Advanced 3D Scour Modeling of Pipeline Water Crossings

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Abstract

This abstract presents a state-of-art approach to three-dimensional scour modeling specifically for pipeline water crossings, with a particular focus on simulating and analyzing the effects of record flood events and their subsequent effects on potential pipeline exposure and free-span lengths. Pipelines traversing water bodies are susceptible to scour, which can result in structural damage and significant economic losses not just from damage to the pipeline but from premature shutdown of the pipeline due to excessively conservative desktop scour modeling. Our research integrates cutting-edge computational fluid dynamics (CFD) techniques and advanced sediment transport modeling, combined with high- resolution bathymetric and topographic field inspection data to provide a comprehensive assessment of scour and span potential in pipeline water crossings under a variety of statistical flood recurrence intervals.

We introduce a novel three-dimensional scour modeling methodology that considers the complex interaction between water flow, sediment transport, pipeline geometry and depth of cover. This approach leverages high-resolution bathymetric and LiDAR data sets, hydraulic parameters, and sediment properties to accurately predict the scour depths and patterns during various flow conditions. Furthermore, the study explores the extreme scenarios by simulating record flood events, which are essential for assessing the pipeline's resilience and safety under extreme hydraulic conditions. The outcomes of these simulations are presented in interactive three-dimensional models and offer invaluable insights for optimizing pipeline design, maintenance, and risk mitigation strategies, ensuring the long-term integrity and reliability of pipeline infrastructure in challenging water crossing environments. This research contributes to the advancement of pipeline engineering practices, with the potential to enhance the safety and sustainability of critical waterborne transportation systems.

1. Introduction

River scour is a type of localized depression caused by the progressive flow of water and sediment traveling downstream. River environments present unique challenges when predicting scour during peak-flood events because of their varying and irregular flow patterns. Fully analyzing and understanding the nuances of river scour is vital when considering major risk factors that can impact pipeline water crossings. If significant river scour exposes a pipeline, or if the entire cross-section of a pipeline is exposed and spanning, the line is exceedingly susceptible to damage or failure. Therefore, it is essential to monitor and predict river scour while making pre-emptive decisions involving high-risk pipeline water crossings.

1.1. Traditional 2D scour modeling approach

The most common and convenient method of predicting river scour utilizes a two-dimensional analytical approach where a single bathymetric transect of the river over a pipeline's path is extracted

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and assessed. A looming pitfall engrained within this method is the assumption that flow velocity is only a function of depth and water surface gradient at each one-dimensional point along the extracted two-dimensional transect. It does not take upstream and downstream bathymetric and manmade features and their ability to affect and divert flow into account and it assumes a uniform flow velocity both upstream and downstream from each one-dimensional point. Once the flow velocity for each one-dimensional point along the cross-section is estimated, several empirical scour depth estimation formulas are utilized by inputting estimated velocity and sediment grain size as primary variables. It becomes problematic when the river section being studied includes bend curvature and the bathymetric contours both upstream and downstream from the pipeline water crossing are not considered within the analysis. Depending on where the pipeline crosses in relation to a bend in the river, there can be dramatic differences in the dispersion of flow velocities along any given transect between the bend and the crossing. In many of these cases, a two-dimensional scour analysis is less dependable when estimating scour depths during peak-flood events.

1.2. Advanced 3D scour modeling approach

Advanced three-dimensional computational fluid dynamics (CFD) models are indeed powerful tools for capturing detailed flow fields and scour mechanisms due to their ability to resolve complex three-dimensional interactions. These models can simulate phenomena like turbulence, sediment transport, and flow-structure interaction with greater precision than simplified two-dimensional models. However, there is a computational load intensity that stems from several factors preventing many from taking on the task. First, it requires high spatial and temporal resolution to accurately resolve fluid and sediment dynamics. Second, complex numerical schemes must be applied in order to solve for the governing equations and sediment transport equations in three dimensions. Last, the process requires extended simulation processing times and significant computational resources that require high-performance computing (HPC) systems. These constraints combine to make full three-dimensional CFD models a less practical path for routine engineering applications.

In this paper, we propose a three-dimensional scour analysis based on a hybrid approach that combines depth-averaged CFD models for the flow field with empirical formulas for sub-grid scour depth estimation. This hybrid method is faster and requires less computational resources than an a full three-dimensional CFD scour analysis while providing a more reasonable multi-dimensional flow field than a traditional two-dimensional scour analysis. A three-dimensional bathymetric and topographic model is used to obtain the directional angles and depth-averaged flow field, and the obtained depth-averaged velocities are employed for each two-dimensional (horizontal) grid point of the three-dimensional mesh to estimate scour depth using empirical formulas (Figure 1). This faster and less resource-intensive method is vastly more conducive to real-time decision-making, feasibility studies, and preliminary remediation designs. DoC Mapping currently has a USPTO patent pending regarding this hybrid approach, which highlights a semi-automated workflow and visualization software that further expedites this service, making it ideal for prioritized efforts.

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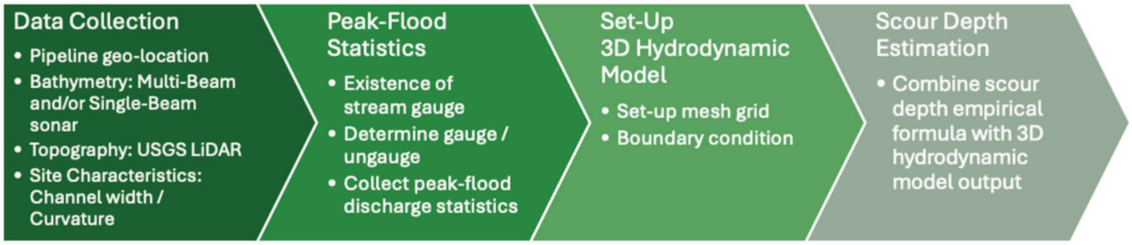

Figure 1. Flow chart of 3D scour modeling.

2. Data Collection

When performing a 3D scour analysis of a pipeline water crossing under extreme peak flood discharge, it is essential to acquire and prepare several high-quality data sets to ensure accuracy and reliability. Data required includes accurate position and elevation of the target pipeline, high-resolution bathymetric and topographic data, sediment properties and peak flood discharge statistical data.

2.1. Pipeline geo-positional data

The ability to acquire accurate geo-positional and elevational data for each pipeline within a water crossing is paramount in the effort to better understand and assess river scour hazards. Within the data collection process, this is the most challenging piece to obtain, analyze and portray. DoC Mapping has accumulated years of experience utilizing electromagnetic locating sensors to map and illustrate depth of cover for a variety of utility types including pipelines, conduits and cables. This type of expertise is key when leveraging the acquired data into a robust scour analysis desktop study.

2.2. Bathymetric data

Bathymetry is the study and measurement of underwater depth and terrain, focusing on mapping features to produce detailed representations of a portion of seabed or riverbed. At pipeline water crossings where conditions and vessel access allow, DoC Mapping employs a high-resolution multi-beam sonar system to generate a precise and detailed bathymetric map of the study area (Figure 2a). This system, equipped with an onboard inertial real-time kinematic (RTK) system, ensures exceptional accuracy during surveys. Additionally, the sonar imagery serves as a secondary verification method in areas with minimal cover depth or pipeline exposure. A bathymetric scope of work is completed with defined upstream and downstream extents for each pipeline water crossing. Resolution of the bathymetric data acquired ranges in resolution from 6 inches up to 3 feet, which enables the rendering of a detailed three-dimensional mesh that includes identifiable riverbed features such as sand waves and remediation materials at the studied bathymetric section of river.

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For further coverage if needed, open-source bathymetric data from NOAA can also be incorporated if upstream or downstream extents need to be expanded for any reason during the desktop study phase (Figure 2b). Revisit studies can also be completed to expand the upstream and downstream bathymetric coverage and gain more context when required. When study sites are relatively small and do not allow multi-beam sonar usage, a single-beam sonar system can be deployed, or bathymetric data can be collected while wading through shallow sections using a range pole to gather elevations. In such cases, NOAA bathymetric data can complement these lower resolution data sets, bridging data gaps and expanding bathymetric coverage.

2.3. Topographic data

Topography refers to the study and detailed description of the physical features of a land surface, including its natural and artificial characteristics. USGS LiDAR data is routinely acquired from Digital Elevation Models sourced from the USGS National Map (Figure 2b) during our process, to contribute bank and shoreline geometry to the bathymetric three-dimensional mesh prior to scour modeling.

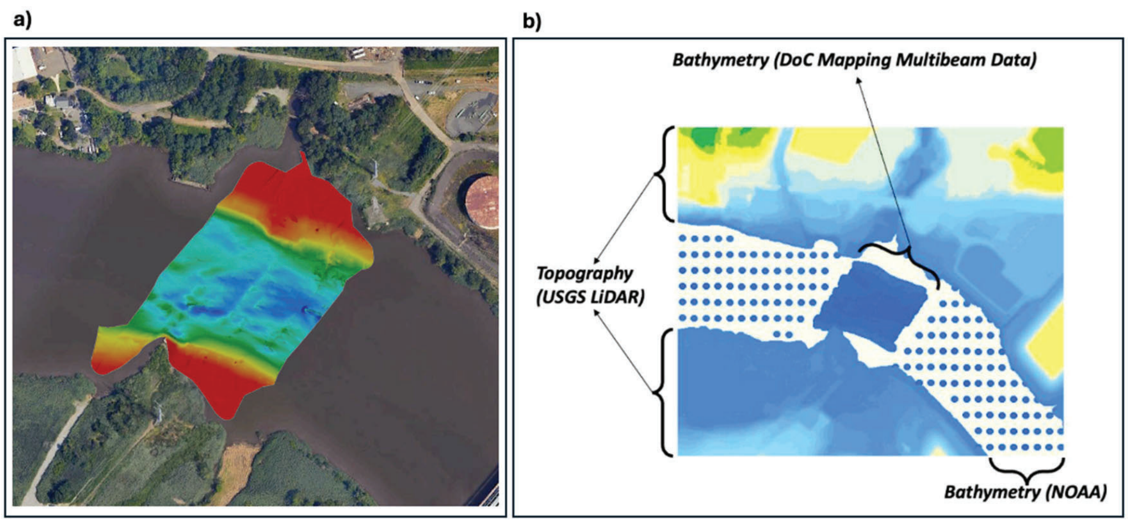

Figure 2. Examples of bathymetric and topographic data. a) High-resolution multi-beam bathymetric data acquired by DoC Mapping. b) Combination of DoC Mapping multi-beam bathymetry and USGS LiDAR topography. Bathymetric data from NOAA is sometimes used to obtain expanded upstream and downstream coverage.

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2.4. Site characteristics

Channel width and the radius of channel curvature, especially if the channel exhibits a curved shape, are researched and calculated. The radius of curvature (*Rc*) of the channel is calculated by identifying the inflection point of the channel and finding the radius of the circular arc that best approximates the curve at that point (Figure 3). The radius of curvature is then divided by the channel width (*W*) to determine the severity of the channel bend. Selecting a channel segment as an arc of a circle for calculating the radius of curvature depends on the inflection point of the river. Since the radius of curvature is a significant factor for bend scour, it is crucial to identify the local curvature radius rather than relying on the overall curvature.

Figure 3. Example of radius of curvature (*Rc*) estimation. Red lines show the inflection points of the channel. In this case, the studied river section is located outside of the bend, so no bend scour is expected.

Sediment characteristics are also crucial elements in understanding the morphological changes of the river. Specifically, the median grain size diameter is a key parameter for sediment transport. Due to limitations in sediment sample analysis during surveys, the optimal approach is to capture a high-quality photo of the sediment sample and compare it with existing sediment sample photos categorized by median grain size.

2.5. Peak flood discharge

To model river scour scenarios under extreme events, historical discharge data at the studied section of river is obtained and analyzed. Peak flood discharge is then estimated using the statistical distribution. The annual peak flood discharge refers to the expected maximum flow rate of water passing through a specific point in a river, stream, or channel during a flood event per year. For

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example, the 100-year peak flood discharge represents the maximum flood discharge that has a 1% probability of occurring in any given year. This does not mean the flood will only happen once every 100 years, but rather that there is a 1 in 100 chance (or 1% likelihood) of it occurring in a single year. It is a statistical measure used in hydrology to describe the magnitude of rare but significant flood events, based on historical data and probabilistic models. The three-dimensional scour model proposed in this paper considers extreme scenarios, such as the 5-year, 20-year, and 100-year peak flood discharges near the pipeline water crossing. It evaluates the corresponding potential scour depths around the pipeline under these conditions, providing critical insights into the pipeline's vulnerability and the severity of scouring during such flood events.

To obtain the annual peak flood discharge near a studied site, historical stream gauge data from USGS or NOAA is utilized. Statistical analysis is performed using the Bulletin 17C[1] method, a standard approach for estimating peak flood discharges at various return periods. Bulletin 17C is a guideline published by the United States Geological Survey (USGS) for performing flood frequency analysis. It builds upon previous versions (Bulletins 17A and 17B) by incorporating advanced statistical techniques and updated methodologies to estimate the probability of peak flood discharges at different return periods. This method applies a statistical distribution model to the historical annual peak flood discharge data, enabling the calculation of peak discharge values for different return periods, such as 5-, 20-, or 100-year events. The Bulletin 17C method ensures accurate and reliable estimates by accounting for variability and uncertainties in historical flood data.

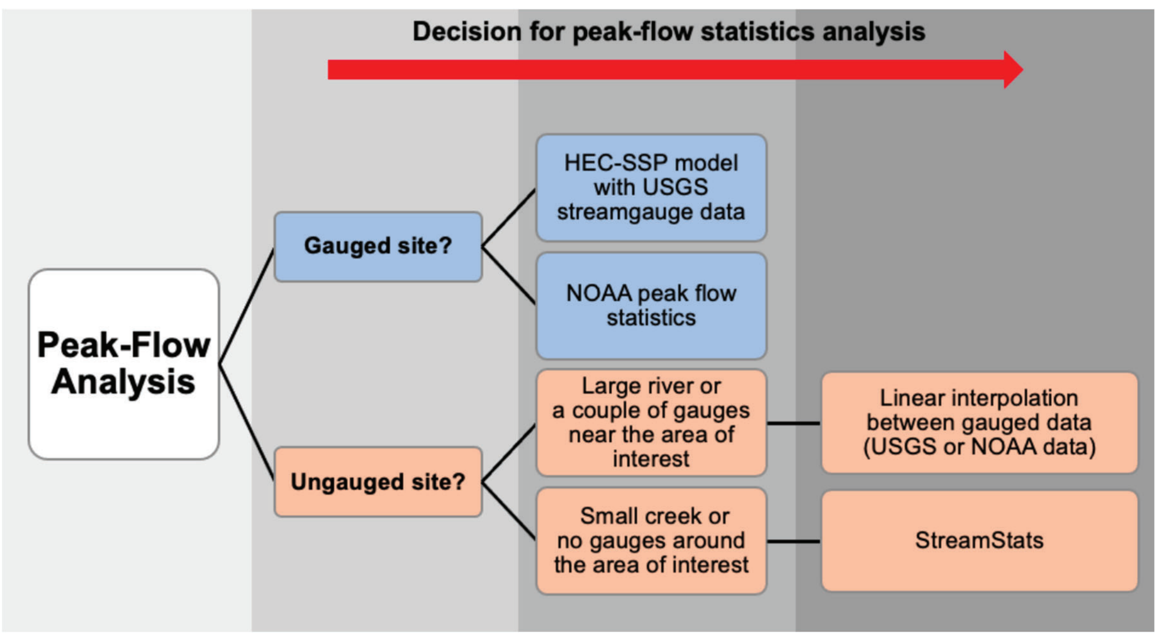

Figure 4. Schematics for model selection for peak-flow analysis based on site-specific circumstances.

[1] England Jr, J. F., et al. *Guidelines for determining flood flow frequency–Bulletin 17C*. No. 4-B5. US Geological Survey, 2018.

If a stream gauge is located near the field site, it can serve as a resource for estimating peak flow statistics using historical annual peak flood discharge data. USGS offers extensive stream gauge data through its online data portal and the Bulletin 17C method can be directly applied using HEC-SSP model, which is developed by USACE, or NOAA peak flow statistics to estimate annual peak flood discharge (Figure 4).

In some instances, stream gauge data may be unavailable, or existing gauges might be too distant from the target site to provide accurate scour estimates. For large rivers, linear interpolation between gauged sites can help estimate peak flow at ungauged locations (Figure 4).

For smaller streams, the absence of nearby gauges poses a common challenge, as most gauges are installed on larger rivers. In such cases, models capable of estimating statistical peak flow discharge for ungauged sites become essential. One particularly useful resource is the StreamStats[2] website, which provides comprehensive streamflow statistics, watershed characteristics, and other hydrologic data (Figure 4). Additionally, StreamStats offers estimates of statistical peak flow discharge for smaller streams and creeks within larger water basins, making it an invaluable tool for hydrologic assessments.

3. Hydrodynamics

An open-source computational fluid dynamics (CFD) model (Lesser et al., 2004)[3] is employed to obtain depth-averaged flow velocities and predict potential scour depths across the entire bathymetric scope of the pipeline water crossing. Typically, depth-averaged flow velocity can be determined using a two-dimensional approach at a single cross-section of the river where the pipeline is located. However, this method often oversimplifies the flow field, leading to uniform flow assumptions along the river's longitudinal direction. Such simplifications overlook the longitudinal interactions of the flow, resulting in less accurate flow estimations. In contrast, the CFD model used in this study adopts a three-dimensional approach, incorporating variations in depth, width (transverse), and length (longitudinal). This makes it particularly well-suited for scenarios where spatial complexity is critical, such as rivers with irregular widths or pronounced curvature. By solving the three-dimensional hydrodynamic equations with fewer simplifications than the two-dimensional model, the three-dimensional approach offers a more realistic representation of actual water system conditions. Furthermore, the availability of detailed three-dimensional bathymetric data from the site enables the creation of a highly detailed three-dimensional flow model, improving the accuracy of scour predictions across the bathymetric scope.

[2] https://streamstats.usgs.gov/ss/

[3] Lesser, G. R., et al. "Development and validation of a three-dimensional morphological model." *Coastal Engineering* 51.8-9 (2004): 883-915.

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The governing equations for the hydrodynamic model are as follows:

$$\frac{\partial(\rho\eta)}{\partial t} + \frac{\partial(\rho\eta u)}{\partial x} + \frac{\partial(\rho\eta v)}{\partial y} = 0 \qquad \text{Equation (1)}$$

$$\frac{\partial(\rho\eta u)}{\partial t} + \frac{\partial}{\partial x}\left(\rho\eta u^2 + \frac{1}{2}\rho g\eta^2\right) + \frac{\partial(\rho\eta uv)}{\partial y} = 0 \qquad \text{Equation (2)}$$

$$\frac{\partial(\rho\eta v)}{\partial t} + \frac{\partial}{\partial y}\left(\rho\eta v^2 + \frac{1}{2}\rho g\eta^2\right) + \frac{\partial(\rho\eta uv)}{\partial x} = 0 \qquad \text{Equation (3)}$$

where ρ is water density (=1000 kg/m3), η is water surface elevation (m), u and v is x and y velocity component, respectively (m/s), and g is gravitational acceleration (m/s2). Two components of depth-averaged water velocity vector at each grid point ($u(x,y)$, $v(x,y)$) were estimated and the magnitude of the velocity was used to predict potential scour depth at each grid point.

A rectangular grid for CFD modeling is created over the area where multibeam and LiDAR data are acquired (Figure 5). The elevation of each grid point is estimated using the multibeam and LiDAR point clouds before initiating the modeling process. Water velocities at the upstream boundary are depth-averaged and adjusted based on the water depth. The free surface water level is assumed to be uniform at the inflow boundary of the model. At the downstream boundary, an outflow condition is applied based on the acquired bathymetric data. The simulation continues until flow velocities stabilize, reflecting equilibrium conditions under the specified peak flow discharge rate and the bathymetric terrain.

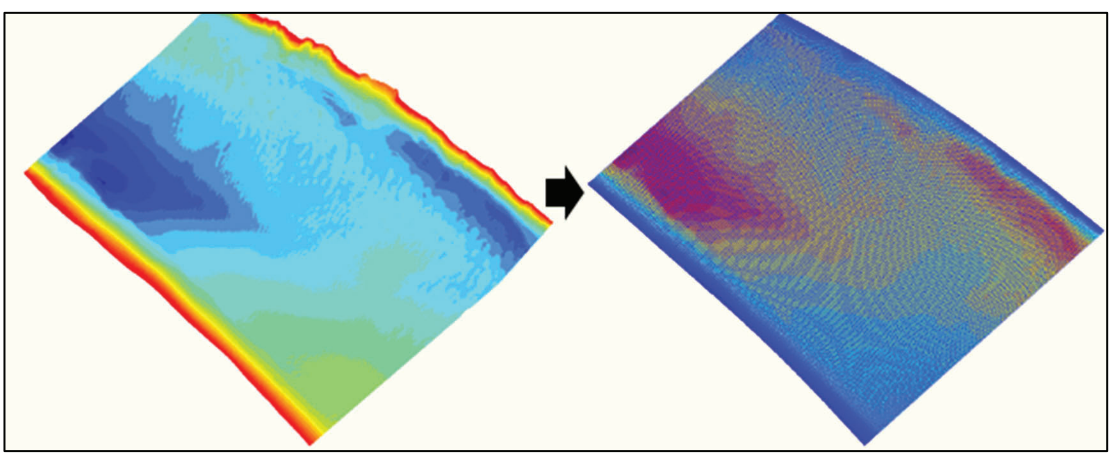

Figure 5. Example of mesh grid generation in the 3D model. Color represents bathymetry and topography.

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4. Scour Depth Calculation

4.1. General scour

General scour refers to the erosion or removal of sediment from the bed and banks of a waterbody caused by the action of flowing water. Unlike local scour, which is focused around obstructions like bridge piers or abutments, general scour occurs over a broader area and is not directly associated with a specific structure. It typically results from natural hydraulic processes.

$$d_s = d_m\left(\frac{V_m}{V_c} - 1\right) \quad \text{Equation (4)}$$

where d_s is the general scour depth below streambed (ft), d_m is the average channel depth (ft), V_m is the average channel velocity (ft/s), and V_c is the critical velocity (ft/s), which is determined by the local water depth and median grain diameter.

4.2. Local scour

Local scour refers to the erosion of sediment around structures within a waterway caused by the accelerated flow and turbulence generated by those structures. This type of scour is typically concentrated in the vicinity of the obstruction or in areas with large bend curvatures, where flow velocities and turbulence are intensified.

4.2.1. Bend scour

Local scour occurs when specific morphological features of the river create localized currents. For instance, in a meandering channel with a large radius of curvature, the river's flow pattern is altered, leading to a more pronounced scour effect. In such cases, larger scour depths are typically observed on the outer side of the river’s bend, a phenomenon known as bend scour.

4.2.2. Dune scour

Dune scour refers to the erosion of sediment around or beneath a dune-like feature in a riverbed or sedimentary environment. Dunes are ripples or small hills of sediment that form in flowing water, typically under conditions of moderate to high flow velocity. These dunes are often created by the movement of water over loose sediment, and they can significantly influence the flow patterns and sediment transport in a waterway.

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4.3. Total scour

The estimation of total scour depth below the riverbed involves combining the maximum scour depth from general scour and bend scour, and then adding the contribution from dune scour. The formula for total scour, as per USBR (2019)[4], is given by:

$$Z_{event} = MAX(Z_{general}, Z_{bend}) + Z_{dune} \qquad \text{Equation (5)}$$

Z_{event} is total scour depth below the riverbed, $Z_{general}$ is general scour depth calculated using Equation (4), which accounts for factors such as flow characteristics, sediment transport, and channel geometry, Z_{event} is bend scour depth, which representing the additional scour in curved river sections due to centrifugal forces and secondary flows, and Z_{dune} is dune scour depth, which representing the scour caused by dune migration and bedform changes. Z_{event} can be another type of local scour depth, such as bridge scour.

4.4. Significance of depth-averaged velocity for each type of scour depth

To estimate the total scour depth, each component of the scour depth including general scour, bend scour, and dune scour requires a depth-averaged velocity at the point along the gridded mesh. Depth-averaged velocity is a key parameter because it represents the averaged flow velocity over the entire water depth at each respective grid point, and directly influences the shear stress and sediment transport processes responsible for scour formation. For general scour, this is typically directly related to the flow velocity and sediment characteristics of the riverbed. Depth-averaged velocity determines the shear stress exerted on the bed, which influences sediment entrainment and transport. For bend scour, the depth-averaged velocity increases along the outside edge of the bend due to centrifugal forces and secondary currents. This amplification creates higher shear stresses, leading to localized scour. Dune scour occurs due to the interaction between flow and bedforms. Depth-averaged velocity influences bedform size, migration rate, and associated scour depths. Higher velocities typically lead to larger dunes and deeper scour.

To estimate depth-averaged velocity, the three-dimensional approach which solves hydrodynamic equations with fewer simplifications than the two-dimensional model, offers a more precise representation. The availability of high-resolution three-dimensional multi-beam bathymetric data further supports the creation of a detailed three-dimensional flow model, significantly improving the accuracy of depth-averaged velocity calculations. This enhanced precision in regard to depth-averaged velocity directly contributes to more reliable scour depth estimations.

[4] Guidelines for Evaluating Pipeline Channel Crossing Hazards to Ensure Effective Burial. U.S. Department of the Interior, Bureau of Reclamation, Technical Service Center: Denver, Colorado

5. Application of Model

The three-dimensional scour model output delivers estimated scour depths for each peak-flood discharge, calculated at every grid point across the bathymetric scope. This comprehensive data set enables the identification of regions prone to significant scour, supporting the design and safety evaluation of pipeline water crossings.

A 3D visualization of the scour depth estimation (Figure 6) further enhances understanding by illustrating the spatial variation of scour depth across the bathymetric area surrounding the pipeline. This visualization highlights high-risk zones, providing engineers and decision-makers with an intuitive tool for assessing scour risks. By presenting the data in a clear and accessible format, the three-dimensional visualization facilitates more informed decisions regarding pipeline risk analysis and the implementation of effective mitigation strategies.

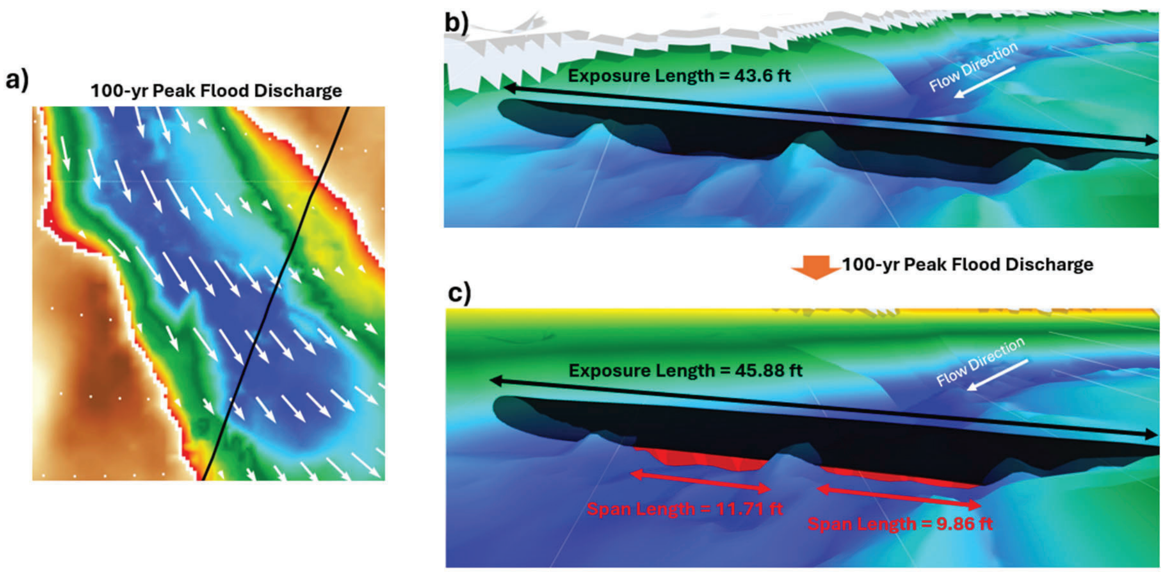

Figure 6. Example of 3D scour analysis and visualization. a) Depth-averaged velocity vector under 100-year peak flood discharge using 3D hydrodynamics model. b) 3D view of surveyed pipeline (black) with surrounding bathymetry (color) and c) surrounding bathymetry after 100-year peak flood event. Estimated scour depth results in the illustrated pipeline spans. Red polygon shows the area between the bottom of the pipeline and the bathymetric surface and measurements are annotated for both total exposure lengths as well as individual span lengths.

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6. Next Steps

The three-dimensional scour analysis in this study employs multiple scour depth estimation formulas at each grid point to predict localized scour depths. These formulas require the median grain size diameter (D_{50}) of the riverbed, which represents the particle size at which 50% of the sediment sample by weight is finer and 50% is coarser. This parameter is vital for sediment transport studies and scour modeling as it characterizes the dominant grain size in sediment and influences erosion, deposition, and sediment mobility processes.

Currently, D_{50} is determined using sediment sample photos collected at the studied site. Future advancements may incorporate techniques such as the analysis of sediment using multi-beam sonar backscatter data to achieve a more comprehensive classification of grain size distribution across the entire bathymetric scope.

DoC Mapping's scour analysis studies primarily focus on pipeline water crossings, which typically are located far from bridge piers, thus eliminating the need for bridge scour estimations in these cases. However, the model's flexibility allows for the inclusion of other local scour types, such as bridge scour or debris scour, in the sub-grid scour depth estimation processes as required for specific scenarios. This adaptability highlights the potential for further expansion and refinement of our three-dimensional scour modeling approach.

7. Conclusion

This study introduces a novel approach to three-dimensional scour modeling for pipeline water crossings, providing a significant advancement in understanding and addressing the risks associated with scour under extreme hydraulic conditions. By combining three-dimensional computational fluid dynamics, empirical scour depth estimation formulas, and high-resolution field data, the proposed methodology enables accurate predictions of scour depths, potential pipeline exposure, and free-span lengths during extreme flood events.

The framework effectively captures the complex interactions among hydraulic forces, sediment transport, and pipeline geometry, offering detailed insights into the performance and vulnerabilities of pipeline infrastructure in demanding environments. The inclusion of interactive three-dimensional visualizations further enhances decision-making by identifying high-risk areas and guiding the optimization of pipeline designs, maintenance planning, and risk mitigation strategies.

This work contributes to the sustainable and reliable operation of critical waterborne transportation systems by offering precise and practical solutions to scour-related challenges. Future research and could extend the applicability of this approach to other infrastructure types, refine predictions with advanced sediment characterization methods, and explore real-time data integration for dynamic risk assessments.

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