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Regional Sediment Management

Approaches for Assessing Riverine Scour

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Abstract

Calculating scour potential in a stream or river is as much a geomorphological art as it is an exact science. The complexity of stream hydraulics and heterogeneity of river-bed materials makes scour predictions in natural channels uncertain. Uncertain scour depths near high-hazard flood-risk zones and flood-risk management structures lead to over-designed projects and difficult flood-risk management decisions. This Regional Sediment Management technical report presents an approach for estimating scour by providing a decision framework that future practitioners can use to compute scour potential within a riverine environment. This methodology was developed through a partnership with the US Army Engineer Research and Development Center, Hydrologic Engineering Center, and St. Paul District in support of the Lower American River Contract 3 project in Sacramento, CA.

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Preface

This study was conducted by the US Army Corps of Engineers (USACE), St. Paul District, USACE Hydrologic Engineering Center, and the US Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL), through the Regional Sediment Management Program funded by the ERDC, under Funding Account Code 1K8078/BF6512; AMSCO Code 008303. The technical monitor was Mr. David P. May.

The work was performed by St. Paul District personnel, Hydrologic Engineering Center personnel, and members of the River and Estuarine Engineering Branch of the Flood and Storm Protection Division, ERDC-CHL. At the time of publication of this report, Mr. David P. May was Chief, River and Estuarine Engineering Branch; Dr. Cary Talbot was Chief, Flood and Storm Protection Division; and Dr. Julie Rosati was the Technical Director for Flood and Coastal. The Deputy Director of ERDC-CHL was Mr. Keith Flowers, and the Director was Dr. Ty V. Wamsley.

The Commander of ERDC was COL Teresa A. Schlosser, and the Director was Dr. David W. Pittman.

1 Introduction

1.1 Background

Rivers *scour* when their hydraulic forces are sufficient to cause erosion, dropping bed elevations locally in response to single flow events. When a channel scours, near constructed features (i.e., bridge piers, culvert outlets, levees, habitat structures), there is a potential risk these elements may fail and no longer function as designed. Failure of these features can result in economic damage, environmental degradation, or human loss of life. Therefore, accurate scour prediction is critical to riverine project design. While methods and equations for calculating scour are plentiful in the literature, guidance on a comprehensive approach to their application is lacking.

1.2 Objective

The objective of this study was to review relevant scour literature, and in consultation with subject matter experts, develop a comprehensive approach to estimating scour. A decision framework was developed that can be readily applied by future practitioners for the calculation of scour potential in riverine environments.

1.3 Approach

This review was completed within the context of an existing project to directly apply existing scour calculation approaches and identify gaps in guidance. The general review approach included the following:

1. Review documentation of relevant scour equations and methods through a detailed literature review.
2. Assessment of available scour equations/methods within the context of an existing project (Lower American River, Contract 3).
3. Determination of gaps in available guidance and consultation with subject matter experts from Hydrologic Engineering Center (HEC) and US Army Engineer Research and Development Center to resolve these gaps.
4. Documentation of a comprehensive approach to calculating scour that can be applied by future practitioners.

2 Review of Scour Methods

Scour (“total scour” in this document) is a combination of four individual components, including

1. long-term scour
2. general scour within a reach
3. bend scour
4. local scour (contraction, bridge abutment, and pier).

Other components, such as bedform and low-flow incision scour (Maricopa County Flood Control District 2013), can also be included; however, this technical report will focus on the numbered components noted above, which generally have the greatest influence. Scour is calculated as a linear depth, with the datum either being the existing channel invert or the top of the water column, depending on the reference. This technical report will use the channel invert as the datum in the scour calculation.

Many of the equations presented in this document can be utilized in both English and metric units; however, this is not universally true. For clarity, the relevant units and documentation of any unit conversions is provided for each variable in the text.

There are a variety of ways to analyze the sub-elements of total scour and arrive at a representative scour depth for use in design. The following sections discuss the different types of scour and the relevant equations/methods used for calculating each type of scour.

2.1 Long-term scour

Long-term scour represents an average degradation of the channel bed over the life of the project. Long-term scour can be estimated by

1. Developing a trend analysis of measured bed elevation data
2. Computing an equilibrium slope or some other channel design heuristic (e.g., Copeland Method)
3. Applying a sediment transport model (e.g., Hydrologic Engineering Center River Analysis System [HEC-RAS]) (USACE 2016) or Adaptive Hydraulics (AdH) (USACE 2019).

Trend analysis can generate accurate predictions of long-term scour if the sediment dynamics are stationary and there are no feedbacks between bed change and hydraulics (e.g., a scour hole that forms during one event reduces or increases the scour potential in a future event). However, trend analysis requires a sufficient record of collected field data (e.g., repeated bathymetry) to be effective. In most cases, these data are not available.

Equilibrium slope heuristics use simple continuity principles to project a condition (generally at bankfull discharge) when the sediment inflow and outflow loads are the same. The US Army Corps of Engineers (USACE) uses tractive force equations and the Copeland Method (in the hydraulic design calculators in HEC-RAS) to compute equilibrium slopes based on channel geometries and sediment properties. Maricopa County also has methods that project an equilibrium slope from a bed control point, such as a dam or bedrock to represent the theoretical long-term scour potential (Maricopa County Flood Control District 2013).

Sediment transport models simulate long-term geomorphological trends. They combine hydraulic characteristics of the stream from the entire flow record and bed material characteristics to determine trends in degradation or aggregation of the channel. HEC-RAS and AdH are sediment transport models developed by the USACE to analyze long-term sediment transport trends (USACE 1993).

If a reach is systemically degrading on the decadal scale, in addition to local scour on the event scale, the final, with project, analysis must account for the cumulative effects of the long-term trend and the local, event scour. The remaining methods, however, all focus on localized, event-scale, scour analysis.

2.2 General scour

General scour includes channel bed degradation processes that impact the entire channel cross section during an event (Natural Resources Conservation Service 2007). There are a variety of means to calculate general scour, including the following:

1. regime equations
2. mean velocity
3. field data review
4. competent velocity.

Wherever possible, analysts should apply as many of these approaches as possible and inform a final scour depth with this full portfolio of information. Each method and/or equation is valid for specific bed material and hydraulic parameters that should be understood and considered in the analysis. The primary focus of this section will be on straight reaches; however, many of these approaches can and should be applied to bends as discussed in a subsequent section.

2.2.1 Lacey Equation

General scour regime equations constitute some of the earliest means for calculating general scour. These equations were developed using concepts by Kennedy (late 1800s), Lacey (1930s), and Blench (1950s–1960s) for Indian drainage canals (Maricopa County Flood Control District 2013). These methods generally utilize common hydraulic parameters within empirical equations to calculate general scour.

The Lacey Equation is one of the early general scour equations, originally developed in the 1930s, and was modified for use by the Bureau of Reclamation as presented in Pemberton and Lara (1984). This regime equation is most applicable in natural systems without an upstream structure that intercepts sediment and for silt-transporting rivers (Maricopa County Flood Control District 2013):

$$\Delta y = Z \cdot 0.47 \left(\frac{Q_d}{1.76\sqrt{d_m}}\right)^{\frac{1}{3}} \tag{1}$$

where:

Δy = the mean scour depth below the channel invert, ft[1] (m)
Q_d = the design flow, ft^3/s (m^3/s)
d_m = the median grain size of bed material in millimeters
Z = n empirical parameter accounting for channel sinuosity based on a categorical classification (Table 1).

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[1] For a full list of the spelled-out forms of the units of measure used in this document, please refer to *US Government Publishing Office Style Manual*, 31st ed. (Washington, DC: US Government Publishing Office 2016), 248-52, https://www.govinfo.gov/content/pkg/GPO-STYLEMANUAL-2016/pdf/GPO-STYLEMANUAL-2016.pdf.

Table 1. Z factors for use in the Lacey Equation (Pemberton and Lara 1984).

Bend Severity	Z
Straight Reach	0.25
Moderate Bend	0.5
Severe Bend	0.75
Right Angle Bends	1.0
Vertical Rock Bank or Wall	1.25

2.2.2 Blench Equation

The Blench Equation was developed for stream reaches that have an upstream structure intercepting sediment (clear water flow) (Maricopa County Flood Control District 2013). This equation uses the concept of a "zero bed factor," which is an empirically derived factor that correlates the median bed material size (d_m) with the scour depth at which no sediment transport occurs. The Blench equation is

$$\Delta y = Z \cdot \frac{\left({Q_d}/{W}\right)^{\frac{2}{3}}}{\left(F_{B0}\right)^{\frac{1}{3}}} \qquad (2)$$

where:

Δy = the scour depth below the channel invert, ft (m)
Q_d = the design flow, ft^3/s (m^3/s)
W = the flow width, ft (m)
F_{B0} = Blench's zero bed factor from Figure 1, ft/s^2 (m/s^2)
Z = an empirical parameter accounting for channel sinuosity based on a categorical classification (Table 2).

Figure 1. Relationship between bed material and Blench's zero bed factor (Pemberton and Lara 1984).

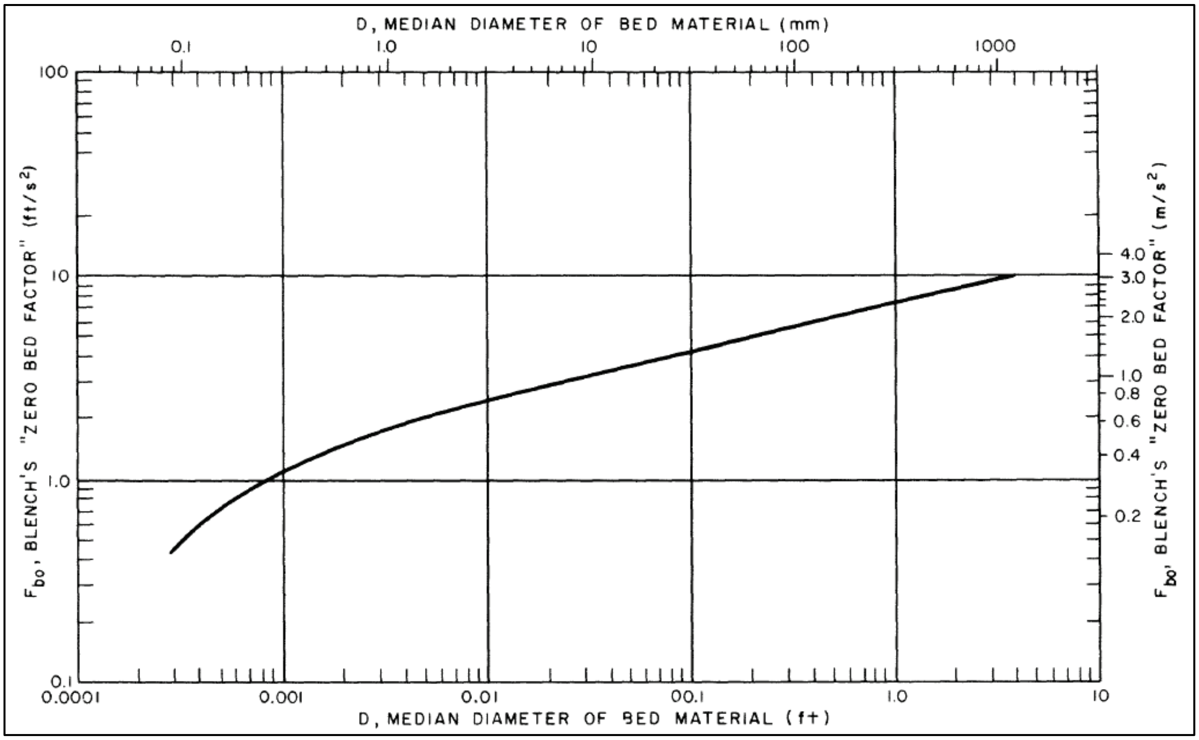


Table 2. Z factors for use in the Blench Equation (Pemberton and Lara 1984).

Bend Severity	Z
Straight Reach	0.6
Moderate Bend	0.6
Severe Bend	0.6
Right Angle Bends	1.25

2.2.3 Zeller Equation

The Zeller equation was developed to estimate scour in bends for sand-bed channels. For straight reaches, the bend portion of the equation (included in the later "Bend" version of the equation) can be ignored (US Bureau of Reclamation 2019). This equation assumes constant stream power throughout the reach.

$$\Delta y = D_{Max}\left(\frac{0.0685 \cdot V^{0.8}}{D_h^{0.4} S^{0.3}} - 1\right) \tag{3}$$

where:

Δy = the scour depth below the channel invert, ft
D = depth. Depth takes several forms in this equation, including the following:
D_{Max}, the maximum cross section depth, ft
D_h , hydraulic depth (flow area divided by top width) of the cross section, ft
V = the mean velocity in the cross section, fps
S = the energy slope, ft/ft.

Inputs of mean velocity, maximum depth, hydraulic depth, and energy slope in the original Zeller Equation (Simons, Li & Associates, Inc. 1985) were intended for use in river bends and therefore based on an upstream cross section that is representative of the bend flow conditions. For use of this equation in a straight river section, where bend hydraulic characteristics will not be influencing the general scour parameters, the study team suggests these input values be based on the cross section where scour is being evaluated.

2.2.4 Neill Incised Equation

The Neill Equation is applicable to areas with constrictions. It is based on a comparison of a constricted channel's bankfull hydraulic characteristics and those of a representative (unconstricted) bankfull channel section. In the absence of an in-person site visit to assess channel bankfull elevations, the hydraulic capacity of a channel between the 1.5 yr and 5 yr flow events (or an effective discharge calculation) can identify the bankfull flow. Determination of the bankfull characteristics requires careful consideration as these values are important in the accuracy of this equation.

$$\Delta y = Z \cdot D_{h\,bf} \left(\frac{Q_d / W}{Q_{bf} / W_{bf}} \right)^m \tag{4}$$

where:

Δy = the scour depth below the channel invert, ft (m)
$D_{h\,bf}$ = the average depth, approximated here as the hydraulic depth (flow area divided by top width), at bankfull discharge, ft (m)
Q_{bf} = the bankfull flow, ft^3/s (m^3/s)
Q_d = the design flow, ft^3/s (m^3/s)
W = the flow width of the design event, ft (m)
W_{bf} = the bankfull flow width, ft (m)
m = the exponent varying from 0.67 for sand to 0.85 for coarse gravel
Z = an empirical parameter accounting for channel sinuosity based on a categorical classification (Table 3).

For the purposes of this analysis, hydraulic depth ($D_{h\,bf}$) (bankfull flow area divided by bankfull flow top width) was utilized in the equation for average depth (which is the parameter presented in Pemberton and Lara [1984]). Hydraulic depth is an output parameter from HEC-RAS. For example, the Lower American River Contract 3 (LAR C3) project used a discharge of 50,000 cfs (approximately the 5 yr recurrence interval for the Lower American River) as the bankfull (channel forming discharge) based on field observations in past studies and review of the hydraulic model results. This discharge was input as a boundary condition in a steady-flow version of the project one-dimensional (1-D) HEC-RAS model to determine the relevant bankfull parameters.

For evaluation of scour within the main channel of systems with wide floodplains, the authors suggest using the top width of the channel (which provides the majority of conveyance) to represent the design flow width (W).

The Neill Incised Equation has an inverse relationship between bed material size and the exponent (i.e., larger material produces a larger scour depth). This empirical relationship was developed based on data in areas with constructions, which may have influenced this inverse relationship. Because of this limitation in the equation’s development, the Neill Incised Equation is only suggested for use in areas where the channel has become constricted with respect to the normal river planform. Additionally, the equation is not valid for bed material sizes smaller than sand or larger than coarse gravel.

Table 3. Z factors for use in the Neill Equation (Pemberton and Lara 1984).

Bend Severity	Z
Straight Reach	0.5
Moderate Bend	0.6
Severe Bend	0.7

2.2.5 US Bureau of Reclamation (USBR) Envelope Curve

The USBR Envelope Curve is based on an unpublished study conducted in 1963 using field data collected in the southwestern United States. This equation is simple in comparison to other equations, only requiring a unit discharge (flow rate divided by width). However, the applicability of the equation is limited to stream slopes of 0.004 to 0.008 ft/ft and medium to coarse sand (0.5 to 0.7 mm d_{50}) (Pemberton and Lara 1984) (Baird et al. 2019). Due to the inherent simplicity of the input parameters, and limited applicability, this equation is generally recommended as a check on other methods.

$$\Delta y = K \left({}^{Q_d}/_{W}\right)^{0.24} \; If \; \left({}^{Q_d}/_{W}\right) \geq 3.45 \tag{5}$$

$$\Delta y = 2.47 + \frac{0.937\left({}^{Q_d}/_{W}\right)}{3.45} \; If \; \left({}^{Q_d}/_{W}\right) < 3.45$$

where:

Δy = the scour depth below the channel invert, ft (m)
Q_d = the design flow, ft^3/s (m^3/s)
W = the flow width, ft (m)
K = 2.45 in.-lb units (1.32 metric units).

2.2.6 Neill competent velocity

Neill's equation for competent velocity is based on the premise that scour will occur in the channel until the mean velocity is reduced such that no movement of bed material occurs. This concept is similar to Blench's "zero bed factor" (Pemberton and Lara 1984); however, it uses an empirical relationship between the mean velocity, V_m, and the competent velocity, V_c, to calculate a depth of scour below the stream bed.

The competent mean velocity values presented in documentation from (Pemberton and Lara 1984) recommends the use of mean depth in this equation (i.e., D_h in Equation 6 below). For the purpose of this analysis, the hydraulic depth (flow area divided by flow top width) is used to represent the mean depth. If the project being evaluated is focused on scour within the channel, it is recommended that the top width and depth only consider the flow within the channel itself (between the bank stations in HEC-RAS). This same approach is applied to the USBR mean velocity, Maynord Bend, and Thorne Bend equations in subsequent sections. Table 4 provides an example of competent velocities for erosion of cohesive materials and Figure 2 provides competent velocities for erosion of cohesionless materials.

$$\Delta y = D_h \left({}^{V_m}\!/_{V_c} - 1 \right) \tag{6}$$

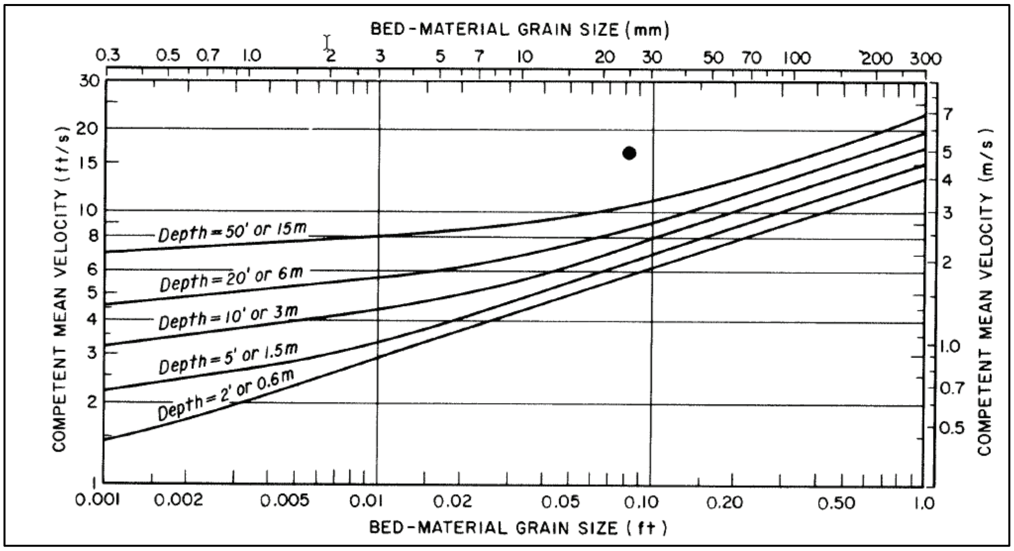
where:

Δy = the scour depth below the channel invert, ft (m)
D_h = the mean depth, approximated here as hydraulic depth (flow area divided by top width), ft (m)
V_m = the mean velocity, ft/s (m/s)
V_c = the competent mean velocity, ft/s (m/s).

Table 4. Competent mean velocities for erosion of cohesive materials (Pemberton and Lara 1984) (table only to be used in the absence of field verified values).

Competent Mean Velocity			
Depth of Flow, ft	Low Values (easily erodible material), ft/s	Average values, ft/s	High values (resistant material), ft/s
5	1.9	3.4	5.9
10	2.1	3.9	6.6
20	2.3	0.7	7.4
50	2.7	0.8	8.6

Figure 2. Competent mean velocities for cohesionless materials (Pemberton and Lara 1984).



2.2.7 USBR mean velocity

The USBR mean velocity approach relies upon a calibrated hydraulic model to predict a mean channel depth for the riverine reach being evaluated for scour at the design discharge. The mean channel depth is then multiplied by Lacey's "Z" factor (Table 5) to determine a depth of scour below the channel invert (Pemberton and Lara 1984).

$$\Delta y = ZD_h \tag{7}$$

where:

Δy = the scour depth below the channel invert, ft
Z = an empirical parameter accounting for channel sinuosity based on a categorical classification (Table 5).
D_h = the mean depth, approximated here as hydraulic depth (flow area divided by the top width), ft.

Table 5. Z factors for use in the USBR Mean Velocity Equation (Pemberton and Lara 1984).

Bend Severity	Z
Straight Reach	0.25
Moderate Bend	0.5
Severe Bend	0.75

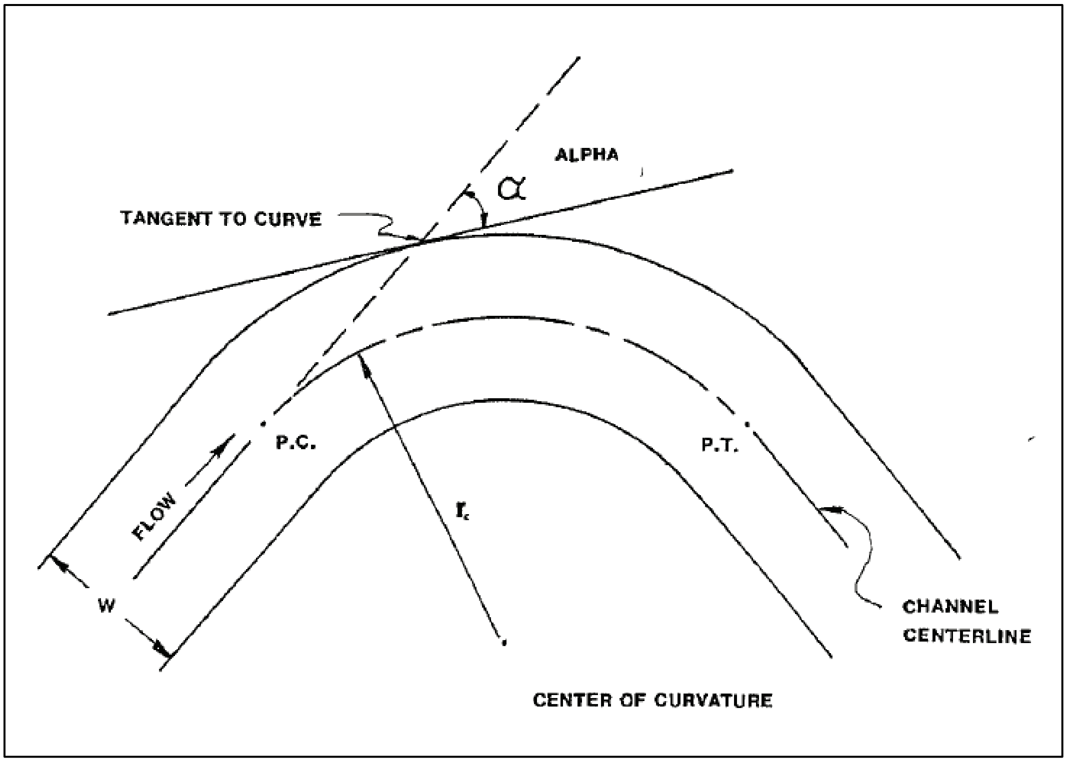
2.2.8 Field data review

The most valuable method for predicting future scour is a thorough field reconnaissance of actual scoured depths in the river being evaluated or on a river with similar features (e.g., slope, bed material, drainage area, hydraulic section, vegetation). Measurements of scour should be collected when safe for field personnel following a flow representative of the design event for the project. Field measurements more appropriately account for the bed sediments, vegetative characteristics, and hydraulic parameters that are unique to a stream and/or reach (Pemberton and Lara 1984). Analysts can also use field measurements of moderate flow events to test the applicability of the scour equations that they apply to larger, design events.

2.3 Bend scour

Channel bends generally have increased propensity for scour as compared to straight reaches. The complex flow patterns in bends have curvature-induced secondary flows as a balance is sought between the centrifugal force and a pressure gradient created by surface tilting (Bai et al. 2019). The secondary currents (velocity components not in the streamwise direction) scour material from the outside of the bend and deposit along the inside of the bend. The most pronounced scour location is usually on the outside bank of the downstream end of the bend. However, it is usually best practice to apply the bend scour results from the point of curvature to downstream of the point of tangency (Figure 3) (Simons, Li & Associates, Inc. 1985).

Figure 3. Channel bend diagram (P.C. represents point of curvature and P.T. represents point of tangency) (Simons, Li & Associates, Inc. 1985).



Many of the regime equations presented previously include categorical (straight, moderate, severe) bend factors. However, several empirical equations have been developed specifically to predict scour in bends, which are presented in this section. In general, application of all relevant bend scour equations is suggested to capture the potential scour depth variability.

2.3.1 Critical bend scour parameters

Bend scour calculations require bend radius parameters, the degree of bend, and a representative upstream cross section. The representative cross section should be upstream of the bend and represent the flow conditions in a straight section with similar hydraulic properties to the bend (e.g., bankfull depths/widths, channel slope, overbank depths/widths, roughness). It is best practice to determine this cross section through field measurements and observation of flow conditions.

The bend radius, R_c, is a commonly used parameter in bend scour equations. The bend radius is typically calculated from the outside of the bend. However, most of the bend equations require a centerline radius (see r_c in Figure 3 above). The authors recommend the use of bend radius based on the outside of the bend since this is the curvature in the location where the most scour is occurring. Bend radius is computed using high-resolution aerial imagery in geographic information system software or by collecting survey data in the field. When calculating bend radius along the outside of the bend, the practitioner must first delineate the bankline, then fit a circle to the portion of the bend where scour is being calculated. In the case of compound bends (i.e., bends that include two or more sub-radii within a larger bend planform), it may be necessary to calculate bend radius (and scour) at multiple locations within the larger bend. Additional detail on bankline and bend radius delineation is included in Appendix B of National Cooperative Highway Research Program (2004).

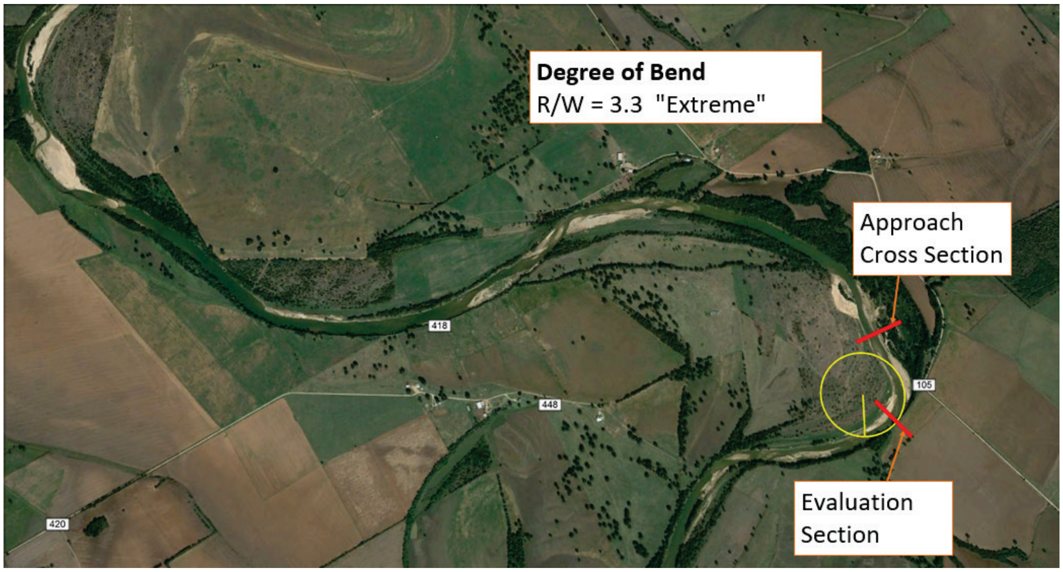
Many of the bend scour equations require the “degree of bend.” This requires practitioners to apply their knowledge of similar river systems and the planform of the river. The ratio of bend radius (R_c) to top width of flow (W) can be used to select the categorical bend degree. Common ranges of R_c/W are included in Table 6. Flow regimes and scour associated with riverine systems that have an Rc/W ratio less than 2 can be unpredictable, and scour equations may not be applicable below this value. Table 6 provides general guidance for selecting the degree of bend, but these values should be used with caution given the variability in channel scour and migration in the natural system. It is the practitioner’s responsibility to define the appropriate degree of bend based on experience with similar systems, riverine planforms, and consultations with system or subject matter experts. A bend radius example for one location within a compound bend on the Brazos River in Texas is included in Figure 4. This bend may require multiple evaluation locations throughout the area of curvature to fully capture the scour variability due to its compound nature.

Table 6. Degree of bend determination upper and lower limits for R_c/W.

Degree of Bend	R_c/W Lower Limit[1]	R_c/W Upper Limit[1]
Straight	>10	NA
Moderate	3-4	10
Severe	2	3-4

[1] Values for Rc/W are based on a combination of author experience and guidance in National Cooperative Highway Research Program (2004).

Figure 4. Degree of bend and approach section example for a compound bend (flow is from top left to bottom right of page).



2.3.2 Zeller bend equation

The general Zeller equation presented in Equation 3 can be applied to bends by adding the bend term in the full equation below. This equation is most appropriate for sand bed channels and assumes constant stream power throughout the channel bend (Simons, Li & Associates, Inc. 1985).

$$\Delta y = \frac{0.0685 \cdot D_{US_{Max}} V_{US}^{0.8}}{D_{h_{US}}^{0.4} S_{US}^{0.3}} + \left(2.1\left(\frac{W}{4Rc}\right)^{0.2} - 1\right) \qquad (8)$$

where:

Δy = the scour depth below the channel invert, ft (m)
D = the depth. Depth takes several forms in this equation including the following:
$D_{US_{Max}}$, the maximum depth of the upstream reference cross section, ft (m)
$D_{h\,US}$, hydraulic depth (flow area divided by top width) of the upstream reference cross section, ft (m)
W = the flow width of the upstream reference cross section, ft (m)
R_c = the centerline radius of curvature, applied here as radius at outside of bend, ft (m)
V_{US} = the mean velocity of upstream flow, fps (m/s)
S = the upstream energy slope, ft/ft (m/m).

Equation 8 assumes the channel bend is represented by a simple circular curve as discussed in (Simons, Li & Associates, Inc. 1985). For compound channel bends, the original form of the Zeller Equation should be used which replaces $\frac{W}{4Rc}$ with $\frac{(\sin\frac{\alpha}{2})^2}{\cos\alpha}$ where α is the angle formed by the projection of the channel centerline from the point of curvature to a point which meets a line tangent to the outer bank of the channel (Figure 3).

2.3.3 Maynord bend equation

Maynord (1996) developed a bend scour relationship based on data from the Mississippi River. This equation is generally limited to sand bed rivers and Rc/W ratios of 1.5 to 10 and $W_{us}/D_{h\,US}$ ratios of 20 to 125 (Maynord 1996). Additionally, Maynord (1996) provided recommendations for safety factors based on the prevalence of observed data.

$$\Delta y = SF \cdot D_{h\,US} \cdot \left(1.8 - 0.051\left(\frac{Rc}{W_{US}}\right) + 0.0084\left(\frac{W_{US}}{D_{h\,US}}\right)\right) - D_{h\,US} \tag{9}$$

where:

Δy = the scour depth below the channel invert, ft (m)
$D_{h\,US}$ = the mean depth, approximated here as hydraulic depth (flow area divided by top width), of the upstream reference cross section, ft (m)
W_{US} = the flow width in the upstream reference cross section, ft (m)
R_c = the centerline radius of curvature, applied here as radius at outside of bend, ft (m)
SF = the safety factor based on Table 7.

For ${R_c}/{W_{US}} < 1.5$ a value of 1.5 should be used for ${R_c}/{W_{US}}$. Similarly, for ${W_{US}}/{D_{h\,US}} < 20$ a value of 20 should be used for ${W_{US}}/{D_{h\,US}}$.

Table 7. Percent of computed D_h/Observed D_h Less than 0.95 versus safety factor.

Safety Factor	Percent of Data Having Computed ${D_h}/{\boldsymbol{Observed}\ D_h}$ Less Than 0.95
1.00	25
1.03	20
1.08	10
1.14	5
1.19	2

2.3.4 Thorne bend equation

Thorne developed an equation for bend scour based – at least partly – on data from the Red River in the southern United States and smaller, gravel rivers in England. The approach encompasses rivers with bed materials ranging from sand to boulders. Scour depth in this equation refers to maximum scour during high, steady, in-channel flows. This approach is not recommended for low-flows, scour variation during a changing hydrograph or flows greater than bankfull stage (Thorne and Abt 1993).

$$\Delta y = D_{h\,US}\left(2.07 - 0.19\ln\left(\frac{Rc}{W_{US}} - 2\right)\right) - D_{h\,US} \qquad (10)$$

where:

Δy = the scour depth below the channel invert, ft (m)

$D_{h\,US}$ = the hydraulic depth (flow area divided by top width) of the upstream reference cross section, ft (m)

W_{US} = the flow width in the upstream reference cross section, ft (m)

R_c = the centerline radius of curvature, applied here as radius at outside of bend, ft (m).

2.3.5 Engineer Manual 1110-2-1601, Plate B41

Engineer Manual 1110-2-1601 (USACE 1994) provides two plates that can be used to calculate scour in bends. These plates compile data, much of it from Thorne and Abt (1993), into two separate charts that can be used to predict bend scour. These charts (contained in Plate B41 of Engineer Manual 1110-2-1601 [USACE 1994]) summarize the data for sand and gravel bed rivers. The practitioner uses known values for mean water depth in the approach channel, center-line radius of the bend, and water surface width to predict the maximum water depth in the bend. The maximum water depth in the bend is a measurement of scour from the top of the water surface to the bottom of the bend scour. The charts are summarized by Equation 11 below for sand and gravel bed rivers (US Bureau of Reclamation 2019).

$$\Delta y = \begin{cases} D_{h\,US}\left(-1.51\log_{10}\left(\frac{Rc}{W}\right) + 3.37\right) - D_{max}\ for\ sand \\ D_{h\,US}\left(-1.62\log_{10}\left(\frac{Rc}{W}\right) + 3.375\right) - D_{max}\ for\ gravel \end{cases} \qquad (11)$$

where:

Δy = the scour depth below the channel invert, ft (m)
$D_{h\,US}$ = the hydraulic depth of the upstream reference cross section, ft (m)
D_{max} = the maximum depth in the design cross section, ft (m)
W_{US} = the flow width in the upstream reference cross section, ft (m)
R_c = the radius of curvature at the centerline of the bend, ft (m).

The Regional Sediment Management Program is currently funding an effort to add these general and bend scour approaches to HEC-RAS. RSM is funding an effort to develop a Riprap and Scour calculator that automatically applies the General and Bend scour algorithms at user selected cross sections, which will eventually simplify this analysis.

2.4 Local scour

Local scour refers to scour induced by local anomalies, usually engineered features such as bridge piers, culvert outlets, bridge abutments, and contractions. Local scour can produce scour depths much larger than long-term or general scour. The HEC-RAS can calculate contraction, pier, and abutment scour in the Bridge Scour editor under the Hydraulic Design Menu, which follows the guidance of Hydraulic Engineering Circular No. 18 (USACE 2016). Equations from HEC-18 implemented within HEC-RAS include calculations of pier, contraction, and abutment scour. Further detail on the application of these equations can be found in USACE (2016) and Federal Highway Administration (2012).

In locations where local scour is calculated, such as bridge crossings, these equations already account for general scour (Federal Highway Administration 2012), and general scour should not be included as part of the total scour calculation. However, for local scour calculations in bends, the authors suggest adding the local scour values to calculations of bend scour to ensure bend hydraulics are considered.

2.5 Total scour

Total scour (T_s) combines the above-mentioned scour calculation methods to determine one representative scour depth for use during a project's design. A summary of these methods is documented in Table 8.

Table 8. Summary of scour approaches to be used in total scour calculation.

Method/Equation	Scour Type	Assumptions/Applicability	Reference
HEC-RAS /ADH Sediment Transport	Long-term, regional scour		(USACE 2019)
Trend Analysis	Long-term scour	Requires long term data	(Maricopa County Flood Control District 2013)
Equilibrium Slope	Long-term scour		(Maricopa County Flood Control District 2013)
Lacey	General scour, bend scour	Natural systems, silt bed channels	(Pemberton and Lara 1984)
Blench	General scour, bend scour	Clear Water Flow (sediment intercepted by upstream structure)	(Pemberton and Lara 1984)
Zeller	General scour	Sand-bed channels Straight Reaches	(Simons, Li & Associates, Inc. 1985)
Neill Incised	General scour, bend scour	Reaches with constrictions, material sizes from sand to coarse gravel	(Pemberton and Lara 1984)
USBR Envelope Curve	General scour	Slopes of 0.004 to 0.008 ft/ft and material sizes of medium to coarse sand (0.5 to 0.7 mm d_m)	(Pemberton and Lara 1984)
Neill Competent Velocity	General scour		(Pemberton and Lara 1984)
USBR Mean Velocity	General scour		(Pemberton and Lara 1984)
Field Data Review	General scour, bend scour	Requires field verification of scour event	(Pemberton and Lara 1984)
Zeller Bend	Bend scour	Sand bed channels	(Pemberton and Lara 1984)
Maynord Bend	Bend scour	$Slope \leq 2\%$, Sand bed channels, Rc/W$^{R_c}/_{W} < 10, {}^{W_{US}}/_{D_{h\,US}} < 125$, overbank depth < 20% of main-channel depth	(Maynord 1996)
Thorne Bend	Bend scour	Not recommended for low flows or flows greater than bankfull	(Thorne and Abt 1993)
EM 1601 Plate B41	Bend scour	Sand and gravel channels	(USACE 1994)
HEC-18 Contraction	Local scour (bridge)	See HEC-18	(Federal Highway Administration 2012)
HEC-18 Pier	Local scour (bridge)	See HEC-18	(Federal Highway Administration 2012)
HEC-18 Abutment	Local scour (bridge)	See HEC-18	(Federal Highway Administration 2012)

Each of the scour methods summarized in Table 8 should be applied as relevant for the system being analyzed. While the results of the individual equations will vary, the application of a plethora of equations/methods is suggested to account for the variability in available methods.

The equations presented below summarize options for combining the various scour types and methods noted in Table 8 to develop a range of total scour depths. Using the maximum value from the general and bend scour analysis will result in an inherently conservative scour depth.

$$T_{s\ avg} = \text{Average}(\textit{Long-term}) + \text{Maximum}\{\text{Average}(\textit{General}), \text{Average}(\textit{Bend})\} \quad (12)$$

The averaging of individual scour approaches can be replaced with evaluations of median, maximum, or minimum to better define the range of anticipated scour.

$$T_{s\ median} = \text{Median}(\textit{Long-term}) + \text{Maximum}\{\text{Median}(\textit{General}), \text{Median}(\textit{Bend})\} \quad (13)$$

$$T_{s\ max} = \text{Maximum}(\textit{Long-term}) + \text{Maximum}\{\text{Maximum}\ (\textit{General}), \text{Maximum}\ (\textit{Bend})\} \quad (14)$$

$$T_{s\ min} = \text{Minimum}(\textit{Long-term}) + \text{Maximum}\{\text{Minimum}\ (\textit{General}), \text{Minimum}\ (\textit{Bend})\} \quad (15)$$

At locations where local scour is evaluated (e.g., a bridge), the summation of the contraction, pier, and abutment scour should be used as the total scour (T_s) value (Equation 16). The HEC-18 equations incorporate general scour in their current form; however, it is suggested that long-term scour be included to represent a future condition that could have degradation prior to the design event.

$$T_s = \text{Sum}(\text{contraction, pier, abutment}) + \text{Average}(\textit{Long-term}) + \text{Average}\ (\textit{Bend}) \quad (16)$$

Ultimately, it will be the practitioner's choice in determining the most appropriate total scour value to use for design. Typically, the average total scour value will be appropriate; however, in cases of low confidence (e.g., poor correlation with observed values or limited observed values, limited availability of representative channel bed data, and/or limited hydraulic modeling) it may be reasonable to use the maximum total scour value. Similarly, the minimum total scour value may be valid in cases of high confidence in the scour results. If the average total scour value is chosen, documenting the range of scour depths is important to provide a complete understanding of the project failure risk.

2.6 Scour uncertainty

The uncertainty surrounding scour calculations includes several components. Applying multiple scour methods that generate different results captures one aspect of that uncertainty.

Uncertain inputs in the scour calculations contribute additional uncertainty to these calculations. Uncertain data required for these calculations include bed material size, hydraulic depth, mean velocity, energy grade slope, top width, and bend radius, etc. Given enough data, a stochastic analysis can be completed using these variables and the associated scour methods to develop a statistical range of scour depth estimates. Analysis can also address epistemic uncertainties like this by collecting additional data or applying higher fidelity models.

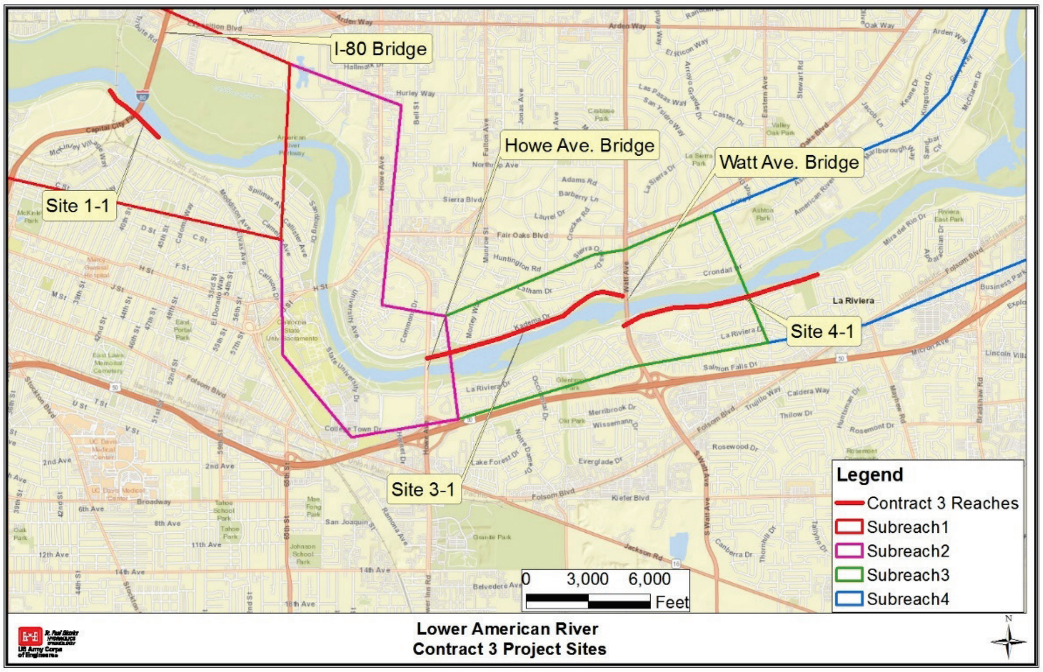
3 Case Study – Lower American River

3.1 Background

The methodology outlined above was developed and followed for the Lower American River Contract 3 (LAR C3) project, which is an erosion protection project located in Sacramento, CA. The Lower American River is predominantly a sand and gravel bed system with the downstream half of the river being confined on both sides by federal levees. Channel scour is anticipated in this system at discharges less than or equal to incipient overtopping of the levees. Therefore, a comprehensive understanding of scour was needed to adequately deter erosion along the channel banks and levee system.

Scour calculations for the LAR C3 project focused on three specific segments of the river called subreaches 1, 3, and 4 (Figure 5). This analysis occurred during the 10% design phase and represented an early review of scour and subsequent design for the project. In most segments, the project will utilize a launchable section of riprap at the toe of the channel to arrest lateral bank erosion (and protect the existing levees). This launchable toe will also provide support for a planting bench intended to provide low-flow habitat. An accurate prediction of total scour depth within each segment was critical to determine the appropriate launchable riprap volume

Figure 5. LAR C3 project extents.



3.2 Scope/Approach

1-dimensional (1-D) and 2-dimensional (2-D) HEC-RAS hydraulic models were available to provide hydraulic inputs to the scour analysis. Total scour was calculated at each 1-D HEC-RAS cross section within each of the three reaches and at two bridges (I-80 and Watt Ave.). This produced a total of 37 unique values of total scour (depth below channel invert) within the project footprint. The project reaches are shown on Figure 5. Scour was calculated at four design flow rates, including 115,000 cfs (100 yr flow), 160,000 cfs (project design flow), 192,000 cfs (levee overtopping flow) for existing conditions and with-project conditions.

The hydraulic characteristics for the analysis came from the 1-D HEC-RAS hydraulic model. Most of the variables required to calculate scour using the equations noted previously are section averaged and can be easily obtained from HEC-RAS output. The 2-D HEC-RAS model was utilized for verification at the 160,000 cfs and 115,000 cfs flow rates for three cross sections. The analysis using the 2-D HEC-RAS model required the user to manually determine the section average variables such as top width, hydraulic depth, and velocity, which made it more difficult to perform the scour analysis.

Bed material data were available from collected samples and indicated the river consists of a combination of sands and gravel base, with a fining of material as the river progresses downstream. The median diameter (d_m) of the bed material was determined from Wolman pebble counts or from direct sieve analysis. The bed gradations were linearly interpolated along the project reaches to provide unique grain sizes for each scour location. The median bed material size is summarized in Table 9.

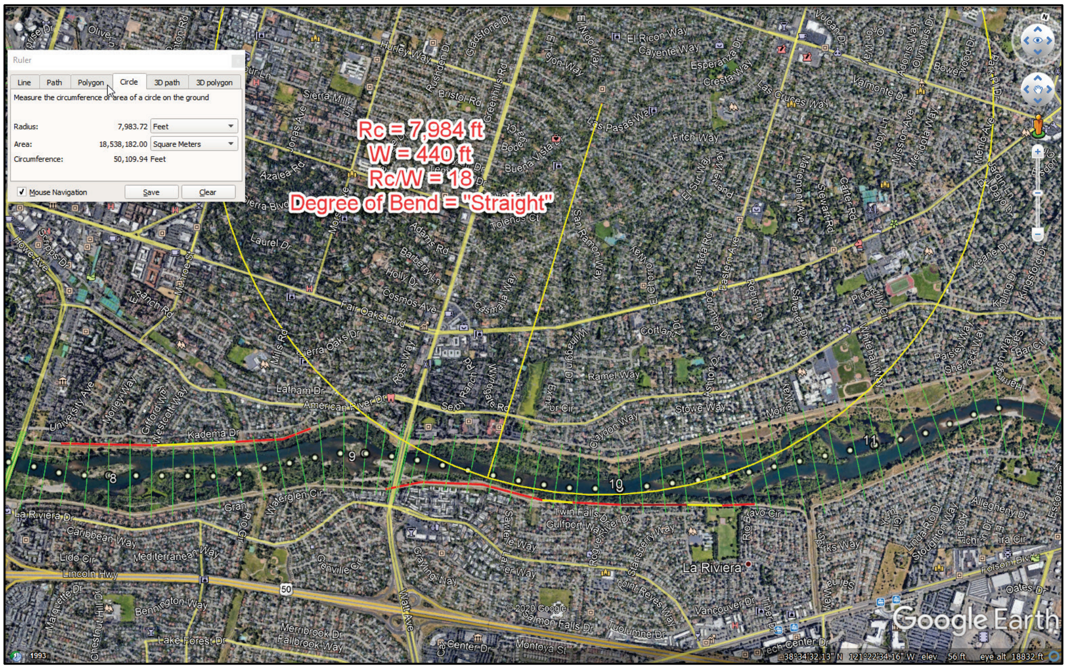
Table 9. Median particle size (d_m) by reach.

Subreach	Median Bed Material Size (d_m), mm)
1	0.68
3	53
4	58

The project reaches include extensive outcrops of erosion resistant material (ERM). Extensive research into the location and depth of this ERM was conducted in 2012. The depth to ERM was determined at each HEC-RAS cross section to determine potential impacts to scour caused by this surface.

The bend radius and flow top width were calculated at each HEC-RAS cross section for each design flow rate to determine the degree of bend for use in the general and bend scour equations. An example calculation is shown in Figure 6. After close review of the river planform, the degree of bend analysis classified all reaches as “straight.” Therefore, all general scour equations used parameters associated with a straight reach and the bend-specific scour equations were not evaluated for this project.

Figure 6. Example degree-of-bend calculation (near River Mile 10 on the LAR).



Ruler

Line | Path | Polygon | Circle | 3D path | 3D polygon

Measure the circumference or area of a circle on the ground

Radius: 7,983.72 Feet

Area: 18,538,182.00 Square Meters

Circumference: 50,109.94 Feet

☑ Mouse Navigation

Rc = 7,984 ft
W = 440 ft
Rc/W = 18
Degree of Bend = "Straight"

After review of the river planform and identification of the channel bed characteristics, several of the scour methods were identified as not applicable. Table 10 provides a summary of the scour methods utilized for the project and provides a justification for why some specific methods were not applied.

Table 10. Summary of scour approaches to be used in total scour calculation.

Method/Equation	Scour Type	Applied on LAR?[1]	Notes
HEC-6T	Long-term scour	Yes	
Trend Analysis	Long-term scour	No	Limited long-term monitoring data
Equilibrium Slope	Long-term scour	No	HEC-6 analysis was available
Lacey	General Scour, Bend Scour	No	Not applicable for material larger than silt
Blench	General Scour, Bend Scour	Yes	
Zeller	General Scour	Yes	Only applied in sand bed portions of river
Neill Incised	General Scour, Bend Scour	No	Only applicable in constricted areas
USBR Envelope Curve	General Scour	No	Energy grade slope and bed material not applicable

Method/Equation	Scour Type	Applied on LAR?[1]	Notes
Neill Competent Velocity	General Scour	Yes	Only produces realistic values for sand bed portion, i.e. in subreach 1
USBR Mean Velocity	General Scour	Yes	
Field Data Review	General Scour, Bend Scour	Yes	Used for verification (historic observations and bathymetric data)
Zeller Bend	Bend Scour	No	No bends in project reach
Maynord Bend	Bend Scour	No	No bends in project reach
Thorne Bend	Bend Scour	No	No bends in project reach
EM 1601 Plate B41	Bend Scour	No	No bends in project reach
HEC-18 Contraction	Local Scour	Yes	Applied in HEC-RAS
HEC-18 Pier	Local Scour	Yes	Applied in HEC-RAS
HEC-18 Abutment	Local Scour	No	Abutments located outside of channel influence

[1] Lower American River

The Lower American River has extensive data and hydraulic modeling available, along with historic scour depths to validate the total scour values in isolated locations. However, detailed long-term monitoring data of the channel bed for use in a trend analysis are limited given the large size of this project reach. This information provided the project team with sufficient confidence to choose the average total scour equation (Equation 12) to calculate total scour values for use in design. The guidance provided in Engineer Manual 1110-2-1601 (USACE 1994) was utilized to calculate the appropriate riprap size and launchable stone volume to address the scour potential at each 1-D HEC-RAS cross section.

3.3 Results

A summary of the scour analysis locations and results are provided in Figure 7 through Figure 10. The results are provided in profile form for the 160k cfs event and are separated by location with the downstream figures representing subreach 1 (Figure 7 and Figure 8) and the upstream figures representing subreaches 3 and 4 (Figure 9 and Figure 10). At the bridges, a range in scour results is not available because the HEC-18 (bridge scour) and HEC-6T (long-term scour) only produce one representative scour depth. Locations upstream and downstream of the bridges have additional general scour equations that produce varying results representing the variability in possible scour depths by method.

Figure 11 and Figure 12 have been included to illustrate the variability in specific general scour equations results. These figures consider only the general scour results (no bridge scour or long-term scour) that produce real values that can be compared.

Figure 7. Downstream reach project extents summary (green lines indicate 1-D HEC-RAS cross sections).

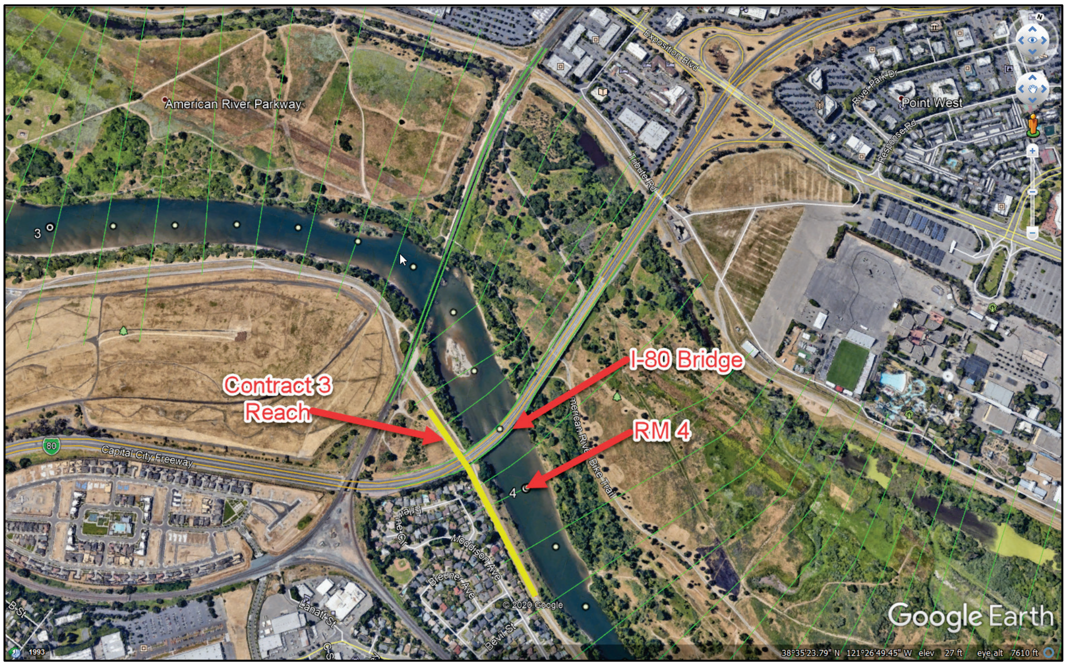


Figure 8. Downstream reach with-project 160k cfs scour results (does not account for ERM).

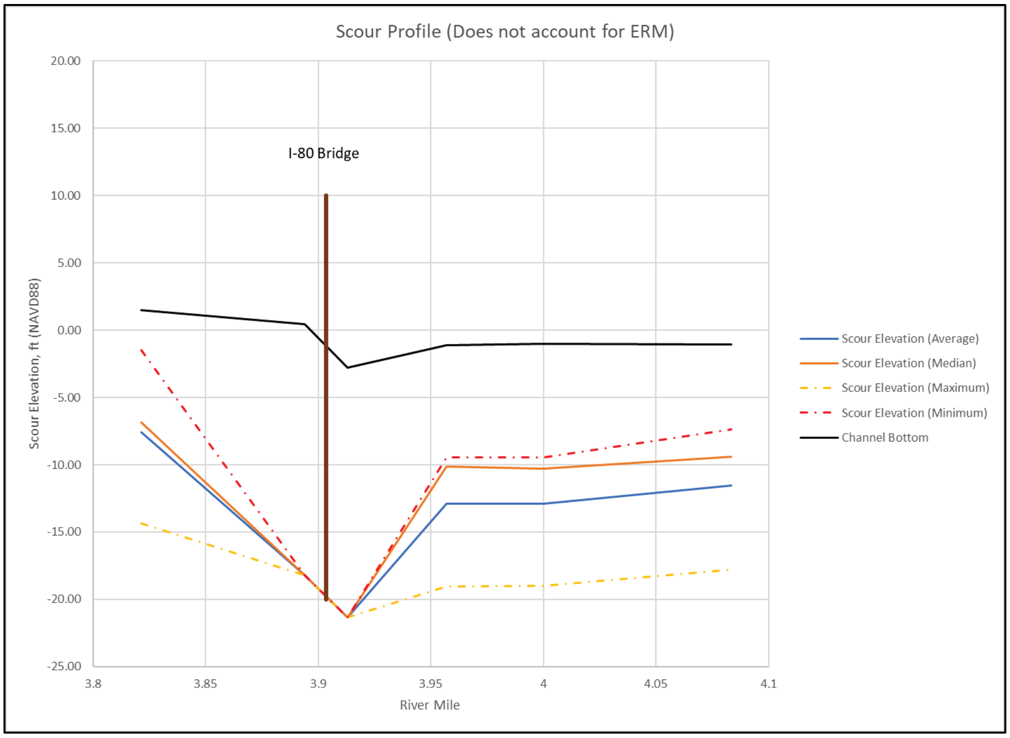


Figure 9. Upstream reach project extents summary (green lines indicate 1-D HEC-RAS cross sections).

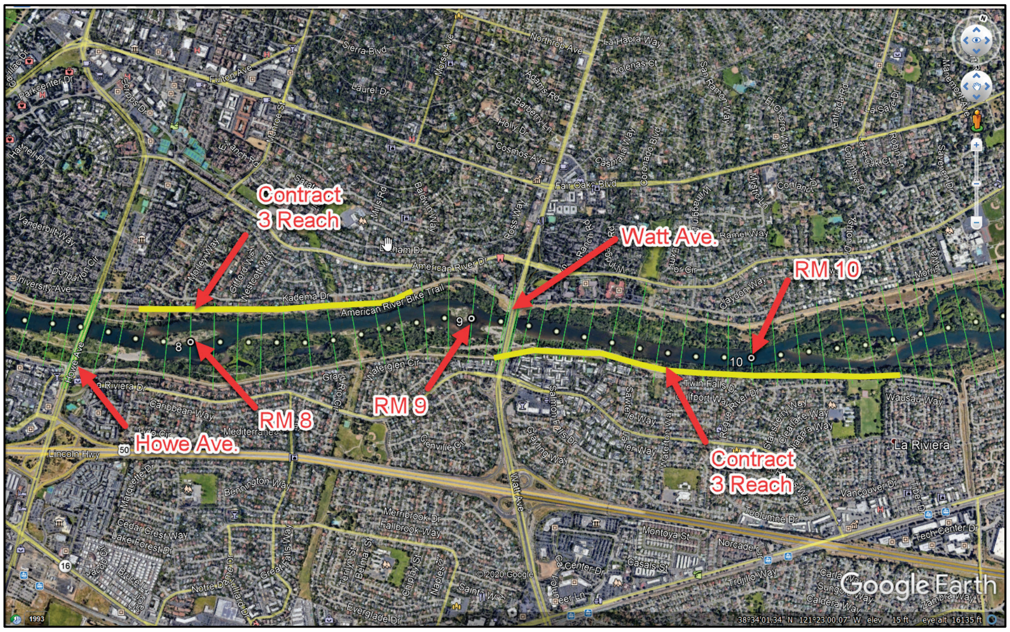


Figure 10. Upstream reach with-project 160k cfs scour results (does not account for ERM) (Note: only two scour equations were applicable to the gravel reaches of this analysis [upstream segment] resulting in no median values for scour..

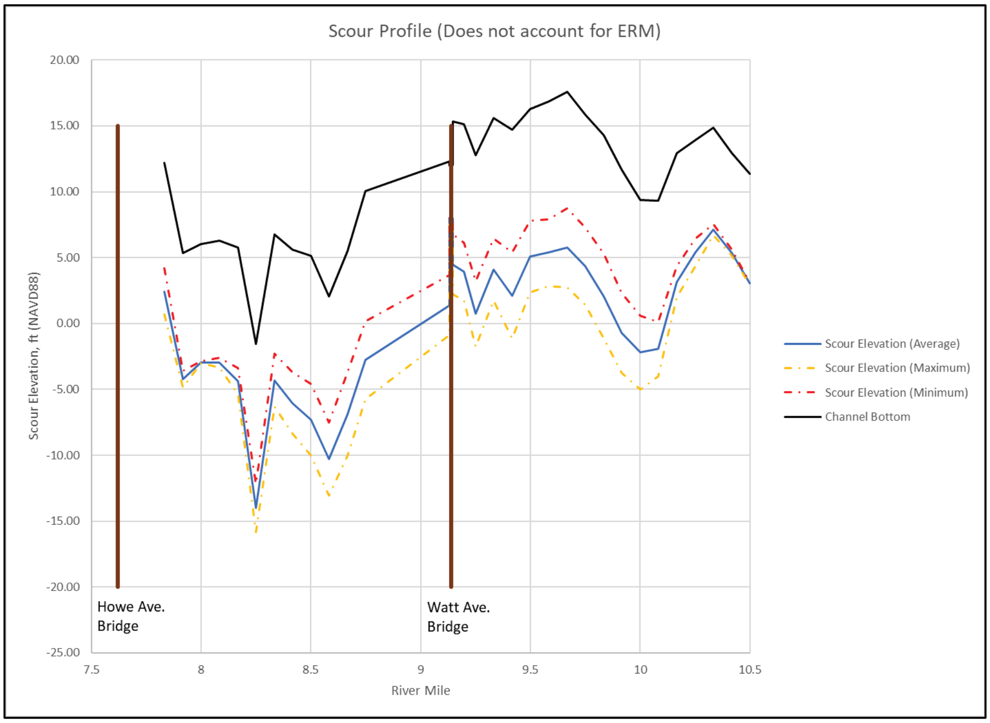


Figure 11. Downstream reach with-project 160k cfs general scour results by method (does not account for ERM) (Note: the Neill incised equation was not included in averaged total scour results as this reach does not include contractions. This chart does not consider bridge scour at the I-80 bridge).

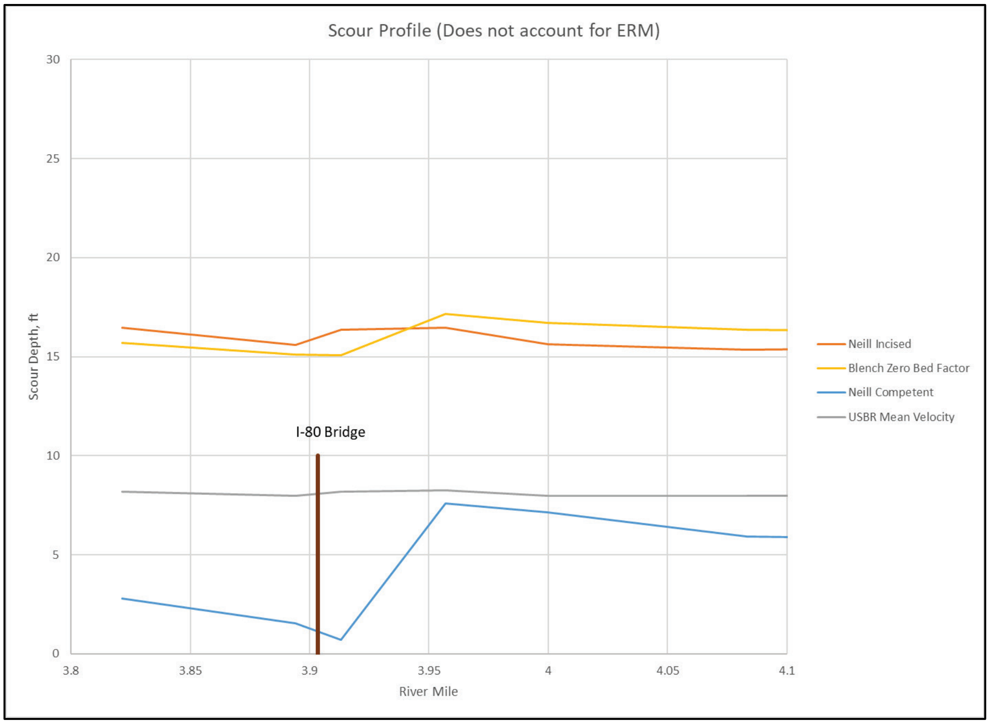
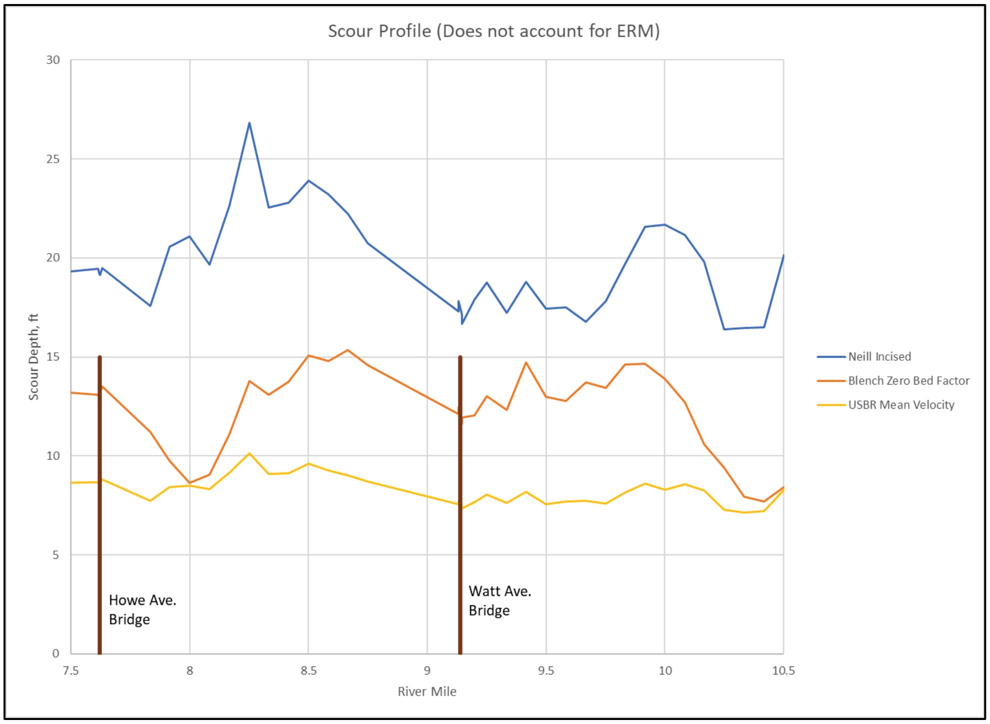


Figure 12. Upstream reach with-project 160k cfs general scour results by method (does not account for ERM) (Note: the Neill incised equation was not included in averaged total scour results as this reach does not include contractions. This chart does not consider bridge scour at the Howe and Watt Ave bridges).



A summary of the 1-D and 2-D HEC-RAS model scour results comparison for the 160k cfs event is provided in Table 11. Given the high uncertainty inherent in scour calculations, the general range in scour difference between the models of 1 to 2 ft was considered acceptable.

Table 11. Comparison of total scour results using hydraulic parameters from 1-D and 2-D HEC-RAS models for 160k cfs with project.

River Mile	Total Scour Depth 2-D[1] Model, ft	Total Scour Depth 1-D Model, ft
3.957	10	12
8	10	9
10.333	9	8

[1] 2-D results were post-processed to cross-section averaged results

Table 12 provides a summary of the range of total scour depths for the sand and gravel portions of the project reaches. Historic scour on the LAR is summarized in Table 13. The project reach has not experienced a flood of the magnitude being evaluated in this analysis with the largest recorded discharge on the LAR to date being 134,000 cfs (recorded in 1986).

Table 12. Summary of calculated total scour depth ranges for 160k cfs with project.

	Average Scour Depth, ft	Maximum Scour Depth, ft	Minimum Scour Depth, ft
Downstream (Sand Bed)	9 - 12	16 – 18	3 - 8
Upstream (Gravel Bed)	8 - 13	8 - 16	7 - 10
I-80 Bridge (Sand Bed)	19	NA	NA
Watt Ave. Bridge (Gravel Bed)[1]	10	NA	NA

[1] HEC-18 results for the gravel bed system at Watt Ave. Bridge resulted in depths less than the general scour results. General scour results were applied at this bridge rather than HEC-18.

Table 13. Summary of historic scour on the LAR.

Location	Scour Depth, ft	Reference
H Street Bridge (River Mile 6.47)[1]	6	(Northwest Hydraulic Consultants 2018)
Fair Oaks Bridge (River Mile 19.75)[2]	17	(Northwest Hydraulic Consultants 2018)
Hazel Ave. (River Mile 22.1)[3]	10	(Northwest Hydraulic Consultants 2018)
Fair Oaks Bridge (River Mile 19.75)[4]	8	(Ayres and Associates 2010)

[1] Eroded by 3 ft from 1941 to 1954 and 3 ft from 1954 to 1980. Caused by local scour and some incision.

[2] Eroded during the period of 1930 to 1957, 6 ft of which occurred from 1949 to 1952 primarily tied to the 1950 flood.

[3] This location had periodic scour and deposition from 1957 to 1992 resulting in the overall scour depth of 11 ft. A cycle of scour during the 1965 flood produced approximately 11 ft of scour that was subsequently filled with sediment.

[4] Based on data collected from 1913 to 1950 with limited change occurring after 1950.

4 Conclusions and Recommendations

4.1 Conclusions

Estimating total scour depth on projects with infrastructure in or near a river can be challenging. The diversity of equations and methods, combined with the inherent uncertainty associated with sediment transport in a natural environment, can be difficult to navigate. This technical report presents a review of some available approaches for assessing scour and provides a case study of their application on an existing project.

4.2 Recommendations

Key observations of the various scour approaches include the following:

- It is important to evaluate all elements of total scour, including long-term, general, bend, and local scour.
- Most of the general and bend scour equations are empirically based; therefore, understanding the origin of the equations and carefully determining which equations are appropriate is critical to ensuring proper application.
- Due to the inherent variability associated with the different scour methods, it is important to calculate scour using as many relevant methods as feasible and combining these results to determine an appropriate value for the total scour depth. A stochastic analysis can also be completed using the input variables and the associated scour methods to develop a statistical range for the scour depth estimate.
- An understanding of the system being evaluated from field visits, review of historical data, expert elicitation (where applicable), and the use of professional judgment is necessary to ensure that scour results are valid.
- Evaluating the possible range of scour depths is critical to understanding the uncertainty associated with the specific project

During design of the project, a factor of safety should be applied to the design elements (e.g., launchable riprap volume). The factor of safety should account both for the uncertainty in the scour calculations and the consequences of failure if the chosen scour value is inaccurate. Ultimately, it is the responsibility of the project team to determine the most appropriate safety factor given their knowledge of the river hydraulics, available data, scour methods applied in the calculations, and the consequences of failure.

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Unit Conversion Factors

Multiply	By	To Obtain
acres	4,046.873	square meters
cubic feet	0.02831685	cubic meters
cubic inches	1.6387064 E-05	cubic meters
cubic yards	0.7645549	cubic meters
feet	0.3048	meters
foot-pounds force	1.355818	joules
hectares	1.0 E+04	square meters
inches	0.0254	meters
inch-pounds (force)	0.1129848	newton meters
kilopounds (force)	4.4482216	kilonewtons
microns	1.0 E-06	meters
miles (US statute)	1,609.347	meters
pounds (force)	4.448222	newtons
pounds (force) per foot	14.59390	newtons per meter
pounds (force) per inch	175.1268	newtons per meter
pounds (force) per square foot	47.88026	pascals
pounds (force) per square inch	6.894757	kilopascals
slugs	14.59390	kilograms
square feet	0.09290304	square meters
square inches	6.4516 E-04	square meters
square yards	0.8361274	square meters
tons (force)	8,896.443	newtons
tons (2,000 pounds, mass)	907.1847	kilograms
tons (2,000 pounds, mass) per square foot	9,764.856	kilograms per square meter
yards	0.9144	meters

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14. ABSTRACT

Calculating scour potential in a stream or river is as much a geomorphological art as it is an exact science. The complexity of stream hydraulics and heterogeneity of river-bed materials makes scour predictions in natural channels uncertain. Uncertain scour depths near high-hazard flood-risk zones and flood-risk management structures lead to over-designed projects and difficult flood-risk management decisions. This Regional Sediment Management technical report presents an approach for estimating scour by providing a decision framework that future practitioners can use to compute scour potential within a riverine environment. This methodology was developed through a partnership with the US Army Engineer Research and Development Center, Hydraulic Engineering Center, and St. Paul District in support of the Lower American River Contract 3 project in Sacramento, CA.

15. SUBJECT TERMS

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