of vertical elevation along station points along the major axis line alignment. This is the higher of (1) the deck classified points minus the low chord or (2) the bare earth ground. Should have same number of points as the 'sta' list. [used for plotting cross section 'bridge envelope']
Example	[364.52, 364.52, 364.52, 364.52, 364.52, 364.32, 364.32, 364.32, 364.19, 364.19, 364.06, 357.75, 357.75, 357.82, 357.82, 357.82, 357.75, 357.75, 357.75, 357.75, 357.95] Edited for brevity... Contains 326 points.



Note: Low Chord is shown on the bridge envelope highlighted in green.

Figure A.29 Elevation values for the low chord at the sample points along the major axis line

29) convey_ar

Attribute Number	29
Name	convey_ar
Alias	conveyance area
Type Details	float
Description	flow conveyance area between the ground profile and the low chord profile.
Example	2929.52

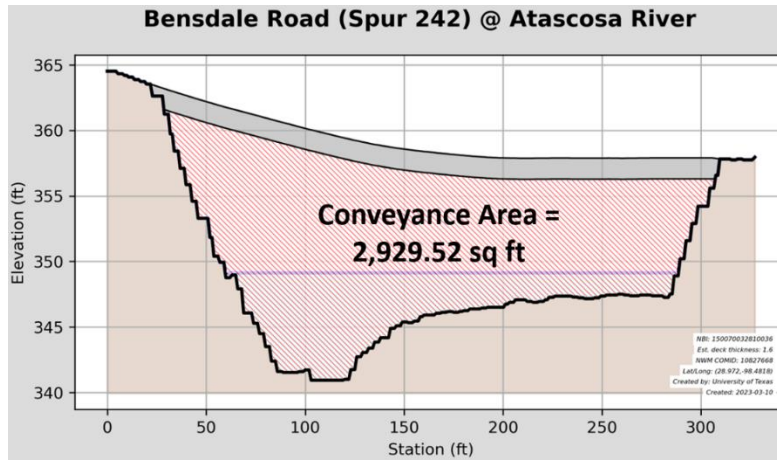


Figure A.30 Flow conveyance area below the low chord of the bridge

30) min_lw_ch

Attribute Number	30
Name	min_lw_ch
Alias	minimum low chord
Type Details	float
Description	Minimum low chord elevation.
Example	356.27

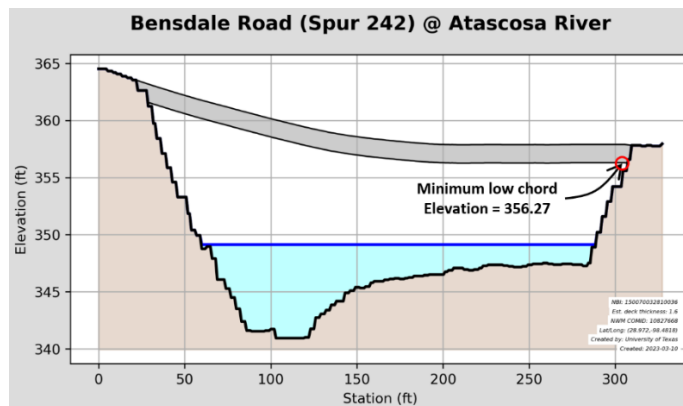


Figure A.31 Minimum low chord elevation

31) min_ground

Attribute Number	31
Name	min_ground
Alias	minimum ground
Type Details	float
Description	lowest ground elevation along the major axis line profile.
Example	340.94

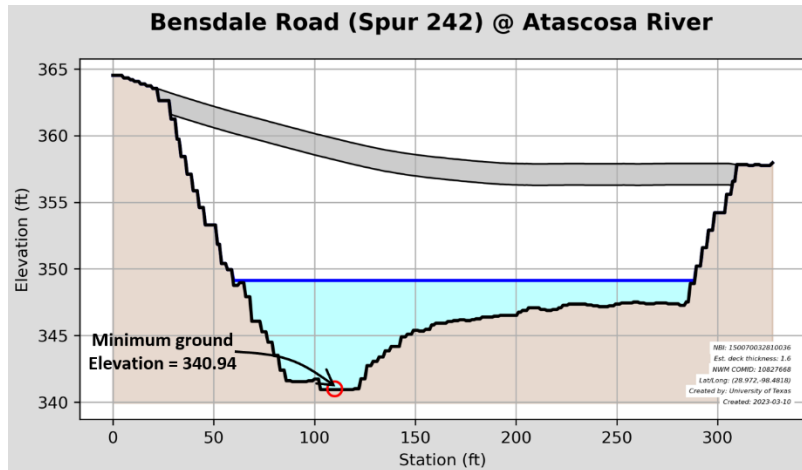


Figure A.32 Minimum ground elevation on the major axis profile (minimum channel elevation on the digital elevation model)

32) hull_wkt

Attribute Number	32
Name	hull_wkt
Alias	bridge hull geometry
Type Details	well-known text (WKT) (Polygon)
Description	Geospatial description of the bridge hull polygons created from creating convex hulls of classified point cloud clusters from LiDAR. Units are specified GeoJSON coordinate reference system.
Example	POLYGON ((2134035.07 13537739.67, 2134035.23 13537743.27, 2134036.31 13537744.51, 2134228.33 13537742.38, 2134274.03 13537741.42, 2134304.11 13537740.26, 2134311.98 13537739.87, 2134312.64 13537739.30, 2134314.58 13537735.74, 2134322.36 13537711.85, 2134323.73 13537707.37, 2134325.57 13537701.30, 2134328.39 13537691.91, 2134294.01 13537691.87, 2134234.41 13537692.21, 2134074.97 13537693.90, 2134046.65 13537694.35, 2134040.01 13537694.66, 2134035.15 13537695.67, 2134034.46 13537696.32, 2134034.77 13537729.30, 2134035.07 13537739.67))



Figure A.33 Coordinate points (x,y) for the bridge hull polygon

33) FATSGTID

Attribute Number	33
Name	FATSGTID
Alias	Fathom Segment Identifier
Type Details	string
Description	The National Water Model segments created too short or too long reaches that are often not sufficient for determining hydraulic synthetic rating curves. Therefore, alternative stream segmentation (hydrofabric) is needed to calculate more appropriate rating curves. The Height Above Nearest Drainage (HAND) calculations (from Dr. Yan Liu at ORNL) created a new set of stream segmentation lines from the Fathom 3 meter DEMs. This is the identifier of that stream segment (with the highest stream order) that crosses the major axis line. If no "FATSGTID" crosses the major axis line, this is the identifier of the stream from that dataset nearest to the major axis line.
Example	25370086

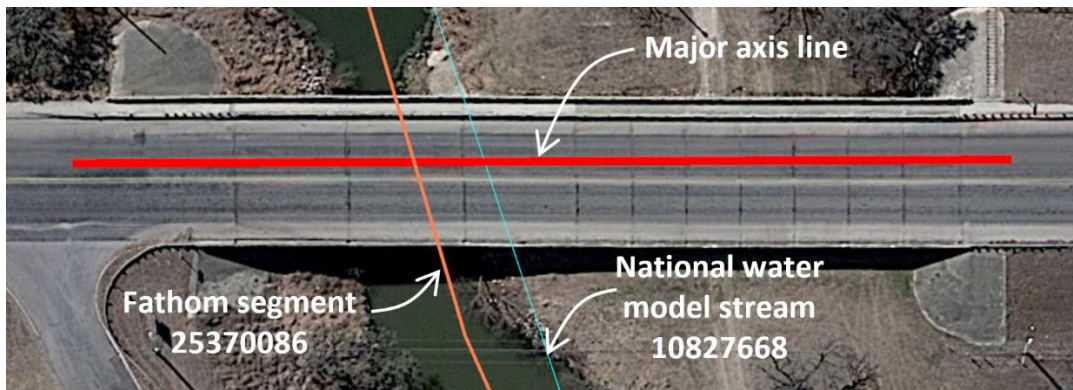


Figure A.34 Fathom Segment Identifier used for indexing stream reaches in flood inundation mapping

34) order_left

Attribute Number	34
Name	order_left
Alias	Fathom Segment stream order
Type Details	integer
Description	Strahler stream order of the "FATSGTID".
Example	4.0

Note: This is used to compare the stream order of the Fathom 3m derived stream segment to that of the National Water Model stream order (attribute 18). If there is a difference, it is likely that there is a 'cross walk' error between the National Water Model hydrofabric and the hydrofabric derived from the 3m Fathom terrain data in Texas.

Figure A.35 Strahler stream order of the Fathom Segment stream

35) dst_new_rv

Attribute Number	35
Name	dst_new_rv
Alias	Distance to new river (Fathom)
Type Details	float
Description	Distance to the Fathom Segment stream nearest to the major axis line. If zero, then the major axis line crosses the "FATSGTID" stream
Example	0

Figure A.36 Distance to Fathom stream nearest to the major axis line

36) feature_id_right

Attribute Number	36
Name	feature_id_right
Alias	National Water Model feature identifier (Fathom)
Type Details	integer
Description	From the "FATSGTID", find the corresponding feature id. This is used to compare the "FATSGTID" to the "feature_id" to determine if the same stream is being referenced
Example	10827668

Note: Value used to check cross-walk of the Fathom 3m hydrofabric to the National Water Model. Should be the same value as attribute 17 – 'feature_id'

Figure A.37 The National Water Model feature-id contained in the Fathom stream data

37) hand_r

Attribute Number	37
Name	hand_r
Alias	HAND synthetic rating curve
Type Details	list of tuple of floats ((pythonic list nomenclature)
Description	Synthetic rating curve for height above nearest drainage (HAND) of the 'FATSGTID' - string of python list of tuples representing pairs of (discharge in cfs) and (depth in feet)
Example	[(0.0, 0.0), (6.4, 1.0), (32.0, 2.0), (75.9, 3.0), (135.9, 4.0), (211.0, 5.0), (291.7, 6.0), (327.0, 7.0), (416.7, 8.0), (631.1, 9.0), (958.0, 10.0), (1406.4, 11.0), (1933.9, 12.0), (2606.4, 13.0), (3384.2, 14.0), (4256.9, 15.0), (5220.0, 16.0), (6276.4, 17.0), (7286.7, 18.0), (8172.6, 19.0), (9783.9, 20.0), (11903.0, 21.0), (14389.7, 22.0), (17048.9, 23.0), (19821.3, 24.0), (22849.6, 25.0), (26004.1, 26.0), (29261.0, 27.0), (32721.4, 28.0), (36781.3, 29.0), (41024.8, 30.0), (44964.6, 31.0), (49880.1, 32.0), (55352.0, 33.0), (61297.7, 34.0), (67823.3, 35.0), (75048.1, 36.0), (82601.7, 37.0), (90690.3, 38.0), (99036.2, 39.0), (107634.7, 40.0), (115972.8, 41.0), (124986.5, 42.0), (134531.5, 43.0), (144235.9, 44.0), (154339.3, 45.0), (164464.3, 46.0), (174804.2, 47.0), (185318.1, 48.0), (195661.8, 49.0), (206506.7, 50.0), (217693.5, 51.0), (228233.2, 52.0), (239884.2, 53.0), (252539.1, 54.0), (265147.5, 55.0), (277586.0, 56.0), (290692.3, 57.0), (303582.1, 58.0), (316766.1, 59.0), (330180.9, 60.0), (343435.1, 61.0), (357393.3, 62.0), (372253.7, 63.0), (388487.6, 64.0), (406431.5, 65.0), (425319.4, 66.0), (444852.4, 67.0), (465861.2, 68.0), (488031.0, 69.0), (509795.9, 70.0), (532624.4, 71.0), (555466.0, 72.0), (579387.0, 73.0), (602435.9, 74.0), (628019.2, 75.0), (654357.0, 76.0), (679996.9, 77.0), (707910.1, 78.0), (737505.6, 79.0), (768437.2, 80.0), (800271.3, 81.0), (835651.2, 82.0), (873609.4, 83.0)]

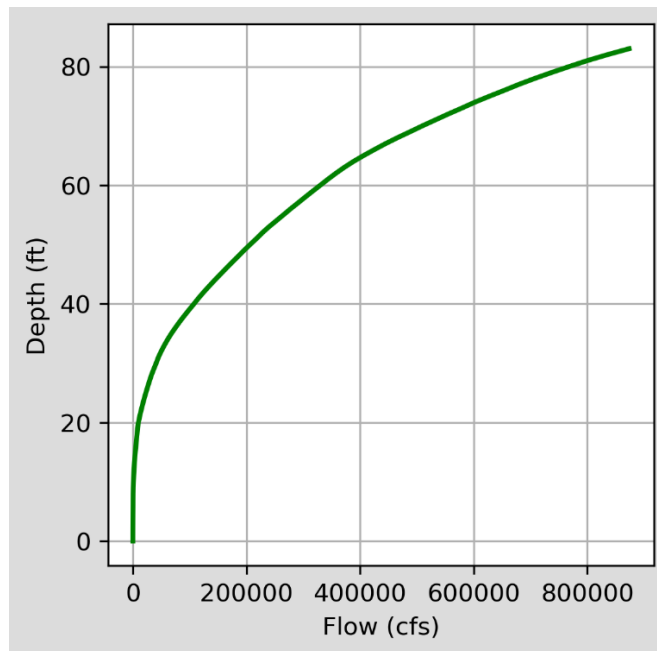


Figure A.38 The Height Above Nearest Drainage synthetic rating curve for the Fathom stream associated with the bridge