A rapid flood risk assessment method for response operations and nonsubject-matter-expert community planning

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Abstract
Flood risk planning and emergency response at community levels rely on fast access to accurate inundation models that identify geographic areas, assets, and populations that may be flooded. However, limited flood modelling resources are available to support these events and activities. We present a computationally-efficient flood model for facilitating rapid risk analysis across a wide range of scenarios and decision support to operational, crisis action, local flood-fight, and community planning efforts. Our flood depth regression method converts publicly-available river stage heights to flood depths, then downscales the depths from gage locations onto high resolution National Hydrography Dataset flowlines and estimates areas and depths of flooding by subtraction of the National Elevation Dataset from modelled water surface elevations. We demonstrate proof-of-principle analyses for historic 2009 Red River of the North flooding in the United States, achieving comprehensive mainstem flood estimation for the length of the river and depth accuracy of 1.4 ft (0.4 m) compared to gage observations, remote sensing, and higher-resolution hydrologic models. We

Abbreviations: ACS, American Community Survey; AHPS, Advanced Hydrologic Prediction Service; DEM, Digital Elevation Model; Esri, Environmental Systems Research Institute; ESP, Ensemble Streamflow Prediction; FDR, Flood Depth Regression; FEMA, Federal Emergency Management Agency; GIS, Geographic Information System; H&H, Hydrology & Hydraulics; HAND, Height Above Nearest Drainage; HAZUS (Hazus), Hazards United States Loss Estimation Model; HIC, Hydrologic Information Center; ISAR, Interferometric Synthetic Aperture Radar; LIDAR (LIDAR), Light Detection and Ranging; MODIS, Moderate-resolution Imaging Spectroradiometer; NASA, National Aeronautic & Space Administration; NAVD, North American Vertical Datum; NDEP, National Digital Elevation Program; NED, National Elevation Dataset; NFIE, National Flood Interoperability Experiment; NGS, National Geodetic Survey; NHD, National Hydrography Dataset; NHWC, National Hydrologic Warning Council; NGVD, National Geodetic Vertical Datum; NWC, National Water Center; NWM, National Water Model; NOAA, National Oceanic & Atmospheric Administration; NRCAN, Natural Resources Canada; NWS, National Weather Service; RADARSAT, Radar Satellite; RRDIN, Red River Decision Information Network; US and USA, United States of America; USEPA, United State Environmental Protection Agency; USGS, United States Geological Survey; VERTCON, Vertical Conversion Software; WSE, Water Surface Elevation.
1 | INTRODUCTION

Floods in the United States are one of the most ubiquitous natural hazards, causing about $7.96 billion in damages and at least 82 fatalities each year (NOAA-NWS, 2017a). However, event-based rapid flood risk mapping based on forecasts is often unavailable, leading to gaps in situational awareness. The Federal Emergency Management Agency (FEMA) maps flood hazards probabilistically to the 0.01 frequency, corresponding to the 1% annual chance “special flood hazard area” for insurance and regulatory purposes. Although some first-order approximation methods were developed for baseline engineering in support of regulatory floodplain mapping and federally-funded risk reduction programs, detailed hydrological and hydraulic (H&H) flood models require extensive resources and years to complete—and, yet, such models are not specifically designed for emergency response or mitigation operations1 (FEMA, 2015; FEMA, 2017a; FEMA, 2018a). For public safety, risk communication, and emergency management, the National Weather Service (NWS) forecasts the time and height of flood crests, as well as when floodwaters will recede, at least a few hours in advance for flooding for small basins or up to several weeks in advance for large river drainages (EASPE, 2002). However, emergency managers are often left with no spatial approximation of a specific flood threat during disaster response efforts due to a lack of readily-available inundation mapping techniques. Despite substantial advances in flood warning systems and computational capacity, most event-based flood mapping occurs well after flood conditions pass and are no longer immediate threats to human populations or infrastructure. Deterministic flood scenario estimates must be rapidly available for a range of risk-based flood severities, or based on incoming real-time data, and must be able to be generated by nonexperts using well-documented, publicly-available data and resources.

As observed during emergency flood response operations across the United States in recent years, uncertainty in forecasting and delays in field verification require response operators to assess risk across a range of scenarios, even as NWS forecasts are very “good” (Murphy, 1993). Flood response events are often multifaceted, requiring risk analysis for events caused by combinations of rain, river-flooding, and hurricane or wind-driven surges. Following the 2011 Missouri and Souris River floods, the NWS identified an “overwhelming sentiment” among emergency managers that flood inundation maps are “critical in the flood response decision making process,” despite some minor discrepancies between the flood maps and observations of flooding; further, the NWS recognised that existing flood inundation mapping methodologies are expensive and time-consuming, and that alternative, cost-effective geospatial flood information methods depicting areal extent and depth of flood flows should be developed (NOAA-NWS, 2012, p. 64). The tools needed to support both response operations and first-order community planning efforts need to be (a) available for a wide range of scenarios (e.g., deterministic, historical); (b) publicly-available and readily-accessible; (c) rapid (e.g., less than 4 hr of runtime); and (d) specifically targeted for use by nonexperts and targeted to practical decision-making (Melnkonyan, 2011; NOAA NHC, 2016; Vaughan & Buss, 1998).

There are a number of additional efforts underway to develop rapid flood modelling tools for crisis action planning, emergency response operations, and community planning efforts. Among others, recent research by the National Water Centre’s National Flood Interoperability Experiment demonstrated that high-resolution, near-real-time riverine inundation maps for much of the continental United States can be created with an approach based on the Height Above Nearest Drainage (HAND) method (Liu et al., 2016; Maidment, 2017; Teng et al., 2017). The HAND method converts forecasted stream discharges to water depths using flow rating curves and then converts those depths to inundation depths using a precomputed raster grid that defines the depths at which different geographic areas become inundated. While designed to support rapid, continental-scale inundation mapping, the method is not yet operational and currently requires super-computing methods not yet available for supporting real-time emergency operations. Additional methods and resources are available through H&H modelling; however, the complexity of required input datasets and run-time needed often does not satisfy the rapid-response information needs of emergency operations.

We present a method and corresponding proof-of-principle analyses to address gaps in flood inundation mapping: a simple and computationally-efficient flood model to facilitate rapid risk assessment for a wide range
of flood scenarios (Figure 1). The method downscales existing low-resolution river gage\textsuperscript{2} data to higher resolution digital elevation models (DEM(s)) using adjusted gage height, National Hydrography Dataset (NHD) flow lines (USEPA, 2019), and regression analysis of floodwater depths derived from the adjusted gage data, similar to simplified conceptual modelling methods described by Teng et al. (2017, p. 206). The model is limited to an essential set of data inputs and parameters and relies exclusively on surface geometry and statistics to predict flood inundation for a user-defined set of scenarios. The computational simplicity of this model allows it to be run rapidly to estimate flood extents and depths. This ease and speed, along with the reliance on publicly-available data, makes the model specifically useful for informing crisis action planning or emergency response decisions, most valuable for communities with limited technical expertise or without access to detailed H&H data or more sophisticated models. We demonstrate the utility of this method along the Red River in North Dakota and Minnesota as a proof-of-principle effort; additionally, we present a limited alternative scenario for spring snowmelt flooding affecting Yerington, Nevada in 2017. Based on these results, we complete a first-order consequence analysis by mapping inundation relative to impacted structures and populations, visualising the impacts of a range of flood severities on both infrastructure and communities.

2 | BACKGROUND

To understand geospatial analysis in emergency management and flood inundation mapping, we must first define some terms that describe processes used to estimate inundation, most notably H&H modelling. In its light detection and ranging (LIDAR) base specifications guidance, the United States Geological Survey (USGS) defines hydraulic modelling as the use of “digital elevation data, rainfall-runoff data from hydrologic models, surface roughness data, and information on hydraulic structures (for example, bridges, culverts, dams, weirs, and sewers) to predict flood levels and manage water resources”; USGS also defines hydrologic modelling as “[t]he computer modelling of rainfall and the effects of land cover, soil conditions, and terrain slope to estimate rainfall run-off into streams, rivers, and lakes. Digital elevation data are used as part of hydrologic modelling].” (Heidemann, 2014). Some errors in DEMs come from hydrologic flattening, described as the “[p]rocessing of a LIDAR-derived surface [... so that mapped water bodies, streams, rivers, reservoirs, and other cartographically polygonal water surfaces are flat and, where appropriate, level from bank-to-bank].” (Heidemann, 2014). Hydrologic flattening is performed to correct for the introduction of “unsightly and unnatural artifacts” from interpolation techniques like triangulation, and hydrologic enforcement reduces potential flow errors by modifying “the elevations of artificial impediments (such as road fills or railroad grades) to simulate how man-made drainage structures such as culverts or bridges allow continuous downslope flow” (Heidemann, 2014; Poppenga et al., 2014).

The NWS encourages a distinction between “flood delineation maps” using Geographic Information Systems (GIS) and the “rigorous data and modelling standards” of a “flood inundation map” (NOAA-NWS, 2012). A GIS-based delineation of 2-dimensional flood extent and 3-dimensional water depths is a hydrologic or hydraulic model postprocess, where water levels versus flow rating curves and other parameterizations are derived from zero-dimensional, 1-dimensional, 2-dimensional, or 3-dimensional parameterizations that

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Flood risk modelling and data usage along a flood event timeline in the absence of detailed H&H estimates. Yellow triangles with exclamation points to highlight those data and models typically not available for rapid flood risk assessment during events.}
\end{figure}
attempt to explain more complex behaviours of water with hydrodynamic equations (Sanders, 2007; see also Teng et al., 2017). One-dimensional hydraulic models use river cross-sections to estimate water surface elevations (WSEs) but do not incorporate river channel bathymetry or hydrodynamic conditions observed in large-scale flooding; 2-dimensional and 3-dimensional models can use 1-dimensional model inputs but need integrated continuous surfaces representative of riverine bathymetry and surrounding floodplain topography for inundation mapping (Merwade, Cook, & Coonrod, 2008).

GIS methods for postprocessing H&H model results are the primary means for mapping flood inundation estimates (cf. NOAA-NWS, 2011). Static flood inundation maps may reflect the dynamic changes in forecasts for expected river stages and heights by referencing precomputed analyses, but these maps are typically compiled in databases for a set of expected hydrologic conditions and referenced dynamically through web services, including GIS (cf. Hearn, Longenecker, Agualdo, & Rahav, 2013; USGS, 2017a; USGS, 2018a). The USGS Flood Inundation Mapping (FIM) Library and NWS Advanced Hydrological Prediction Service provide suites of inundation maps for fewer than 250 sites in the United States as of 2019—for reference, there are roughly 3,144 counties in the United States with more than 89,000 local governments and more than 3.5 million miles of streams and rivers, illustrating that these inundation libraries are reasonably prioritised for highly populated areas (EASPE, 2002; NOAA-NWS, 2017b; NOAA-NWS, 2017c; U.S. Census, 2019; USEPA, 2019; USGS, 2019). These inundation data are postprocessed using GIS techniques to represent flood extents (horizontal) and flood depth at gage (vertical), although raster-based depth data are not commonly accessible, except from the USGS FIM Library (cf. USGS, 2019), possibly due to the large files size associated with raster data or limited bandwidth for transmission. These National Oceanic & Atmospheric Administration-National Weather Service (NOAA-NWS) analyses suggest that gage-based methods can be applied to flood risk assessments, with results presented quantitatively and with qualitative categorization, corresponding to minor, moderate, and major flood stages on forecast hydrographs (Bales & Wagner, 2009; NOAA-NWS-2017d). Yet, lessons learned from historic flooding on the Red River of the North (“Red River”) in 1997 and more recently in record floods on the Souris River in North Dakota in 2011 reveal that NWS forecast products are often difficult for emergency managers and the public to interpret (Pielke Pielke & Roger, 1999; Bales & Wagner, 2009; NOAA-NWS, 2012).

As a critical foundational dataset for both H&H and simplified flood modelling, the USGS National Elevation Dataset (NED) is considered the “best available elevation data” for large area coverage, providing standardised DEMs for the United States and its territories in “consistent resolution, coordinate system, elevation units, and horizontal and vertical datums” (sic) with 1-arc second (30-m) grid resolution chosen for file size with overall vertical accuracy of about 14.9 ft (4.9 m) at the 95% confidence level nationally, though some local areas may be accurate to within 1.2 ft (0.4 m) in flat terrain and up to 2.4 ft (0.7 m) in hilly terrain (Gesch, 2007; NRC, 2009; Osborne et al., 2001; Sanders, 2007; Tighe & Chamberlain, 2009). By contrast, LIDAR-derived elevation is available for at least 30% of the United States as of the most recent complete inventory assessment in 2013, with vertical accuracy averages of a few inches (centimetres) and coverage expanding (Gesch, 2007; Heidemann, 2014; NOAA, 2018; NRC, 2009; Osborne et al., 2001; Sanders, 2007; Stoker, 2013). Although DEMs are used ubiquitously in emergency management to determine flood extents and depths, there is little guidance as to which DEM or technique is best for flood inundation mapping and under what conditions, leaving nonexpert practitioners without the information they need to accurately use the data. Oftentimes the highest resolution DEM is assumed to give the “best” or most accurate flood inundation estimates; however, review of spatial resolutions by Sanders (2007) finds that flood models incorporating high resolution LIDAR-based DEMs are preferable due to both horizontal and vertical accuracy—indeed, a balanced combination of high resolution and vertical accuracy is ideal. Some DEMs based on LIDAR and airborne interferometric synthetic aperture radar (ISAR) often include structures from the built environment or vegetation, requiring additional processing of ground elevations for flood modelling, though Sanders (2007) notes that the USGS NED is “remarkably smoothed” (see also, Heidemann, 2018). Taken together, these previous results suggest that NED DEM data do not require further smoothing to meet the accuracy required for inundation analysis for emergency management, though the NRC (2007; 2009, p. 36–37) finds the NED unsuitable for regulatory floodplain mapping due to the data’s age, resolution, and aerial photography survey means.

The flood inundation mapping methodology reported herein relies on the premise that coarse scale, low-resolution river gage data can be disaggregated into individual components representative of topography and water depths above river banks and over land areas that are not normally flooded. The NWS provides river stage forecasts as height above an assumed gage zero or zero datum elevation, described “in hydrologic terms [as] a reference ‘zero’ elevation for a stream or river gage” (NOAA-NWS 2017d). The USGS refers to gage zero as the
“base, or 0.0 gage-height (stage), for a gage,” also referred to by USGS as the datum for a gage “surveyed in from known benchmarks or with precision GPS” or elevation “when the base gage-height has been determined from less accurate means, such as maps, barometer, etc[.]” (USGS, 2017b). Most DEMs do not reflect riverine bathymetry—due to spectral reflection, for example, in the case of LIDAR or satellite-derived DEMs (cf. Mersel, Smith, Andreas, & Durand, 2013; Toscano, Acharjee, McCormick, & Devarajan, 2015)—and therefore require some estimate of river channel depths or gage height corrections to produce estimates of flood depths laterally, over land areas beyond river banks. Using DEMs such as the NED, channel depth can be estimated by subtracting the gage zero elevation value from the ground elevation at a river gage or, more simply, floodwater depth at gages can be estimated by subtracting the ground elevation of the river gage from total river stage elevations calculated by hydrologic models.3

The ability to monitor floods with remote sensing platforms progressed greatly in recent years, a result of the concerted effort of international space agencies to address flood emergencies that are expected to cost nearly $1 trillion worldwide by 2050 (Hallegatte, Green, Nicholls, & Corfee-Morlot, 2013; Schumann, Bates, Horritt, Matgen, & Pappenberger, 2009). Remote sensing requires timely processing and validation for producing flood extents, however, which become accessible often within a 48-hr production window starting from the time of image collection, if licensing considerations allow; further, depending on sensor type, imagery collection is highly dependent on daylight and weather conditions that obscure the view of floodwaters, with resultant products typically representing binary “wet” or “not wet” conditions on the ground and not providing estimates of water depth, which are critical to damage analysis (Schumann, 2017). Flood extents derived from remote sensing may assist with model calibration, as it is used here, although assimilation of remotely sensed data in hydrodynamic models currently requires complex, time-consuming, nonlinear and unstable mathematical solutions, and expert skillsets (Schumann, 2017), significantly limiting utility for emergency operations.

The flood inundation mapping technique that we demonstrate is not intended to replace or otherwise supplant high-resolution, high-accuracy river bathymetry, hydraulic, or hydrologic models, but rather to support rapid decision-making during time-short emergency operations by deriving floodwater extents and depths from forecasted or observed river stage heights using readily-available data. Notably, myriad hydrodynamic models estimate high-accuracy forecasted river stage heights, so our GIS-derived inundation estimates remain a postmodel process. While detailed channel shape and roughness coefficients are required for higher-order H&H modelling, which can be studied and developed in greater detail outside the time-short emergency response context, accurate and simple bathtub methods for volumetric flood extent and depth estimation can be based on gage-derived water surface and DEM-derived ground surface elevations.

3 | STUDY AREA

We selected the Red River to demonstrate and evaluate the accuracy of our riverine inundation mapping technique relative to historic 2009 flooding along the river’s main stem (Figure 2). Within the United States, the Red River is the physical border between North Dakota and Minnesota, draining a land area of nearly 40,000 mile² (103,600 km²) and encompassing numerous smaller watersheds, with headwaters formed by the Ottertail and Bois de Sioux Rivers. The main stem of the Red River begins in the Turtle Mountains at an upland elevation of about 2,300 ft (701 m), flowing northward and gently downhill through a level, wide, flat valley that allows for substantial surface water storage, to an elevation of about 750 ft (229 m) at the international border with Canada (Miller & Frink, 1984). Water flow across the Red River valley is uniquely slow, due to a decreasing slope of only 11 in. per mile (17 cm per kilometre) from Fargo northward to Canada, with flow regulated by several dams and reservoirs operated by local, state, and federal officials, and several cities and most agricultural lands protected from flooding by levees (RRDIN, 2018). Floods occur quite regularly along the Red River due to its flat topography, with major floods in 1828, 1897, 1997, and, relative to our study, in 2009, when the river rose to a record flood stage of 40.82 ft (12.45 m) at Fargo caused by a synchrony of spring thaw, ice jams, and rain and snowstorms occurring between March and April in the United States (RRDIN, 2018).

4 | METHODS

We demonstrate a flood depth regression (FDR) method requiring: (a) calculation of water depth at each gage location, (b) interpolation of water depths between river gage locations, (c) estimation of WSEs along the river path, and (d) projection of these WSEs from the river path into the surrounding topographic floodplain.

We test and apply the FDR method for rapid flood inundation estimation to the 2009 flooding of the Red
River based on NWS/USGS river gage observations from the Bois de Sioux headwaters, beginning at White Rock Dam, South Dakota, and continuing northward through Fargo and Grand Forks, North Dakota, to the Canadian border. Beginning with zero-dimensional gage-height measurements at the sparse set of gage locations along the river, we use the NHD flowline and corresponding NED ground-elevations to estimate inundation depths and flood water-surface elevations (WSEs) both along the path of the Red River and in the 2-dimensional floodplain region that surrounds it. Our methodology includes several detailed steps performed with industry-standard GIS and statistics software (Esri ArcMap 10.5.1 and MathWorks MATLAB 8.6) along with readily-accessible, open-source geospatial data.

First, we download river gage data from the NWS and USGS and review for key attributes and spatial accuracy (NOAA-NWS, 2018). All gage data are converted from NGVD29 to NAVD88 using VERTCON4 for consistency with the USGS NED DEM (NOAA-NGS, 2018). Next, we download DEMs from the USGS NED at 1-arc sec (30-m) horizontal resolution, as well as high resolution stream location data from the USGS/United State Environmental Protection Agency (USEPA) National Hydrography Dataset (NHD+ Version 2), which is spatially-derived from the 1-arc sec (30-m) NED data (Petty, Noman, Ding, & Gongwer, 2016; USEPA, 2018; USGS, 2018c).

After collecting the elevation and stream data, we apply a series of conversions to ensure horizontal and vertical consistency. To estimate the maximum flood extent for this case study, stage-height measurements for gages along the main stem of the Red River are used to assign peak WSEs from the March–April 2009 flood from the Bois de Sioux headwaters at White Rock, South Dakota to the Canadian border. Along these 292 miles (470 km) of river path, there are nine federally-maintained gages along the main stem that sample river height with an average distance apart of about 25 miles (40 km). For each of these nine gages, we first calculate channel depth ($c_i$) at each gage $i$ as the difference between DEM ground elevation ($z(g_i)$) and the elevation of gage zero ($g_0i$). We then subtract channel depth from gage height ($h_i$) to calculate water depth ($d_i$) at each gage location.

$$c_i = z(g_i) - g_0i$$
$$d_i = h_i - c_i$$
To predict WSEs along the Red River flowline, we first interpolate water depth along a series of evenly spaced points that span the length of the river from White Rock Dam to the border with Canada. We convert the NHD flowline to points spaced 0.6-miles (1-km) apart, and specify these points as having latitude and longitude \((x_j, y_j)\). Assuming that water depths at these sampled flowline points are influenced most by nearest gauges, we use inverse distance squared weighting to estimate water depth. In doing so, we assign each evenly spaced point \((x_j, y_j)\) along the flowline a depth \(d(x_j, y_j)\) that is a weighted average of surrounding gage depths \(d_i\), based on the Cartesian distance \(L\) between points \((x_j, y_j)\) and gage locations \((x_i, y_i)\).

\[
d(x_j, y_j) = \frac{\sum_{i=1}^{n} \frac{d_i}{L((x_j, y_j), (x_i, y_i))^2}}{\sum_{i=1}^{n} \frac{1}{L((x_j, y_j), (x_i, y_i))^2}}
\]

To predict flood depths as a continuous function, these depths are fit as a function of flowline distance using a fifth-degree polynomial regression model. We calculate WSE (Figure 3a) by adding water depth to ground elevation along the river path. Fitted inundation depths \(d_j\) are then added to NHD ground elevations \(z_j\) to estimate WSE \(e_j\) along the flowline path (Figure 3b).

\[
e_j = d_j + z_j
\]

To project these water elevations \(e_j\) along the river path outwards to generate a 3-dimensional floodplain \((e(x, y))\), we create a surface using the modelled flowline WSEs by applying an inverse distance squared weighted interpolation:

\[
e(x, y) = \frac{\sum_{j=1}^{n} \frac{e_j}{L((x, y), (x_j, y_j))^2}}{\sum_{j=1}^{n} \frac{1}{L((x, y), (x_j, y_j))^2}}
\]

We then subtract the DEM elevation surface from the interpolated floodwater elevations surface to produce a raster map of flood inundation depths:

\[
d(x, y) = \max(0, e(x, y) - z(x, y))
\]

The subtraction of DEM values from the WSE produces both positive and negative values in the resultant surface, where negative values are ground elevations where there is no flooding. The nonflooded, negative values are discarded, and the remaining areas with positive values are kept, representing a 3-dimensional floodplain water depth surface ("depth grid"). A final step in this process converts the 3-dimensional flood depth surface into a vector polygon that represents a 2-dimensional flood extent.

5 | RESULTS

As above, after interpolating water depth values between the set of nine scattered gage points, we apply the interpolated gage depths to the NHD flowline points to find

![Figure 3](image-url)

**Figure 3**  Gage data are used to define flood depth and water-surface elevations (WSEs). (a) At a gage site, flood WSE is calculated from the gage-zero plus the gage height. From this, the local flood depth can be inferred by subtracting the gage-site digital elevation model (DEM) flowline elevation from the flood WSE. Because the flowline DEM elevation is equal to the ground elevation at the normal river banks, the inferred flood depth is equal to the inundation depth at those banks. (b) Flood WSEs (blue) at gage sites are the sum of gage datums (green) and gage height readings (red). Flood depths (purple, vertically exaggerated for visualisation) in the vicinity of the gages are the difference between flood WSEs and gage-site DEM elevations. National Weather Service (NWS) gage station identification for the study area can be found in Appendix A.
the best fit function of depth for the 2009 flood (Figure 4):

\[ f(x, y) = -0.669x^3 + 1.319x^4 + 4.959x^3 - 7.297x^2 + 1.079x + 29.56 \]

Compared to river gage heights observed for the 2009 flood, the FDR flood depth grid outperforms or matches remote sensing observations by providing water depth information that can be used for depth-damage estimation for built environment impacts. The remote sensing observations, however, include areas of backwater flooding from tributaries as well as ponding, occurring from localised precipitation or meltwater drainage in smaller watersheds distant to main stem flooding, that the FDR method may miss due to use of one NHD flowline only. The full table of interpolations, regression coefficients, and errors for the 2009 Red River gage values is included in Appendix A1, and we caution against extrapolating depths outside of the range of first and last gages.

We compare the results of the FDR method to H&H-modelled flood extents from the Red River Decision Information Network (RRDIN), observed flood extents developed by Canada’s Department of Natural Resources (NRCAN) and based on Radar Satellite (RADARSAT) imagery analyses of the 2009 Red River flood, and with raw imagery from the National Aeronautic & Space Administration (NASA) Aqua satellite's Moderate Resolution Imaging Spectroradiometer (MODIS). It is important to note that the FDR method uses peak flood measurement for each gage, whereas the H&H with which we compare our results is modelled for only the Fargo gage; moreover, we would not expect the FDR results to match exactly due to differences in data and techniques applied. Nonetheless, the FDR gage-based flood extent and 3-dimensional depth grid for the 2009 flood align very well horizontally in spatial comparison.

FIGURE 4 Interpolations and best fit model with residuals, demonstrating that the flood depth regression (FDR) method decreases the sinusoidal depth variance introduced from interpolation. (a) National Weather Service (NWS)/United States Geological Survey (USGS) river gage locations on a 3-dimensional scatterplot (points) with interpolated gage depths (red line). (b) Interpolated gage depths applied to 1-km interval National Hydrography Dataset (NHD) flowline points along the Red River path (red line) with best fit quintic polynomial for gage depths applied to the 1 km NHD flowline points (blue line). (c) A 1-dimensional plot of interpolated gage depths along the NHD flowline (black dots) and the best fit quintic polynomial model (blue line) with 99% prediction bounds (blue dotted lines). (C-bottom) Plot of residuals showing the difference between the interpolated depths (y) and best fit modelled depths (\(\hat{y}\)). (d) The 3-dimensional surfaces showing vertically-exaggerated digital elevation model (DEM) elevations for the Red River Valley with the regressed water depth surface delineating flood extent.
with both H&H-modelling and remote sensing-based observations. We describe our horizontal results qualitatively as a quantitative comparison of flood extents is not possible given differences in how the extents were created; however, though some modelled depths at gage are within 0.1 ft (0.03 m) of the observed depths, the average difference between modelled and observed depths across all gages is 1.4 ft (0.4 m) with root mean squared error of 1.82 ft (0.6 m). Plots of the interpolated depths, best-fit quintic polynomial regression model, and residual errors are shown in Figure 4, with our full modelled-versus-observed results tabled in Appendix A.

Acquired from the RRDIN, the H&H modelling, based on a river stage height of 40.5 ft (12.34 m) at 1/9 arc sec (1-m) horizontal resolution, is slightly less in overall area compared to our FDR gage-based flood extent, as the observed stage height at Fargo was 40.84 ft (12.45 m). As shown in Figure 5, the H&H flood estimate extends into areas with flood control, whereas the FDR flood extent is trimmed to remove protected areas where

![Figure 5](image_url)

**Figure 5** Flood extents (depth > 0) predicted with the flood depth regression (FDR) method (centre) compared to H&H model extents (left) and remote sensing observations (right panels) for the 2009 Red River flood. National Weather Service (NWS) gage identifiers are included in Appendix A. (a) Comparison with Red River Decision Information Network (RRDIN) H&H model flood extent for 40.5-ft (12.35-m) flood stage at Fargo is nearly the same, spatially, as the FDR method; however, the H&H model flood estimates are limited to areas nearest to the Red River, also indicating flooding inside areas with flood control even though levees were expected to—and did—prevent flooding through the 41.0-ft (12.5-m) stage. The squares toward the northern extent of the H&H results reflect the constrained nature of using light detection and ranging (LIDAR) grids. (b) The full extent of the FDR method, reflecting maximum flood conditions for the full length of the Red River’s 2009 flood. (c) Remote sensing flood extents from Natural Resources Canada (NRCAN) reveal straight line artefacts and an incomplete assessment of flooding compared to topography, as demonstrated by the FDR method’s larger flood footprint. (d) At Grand Forks the FDR method is closely aligned to the remote sensing observations.
flooding is not expected; further, the H&H model is available only for the Fargo area, limiting a quantitative areal comparison between the FDR and H&H extents, and the H&H model reflects straight line artefacts from the small-area LIDAR DEM tiles used in that analysis, further limiting direct spatial comparison. Both the H&H and FDR flood extents tend to over-flood some areas north of the Fargo river gage that did not actually flood in 2009 due to levee-and-sandbag flood controls. Both flood extents, however, provide useful guidance for “what-if” scenarios supporting crisis action planning.

The NRCAN observed flood areas from RADARSAT, depicted as the official 2009 flood extent from RRDIN, were limited by collection areas or otherwise reduced spatially, resulting in artificial straight lines that do not follow local topography. Such cases occur from the Grand Forks area northward to Pembina at the Canadian border, with the FDR flood extent outperforming the NRCAN remote sensing observations in this case. We compared the FDR and RRDIN flood extents spatially by estimating the area of U.S. Census blocks totally or partially flooded by the FDR flood extent, we find that the RRDIN flood extent underestimates observed flooding by an average of 1–2 mile² (1–5 km²), with a few blocks underestimated by up to 500 mile² (binned as between 500 and 1,000 km) along northern reaches of the Red River. However, the NASA MODIS Aqua sensor acquired cloud-free, true colour imagery at 250-m spatial resolution on April 9, 2009, which is 8 days after the flood crest at the Oslo,
FLOOD DEPTH REGRESSION (FDR)-MODELLED FLOOD EXTENTS FOR MODERATE FLOOD STAGE OF 11 FT (3.4 M) AT THE NATIONAL WEATHER SERVICE (NWS) WALKER RIVER AT MASON NEVADA GAGE FORECAST POINT OVERLAIPOINTED ON A CORECTIFIED UNITED STATES GEOLOGICAL SURVEY (USGS) BASE MAP OF THE 1997 FLOOD OF RECORD AT YERINGTON, NEVADA WITH A FLOOD EXTENT DERIVED IN 1997 FROM REMOTE SENSING (LIGHT BLUE) (FEMA, 2017C; URS, 2013). THE FORECASTED MODERATE FLOOD STAGE DURING THE SPRING SNOWMELT OF 2017 WAS EXPECTED TO STAY MOSTLY WITHIN THE BANKS OF THE WEST WALKER RIVER THROUGH YERINGTON (DARK BLUE POLYGONS, MOSTLY CONSTRAINED TO THE RIVER CHANNEL WITH SOME DISCONNECTED PONDING), THOUGH SOME FLOODING COULD OCCUR ALONG IRRIGATION DITCHES AND CANALS AWAY FROM THE RIVER'S MAINSTEM (GREEN NATIONAL HYDROGRAPHY DATASET [NHD] FLOWLINES). IN CONSIDERING FORECAST UNCERTAINTY, THE FDR METHOD PERMITS THE DEVELOPMENT OF ADDITIONAL FLOOD EXTENTS BASED ON STATISTICAL ERROR: ACCORDINGLY, FLOOD EXTENTS FOR 1 DELTA ERROR (RED) AND 2 DELTA ERRORS (PURPLE) REVEAL THAT YERINGTON MIGHT HAVE OBSERVED FLOOD DAMAGE WITH SLIGHTLY HIGHER RIVER STAGE.
Minnesota gage, 4 days after the crest at the Drayton, North Dakota gage, and 6 days prior to the crest at Pembina (NASA, 2009). Although floodwaters were receding for Oslo and Drayton in Figure 6, the FDR flood extent reveals a plausible maximum flood extent based on gage observation compared to Aqua imagery observation.

As an alternative scenario for considering the accuracy and use cases for the FDR method, we developed flood extents and depth grids in May 2017 for snowmelt runoff and flooding on the West Walker River at Yerington, Nevada (data not shown). The Walker River is the main surface water source for Walker Lake, a perennial, terminal lake in the basin and range topography of
the Mason Valley of Nevada fed primarily by snowmelt originating in the Sierra Nevada mountains. The lake provides freshwater for irrigation to the predominantly agricultural lands near the town of Yerington and about 1,000 homes are at risk of flooding from the river (URS, 2013). In April 2017, NWS forecasters projected that spring snowmelt flooding on the Walker River could reach levels similar to the flood of record (KOLO-TV, 2017), which caused about $19.5 million in damages in Lyon County after a “pineapple express” weather system dropped more than 11 in. (28 cm) of rain on the 180%-of-average mountain snowpack in January 1997 (Nevada DWR, 1997; USGS 1997). FEMA supported the State of Nevada through recovery from severe winter storms, floods, and mudslides that occurred in January 2017 (FEMA, 2017c). We collaborated with federal, state, and local officials to produce several flood extents for a moderate flood stage of 11 ft (3.4 m) at the NWS forecast point at Mason, Nevada (nearest to Yerington) using the FDR method on the 30-m NED, as higher resolution or H&H modelling of potential flood conditions was not available (M. Sippel 2017, personal communication, 20 May). Using NWS moderate flood stage heights for gages both upstream and downstream of Yerington, using the FDR method, on May 26, 2017 we provided the flood extents depicted in Figure 7 to FEMA’s field office for emergency planning decision support. As this map shows, our FDR-modelled moderate flood stage inundation estimate suggested that there would be little flooding beyond the channel of the West Walker River near Yerington, aligning close to the actual crest of the West Walker River at 10.93 ft (3.3 m) on June 22, 2017 (KOLO-TV, 2017; NOAA-NWS, 2019).

### Table 1
Census population and American Community Survey (ACS) exposures with FDR best fit and hi/lo error estimates

| Method of flood estimate                               | Exposure type               | Minnesota | North Dakota | South Dakota |
|----------------------------------------------------------|-----------------------------|-----------|--------------|--------------|
| Remote sensing (NRCAN)                                   | Census 2010 Population      | 7,471     | 20,049       | 2            |
| Remote sensing (NRCAN)                                   | ACS 2010 Housing Units      | 3,286     | 8,063        | 1            |
| Model low CI bound w/ flood protection\(^a\)              | Census 2010 Population      | 9,689     | 64,639       | 1            |
| Model low CI bound w/ flood protection\(^a\)              | ACS 2010 Housing Units      | 4,267     | 27,701       | 1            |
| Model fit w/o flood protection\(^b\)                     | Census 2010 Population      | 13,474    | 118,355      | 43           |
| Model fit w/o flood protection\(^b\)                     | ACS 2010 Housing Units      | 6,059     | 52,397       | 21           |
| Model fit w/ flood protection                             | Census 2010 Population      | 0         | 102,440      | 0            |
| Model fit w/ flood protection                             | ACS 2010 Housing Units      | 0         | 45,191       | 0            |
| Model high CI bound w/o flood protection\(^b\)           | Census 2010 Population      | 22,482    | 132,846      | 48           |
| Model high CI bound w/o flood protection\(^b\)           | ACS 2010 Housing Units      | 9,579     | 59,021       | 23           |
| Model high CI bound w/ flood protection                  | Census 2010 Population      | 0         | 149,705      | 0            |
| Model high CI bound w/ flood protection                  | ACS 2010 Housing Units      | 0         | 66,569       | 0            |

Abbreviations: ACS, American Community Survey; FDR, flood depth regression; NRCAN, Natural Resources Canada.

\(^a\)Includes only federal flood control structures.

\(^b\)Assumes natural valley floodplain (cf. FEMA, 2017b).

### Figure 9
The application of the new rapid flood risk assessment method to decision-making over the timeline of a flood event.
6 | DISCUSSION

Although sandbagging and other mitigating flood-fight activities in 2009 prevented floodwaters from overtopping local levees and flood control structures, the FDR analysis method described here supports deterministic analysis based on error in the forecasts and modelling—for “what if” impact analysis of the event if floodwaters were higher than expected. Although the NWS adopted a probabilistic Ensemble Streamflow Prediction method in the mid-2000s, both the forecasts and observations for the 2009 Red River flood are treated deterministically in our demonstration. The FDR-modelled flood extent can be used to assess exposure of population and built environment (Figure 8). Though excluded from the best fit model for mapping the observed 2009 flood, we also estimated exposures in “protected” areas (Table 1).

The FDR method is based on interpolating water depth values between gage point locations, which can introduce error. We use inverse distance weighting to avoid modifying gage measurements; however, sinusoidal variance in water depth occurs between gage points when subtracting DEM values from WSE values, which is likely caused by significant terrain slope that act to “pull” up or down water depth estimates (cf. Amante & Eakins, 2016, p. 130). Thus, we find it both (a) preferable to interpolate water depth values between gage locations first, because WSE-only interpolation between gage points introduces far more variance than depths (e.g., the standard deviation of depth is 8.5 ft (2.6 m), whereas WSE is 60.6 ft (18.5 m)), and then add the interpolated depths to flowline point DEM elevations to estimate WSE; and (b) necessary to smooth the interpolated water depth values with linear regression to remove sinusoidal variance by flattening erroneous peaks and troughs to more accurately distribute the predicted, downscaled water surface over the topographic surface. Other interpolation methods, such as splines, kriging, or kernel density smoothing, introduce additional, unnecessary parameterizations or other errors (Merwade, 2009, p. 170). Notably, for flooding in South Carolina in 2015, the USGS used “topo to raster” interpolation methods available in Esri’s ArcGIS software, sometimes with river cross-sections to constrain flooding laterally when using point-based field measurements of depth (Musser, Watson, Painter, & Gotvald, 2016). Indeed, too few terms in regression modelling, including cubic and quadratic polynomials, tends to under-fit the gage depth values, while too many terms over-fits and adds unwanted error.

Another consideration when subtracting DEM values from interpolated WSE values relates to areas of flooding that are hydraulically disconnected from mainstem floodwater sources. Such disconnected ponds of floodwater were observed in the FDR analysis, displayed in Figures 4a, 6, and Figure 8b,c; however, for the Red River, these disconnected ponds were generally quite small in area, due in large part to the river’s gentle valley and slope. For Yerington, Nevada, the disconnected ponds nearest the West Walker River were useful artefacts for assessing local flood control decisions, as the irrigation ditches and canals depicted in Figure 6 as “All NHD Flowlines” are sourced from the mainstem; however, in our analysis, the Anaconda Copper Mine, disconnected from the West Walker River, was shown to be flooded despite local flood control devices known to prevent flooding of the mine. In developing the FDR use case for the Yerington scenario, we manually edited the flood extent to show the mine as not flooded, similar to trimming out the levee-protected areas of the Red River analysis. Though disconnected flooding may at first glance raise alarm about excessive flood estimates, we recommend careful review of the resultant flood extents for consideration of local topographical errors or flood control not otherwise reflected in the DEM. In the case of Yerington, in Nevada’s highly variable basin and range topography, the NED was considered the most accurate elevation dataset to assess the moderate flood stage potential, as both medium-resolution IfSAR DEM and high-resolution LIDAR DEM contained erroneous artefacts, including vegetation and buildings, which caused more substantial disconnected flood estimates. Moreover, similar to the NRC (2009, p. 26) finding that elevation differences between geodetic model datums “are immaterial to flood mapping as long as elevations are referenced to the same datum,” we find that flood extents produced with the FDR method are accurate on the NED because all gage data, flood depths, and topography are consistent within the NAVD88 vertical datum. Further, though there are elevation differences across DEMs of differing resolutions or sources, leading to differing derived flood extents on spatial comparison, the conversion of gage heights and depths to the vertical datum of the DEM is a critical component of the FDR method’s accuracy. In this instance, uncertainty across DEMs may be a good thing, where estimates of disconnected flooding perhaps lead to increased awareness of flood risk, monitoring, and preparedness.

Our approach ensures that we meet Tobler’s first law of geography (Tobler, 1970)—that near things are more related than distant things such that river gage measurements have strong spatial autocorrelation—while simplifying our model. The method also supports Horton’s laws for stream ordering such that water flows and increases in depth downstream as a function of terrain (slope and valley). This simplification does not physically describe water movement downstream, either at the lateral...
margins of the flood surface or in relation to other nonlinear or unstable wave or water actions. However, we avoid statistical overfitting by assuming that our limited sampling of water depths at river gages is related to the overall estimation of water depths along the river flowline path such that we can add smoothed water depths to a smoothed DEM to estimate flood extent inferentially. If there were more river gages from which to sample, we might infer other information about the river, such as slope, channel shapes or depths, or roughness coefficients, but our primary concern in developing flood extent is floodwater depths along the elevation path of the river.

While insufficient to inform planning and response operations by themselves, gages can be used to identify areas expected to be underwater, when, and at which depths, when considered relative to the topography of the surrounding area. Such analysis is useful both for and beyond emergency management, as accurate spatial representation of surface water is vitally important to public health, agriculture, and ecological conservation management practices (cf. Fluet-Chouinard, Lehner, Rebelo, Papa, & Hamilton, 2015). As shown in Figure 3, the flood extent predicted using FDR is closely aligned with the RRDIN H&H model, as well as post hoc remote sensing observations for the 2009 flood near Fargo, as would be needed for a wide range of use cases. The FDR flood extent, at 30-m horizontal resolution, is much higher resolution than available imagery sources and represents an efficient, accurate compromise over using very-high resolution (1/9 arc-second [1-m]), spatially-constrained H&H modelling.

Though remote sensing has become a customary expectation for emergency management and flood monitoring, the FDR method described here provides a rapid risk assessment available sooner and more immediately suited to rapid, practical decision-making. Remote sensing imagery is only available post hoc and is largely 2-dimensional and either does not or cannot estimate water depths, often missing flood crests, which limits applications for rapid risk or damage assessments. As shown in Figure 4, remote sensing observations are often limited to irregular collection areas, resulting in artificially straightened flood boundaries that do not coincide with topographic features. This effect is visible from Grand Forks northward to Pembina, where modelled flood extents are more informative than limited remote sensing observations. The FDR technique provides both a 2-dimensional flood extent and 3-dimensional depth grid, which, combined with depth-damage relationships, establish the basis for conducting risk and loss assessments for crisis action planning or community planning needs. With manual processing, the method runs in under an hour for most scenarios evaluated and can be further optimised to run in a matter of minutes for smaller geographic areas, as our forthcoming reporting reflects testing on river stage forecasts and flood response operations at FEMA during 2016, 2017, and 2018. In the recent case of Hurricane Harvey in 2017, FEMA supplemented the U.S. Army Corps of Engineers’ H&H modelling with gage-depth interpolation only (no regression or smoothing) to achieve a comprehensive estimate of flooding on numerous streams and rivers in Texas, with run-times totalling several hours and the flood estimates supporting urban search and rescue teams in the field.

Responding to similar inundation mapping needs, and following extensive testing and social science research, the NOAA National Hurricane Center (NHC) began issuing to the public an official hurricane storm surge flood potential graphic for emergency management in about 2014 (cf. NOAA-NHC, 2016). In order to evaluate the effectiveness of the storm surge flood inundation map, the NHC sponsored online surveys and focus groups to elucidate key components of information visualised on the map, evaluating cartographical symbolization of floodwater depths, including map colours, depth range classes, and potential hazard categorised as low, moderate, high, or extreme (ERG, 2013). In Figure 8, panel C, we present the peak stages of the 2009 Red River flood using the NHC storm surge flood inundation mapping scheme of low (dark blue, depths less than 3 ft [1 m] above ground), moderate (yellow, depths of 3 to 6 ft [1–2 m] above ground), high (orange, depths of 6 to 9 ft [2–3 m] above ground), and extreme hazard (red, depths greater than 9 ft [3 m] above ground), while adding an additional depth class for less than 1-ft [0.3 m] of water to further define flood depths for informing flood fight activities like sandbagging. Considering the successful operationalization of the NHC potential storm surge flooding graphic for forecast-based decision support, we call for further research into riverine flood inundation mapping for risk communication using the FDR and similar methods.

Rapid flood risk analysis using the FDR method can be extremely effective at evaluating and informing emergency response efforts in the time between when the event occurs, when forecasts and real-time gage data first become available, and when remote sensing imagery first becomes available. Figure 9 reflects this time window and the applications of the types of results produced by the FDR method. For response planning or exercise scenarios, ideally before the onset of flooding, the FDR method may be used in the absence of advanced H&H...
modelling to develop flood inundation scenarios with historical river gage observations to assess needs for more detailed, event-specific H&H modelling—for the Red River, other major-to-record floods occurred as long ago as the 1820s, when the present-day large population centres were unaware of floodplain development consequences. Further, inundation scenarios for reliable forecasts of long-term to short-term onset of flooding can be developed cost-effectively with the FDR method, allowing emergency managers and local officials to consider evacuations, sandbagging and other flood fighting operations, and the overall potential for local impacts and losses. To that end, the FDR method may be used to develop inundation depth grids for use in loss estimation models such as Hazus, developed by FEMA, which allows for quickly importing custom flood-event depth grids for loss and impact estimation on emergency response timelines (cf. FEMA, 2018b). At a state and federal level, using the FDR method to quickly assess damage to infrastructure, businesses, or buildings, in general, can assist with rapid damage assessment in near real-time, validated as remote sensing and other observations become available, for use in expediting and supporting emergency declarations, insurance liabilities, and other fiscal consequences to local, regional, and national markets.

7 | CONCLUSION

Emergency managers and first responders require accurate and scalable geospatial data decision support in flood response operations. In addition, communities need a rapid method to support flood risk assessments for crisis action planning efforts at high resolution that does not require significant computing power or modelling expertise. This study presents the FDR method, an accurate methodology for rapid river-gage-based analysis, applied to and validated against observed flood conditions on the Red River of the North in 2009, for mapping expected inundation and exposures to observed flood conditions for risk assessment and response operations decision support. Historically, flood inundation mapping relies primarily on complex, costly, and time-consuming H&H modelling for emergency response operations—sometimes with model simplifications or assumptions that affect significantly the resulting inundation maps created as a postmodel process with GIS conversions. We do not suggest that hydrology and hydraulics models are unnecessary, but instead present a method that can support the needs of flood risk and emergency managers for timely, cost-effective, and accurate inundation mapping analyses.

**DISCLAIMER**

The views and conclusions contained in this report are those of the authors and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Department of Homeland Security and/or Federal Emergency Management Agency.

**DATA AVAILABILITY STATEMENT**

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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**ENDNOTES**

1 We use the term “mitigation” broadly in this report, referring to any action or actions undertaken to reduce exposure to or consequences of a flood risk event.

2 We use the USGS spelling of “gage” rather than “gauge” (cf. USGS, 2018b). We demonstrate our technique using NOAA-NWS forecast and observation data, and, as such, present stage heights and water depths in US/Imperial units first with SI conversions next.

3 This simplification in the gage data may produce errors, however, and Merwade (2009) cautions that interpolation methods, such as inverse distance weighting (“IDW”), may result in inaccurate river bathymetry surfaces. Additionally, direct contact with USGS staff, local hydrologists, or engineering firms may yield more accurate gage and channel data, if needed.

4 The VERTCON software computes a modelled difference between the orthometric heights of NAVD88 and NGVD29 vertical datums and is generally accurate within about 1 in. (2 cm). However, given uncertainties in the datum transformation model, method, or physical differences in height systems, some errors in “rare cases” may be about 7.9 in. (20 cm) or more (cf. NOAA-NGS, 2018).

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### TABLE A1  
Data table of interpolation, regression coefficients, and errors for the 2009 Red River gage values and modelled depth

| Gage location | White rock | Wahpeton | Hickson | Fargo | Halstad | E. Grand Forks | Oslo | Drayton | Pembina |
|---------------|------------|----------|---------|-------|---------|----------------|------|----------|---------|
| NWS gage ID   | WHRM5      | WHNN8    | HICN8   | FGON8 | HILN8   | EGFM5          | OSLM5| DRTN8    | PBNN8   |
| 2009 flood max gage height | 10.74* | 17.50 | 39.04 | 40.84 | 40.63 | 49.33 | 38.37 | 43.82 | 52.71 |
| Gage zero elevation** | 960.06 | 943.77 | 877.44 | 862.74 | 827.74 | 780.07 | 773.77 | 756.18 | 740.78 |
| Total gage height WSE (gage zero plus max gage height) | 970.80 | 961.27 | 916.48 | 903.58 | 868.37 | 829.40 | 812.14 | 800.00 | 793.49 |
| NED NHD flowline elevation | 968.33 | 951.79 | 890.70 | 877.83 | 838.47 | 798.12 | 785.36 | 768.86 | 756.75 |
| Estimated channel depth (NED minus gage zero) | 8.26 | 8.03 | 13.27 | 15.09 | 10.73 | 18.05 | 11.59 | 12.68 | 15.97 |
| Estimated flood depth (max gage height minus channel) | 2.48 | 9.47 | 25.77 | 25.75 | 29.90 | 31.28 | 26.78 | 31.14 | 36.74 |
| Interpolated flood depth | 2.48 | 9.48 | 26.85 | 25.80 | 29.99 | 31.31 | 26.78 | 31.44 | 36.74 |
| Estimated WSE (NED plus flood depth) | 970.81 | 961.27 | 917.55 | 903.63 | 868.46 | 829.43 | 812.14 | 800.30 | 793.49 |
| Interpolated WSE | 970.80 | 961.25 | 916.47 | 903.59 | 868.38 | 829.40 | 812.14 | 800.02 | 793.49 |
| Modelled flowline depth*** | 2.41 | 13.15 | 23.55 | 26.80 | 29.60 | 28.69 | 28.65 | 31.24 | 36.40 |
| Delta error for Modelled depth | 1.82 | 1.77 | 1.77 | 1.77 | 1.77 | 1.77 | 1.77 | 1.77 | 1.81 |
| Modelled Total gage height WSE (NED plus Modelled depth) | 970.73 | 964.94 | 914.25 | 904.62 | 868.08 | 826.81 | 814.01 | 800.10 | 793.15 |
| Modelled 2009 Total Gage Height | 10.67 | 21.17 | 36.82 | 41.88 | 40.34 | 46.74 | 40.24 | 43.92 | 52.37 |
| Difference: Modelled and observed Total gage height WSE**** | −0.07 | 3.67 | −2.22 | 1.04 | −0.29 | −2.59 | 1.87 | 0.10 | −0.34 |

*Estimated from USGS Gage ID USGS050000 (Bois de Sioux River at White Rock Dam, South Dakota, as headwaters to the Red River of the North). **All values listed in feet and converted to NAVD88 vertical datum. ***Quintic polynomial regression with \( r^2 = 0.9597 \). ****RMSE: 1.82 ft.