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Comparison of General Scour Prediction Equations for River Crossings

Christine Lauchlan[1] and Richard May[2]

ABSTRACT

Often when building structures in the river environment it is necessary to know whether the bed of a natural river is subject to degradation. For instance, the depth of burial for pipelines and the foundation requirements for bridge piers and abutments require some knowledge of what the river bed level is likely to be under certain conditions or over certain time scales. The natural scour that a site may experience can be due to long term morphological development of the system or shorter-term degradation due to higher-than-average flow velocities during floods. Both types of scour of bed material are often termed “general scour”. The present study compares a variety of general scour prediction methods for estimating scour depths during a single flood event. For comparison of the methods three case studies are used. Initially, each river section was checked against ‘regime’ channel characteristics. Then each of the scour prediction methods was assessed for applicability to the channel type before being applied to generate an estimate of the general scour depth for a 200-year return period flood event. It was found that a wide range of predicted scour depths was possible for a single flood event in each case. The reasons for the different predictions are discussed in detail and recommendations for choosing the most appropriate prediction equation are provided.

INTRODUCTION

Natural river systems exist in a dynamic state. The flow and sediment movement in the channel(s) varies over time and space and can alter the channel dimensions. Under certain flow conditions sediment can be transported with the flow while for other flows it remains stationary. There is also often a wide range of sediment sizes present on the riverbed so the sediment transport rate can vary. In order to undertake engineering works in this type of environment it is therefore necessary to be able to quantify the likely changes to the system for given conditions or over certain time spans. Particular attention is often given to estimating how the bed level of the channel may change under flood flow conditions.

This problem involves a wide range of sediment and flow parameters including the sediment size and grading, flow velocity, channel width, depth and shape. Further complications arise as often under flood conditions the flow cannot be contained within the main channel and is distributed over floodplain regions.

Many authors have proposed empirical relations to quantify general scour depth. The basis behind these relations and general scour relationships in general is discussed in more detail in the companion paper. In the present paper we will compare a number of existing general scour prediction formulae for three different rivers. Various difficulties arose when attempting to apply each method and these are discussed in detail.

METHODOLOGY

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In total 11 general scour prediction equations were compared in this study. Each equation was assessed for its key parameters and applicability to particular river types or conditions. A detailed summary of each of the formulas is provided in Table 1. The general scour analysis is used to determine what the predicted bed level change would be for a short-term flood event. The long-term change of the sediment bed level is not addressed here.

In order to compare these different prediction methods it was first necessary to assess the existing river channel configuration. This relates to the 'regime' concept whereby alluvial channels that are in regime appear to operate in a quasi steady state without significant long-term variations in channel size and depth. The characteristic features are considered to be the shape and size of the main channel when flowing at just bank-full conditions and also the longitudinal gradient of the channel. The bank-full condition refers to the main incised river channel. For natural rivers this is typically found to be the peak flow rate occurring in a flood with a return period of about 1.6 years (which corresponds statistically to the most probable maximum annual flood). For this study the methodology of May, Ackers and Kirby (2002), hereafter referred to as the CIRIA Manual, was used to assess the river conditions, in conjunction with the HR Wallingford Regime Tables.

If the river channel under the dominant discharge is found to be in a regime state then the next step is to assess how the channel may adjust to a flood flow event. Using the existing channel dimensions and predicted water depths for both a 100-year and 200-year return period event estimates can then be made of the likely general scour depths. Water depths and flow areas were calculated using a one-dimensional hydraulic model. Each of the 11 formulae was applied in turn, using the same initial conditions.

CASE STUDY 1

This river has a length of 64km, with a catchment are of 1940km^2. It has an average bed slope of 0.013. The river regime is characterised by spring floods due to snowmelt and low water levels during the winter. Information supplied from gauging stations at a number of locations along the river was used to assess the dominant and flood flow conditions. The river is substantially braided over large reaches.

The river channel pattern has been shown to vary over time. In 1945 the river was extensively braided, whereas in subsequent maps there appears to be a single main channel with a number of smaller peripheral channels. There is a small channel located close to the left-bank of the floodplain in both 1955 and 1976 maps. It appears to branch off the river upstream of the crossing and follow the edge of the valley before rejoining the main river channel.

The bed sediment in the river is gravel, with a d_{50} = 39mm, and a geometric standard deviation, $\sigma_g \approx 2.2$. The bank-full, 100-year and 200-year return period discharges were 75m^3/s, 243m^3/s and 278m^3/s respectively.

The cross-sectional shape of the channel at the engineering point of interest is shown in Figure 1, while the predicted scour depths are compared in Figure 2.

CASE STUDY 2

This case study is for the same river as in Case Study 1 but located further downstream, after the confluence with a major tributary. Comparison of the river plan-form at the crossing shows a range of channel and floodplain shapes. In 1945 the river formed a single main channel with a number of smaller channels crossing the floodplain. In 1956 the river flowed in two main channels, adjacent to either side of the active channel region. Then in 1976 the river plan-form shows further changes in the period 1956 to 1976, with flow in one main channel near the northern bank and two smaller channels across the floodplain. One of the smaller channels appears to be a cutoff section of a former, larger channel.

The braided channel network appears to be very active across the entire active channel region. There are two main channels and a number of smaller interconnected channels. It can be expected that the river will continue to actively migrate across the active channel region. The same characteristic bed material sizes as for Case 1 were used. The channel slope along this section of the river is 0.007. The bank-full, 100-year and 200-year return period discharges were 150m^3/s, 500m^3/s and 595m^3/s respectively.

The cross-sectional shape of the channel at the engineering point of interest is shown in Figure 3, while the predicted scour depths are compared in Figure 4.

CASE STUDY 3

This is a large gravel bed river, whose morphology changes along its length. It has a length of 1364km, with a total catchment area of 188,000 km^2. As with the river mentioned previously, this river is characterised by spring floods due to snowmelt and low water levels during the winter.

In areas to the west it is either meandering or braided in form. Along part of its length, however, the river is confined in narrow gorge. Along its whole length there is substantial sediment transport, giving the potential for large and rapid morphological change. In particular, many areas along the river are characterised by significant lateral movement.

At the site used for the present analysis the river is characterised by a wide floodplain with a number of braided channels. There appears to be one main channel, with approximately four smaller channels criss-crossing the floodplain. Historical records show that substantial changes to the channel arrangement have occurred and the river is very active in this region.

The bed sediment in the river is gravel, with a d_{50} = 25mm, and a geometric standard deviation, $\sigma_g \approx 3.4$. There is a wide range of sediment sizes in the river and it is likely that armouring of the sediment bed occurs due to preferential movement of the finer material. The channel slope in the area under consideration is approximately 0.003. The bank-full, 100-year and 200-year return period discharges were 338m^3/s, 1241m^3/s and 1381m^3/s respectively.

The cross-sectional shape of the channel at the engineering point of interest is shown in Figure 5, while the predicted scour depths are compared in Figure 6.

DISCUSSION

A number of difference and difficulties arose when attempting to apply each of the formulae. One of the key problems was defining the main incised channel dimensions. For each of the rivers studied there were multiple braided channels with historical evidence of active channel movement. Under flood conditions it was not known how the low-flow cross-sectional properties would change. Therefore, for the analysis the deepest low-flow channel was chosen as the main incised channel. It was also assumed that the channel would not widen under the flood flow. This was based on the idea that it is unlikely that a full adjustment of the channel to the higher flow regime would be achieved during an individual flood. This assumption has considerable impact on many of the formulae tested. A discussion of each method is provided.

Lacey (1930, 1933)

The method of Lacey (1930, 1933) is one of the earliest methods for estimation of general scour depths. It links the scoured flow depth to the flow rate and a sediment parameter. The difficulty in applying this method arose from the inclusion of the 'silt' factor. In the present case studies the bed material is gravel, with a median size of around 20-30mm. This produced very large values of f and correspondingly low scour depths. In most instances the method indicated no scour would occur for the given flood flows. This contradicted the results from the other methods tested. Due to this result the scour depths predicted by Lacey are not included in the comparison.

Blench (1969)

This method was developed for in-regime canals and has been applied satisfactorily to well-maintained sand bed irrigation canal systems. The gravel bed formula was derived based on large gravel rivers.

The method is dependent upon the flow rate, the channel width and the sand size and provides reasonable estimates of scour depths for each of the three cases. As d_{50} increases the scour depth y_s decreases, while increasing B or Q increases y_s.

Neill (1973)

This is a very general method based on the competent velocity concept for movement of the bed material. It differs from the other predictions mainly for Case 3. In this instance, there are multiple channels in the system and once the flow moves out of bank for the 200-year flood event the proportion of the total flow in this main channel is substantially reduced and the velocity in the channel reduces accordingly. This implies that the scour potential and calculated scour depths do not increase as quickly with increasing flood stage for compound and multiple channel systems.

Also, the redistribution of the channel area to account for scour is subjective. Neill suggests a graphical redistribution of area based on known characteristics of the site. For the present comparison a channel shape factor, as given in the CIRIA Manual was used so that the method can be directly compared to the other prediction formulas.

Charlton (1982)

This formula was developed specifically for application to gravel bed rivers. It requires detailed information on sediment sizes, which can be difficult to obtain, particularly the d_{50Z} term, which is the median sediment size measure along the minor axis. This would not normally be obtained from a particle size distribution curve. The channel width term was found to be the most sensitive parameter. The method provides a way to estimate an effective channel width for scour, which is very similar to that given by Kellerhals (1967).

Simons and Albertson (1963)

This method provided scour depths similar to the overall average general scour depth for each case. The scour depth is mainly a function of the flow rate, with an empirical factor to account for the channel type. As the flow rate increases so too does the scour depth.

Kellarhals (1967)

The method of Kellarhals was developed for gravel bed rivers and is principally dependent on the channel width. The channel width used in the calculations is an effective width, based upon the flow rate. The original method does not deal with multiple channels or channels with floodplains so the flow rate chosen for the calculations was the flow rate in the main incised channel only.

Holmes (1974)

A key parameter in this method is the waterway width, which is defined as the width of channel carrying 80% of the flow. To use a width value based on this definition for the present cases would have produced very small scour depths due to the wide braided nature of the channels. It was found that a better general scour estimate was obtained by using the flow width associated with the main channel(s).

Melville and Coleman (2000) note that various authors have commented that this method does not appear to have a very logical basis and does not account for the effect of sediment size at all.

Mirtskhoulava, Ts.E (1967, 1991)

This method is applicable to non-cohesive sediments. There are also versions of this method developed especially for cohesive material and additional factors can be included to account for the effects of sediment armouring of the bed and/or scour hole.

One of the key parameters is the near-bottom velocity at the roughness height prior to scouring. The author gives guidance on how to estimate the roughness height and near-bottom velocity but these methods are not in general application. Also, it is not clear what the datum for the depth of flow after scour is, whether it is below the flood level or bank-full level.

Maza Alvarez and Echavarria Alfaro (1973)

As detailed in Melville and Coleman (2000) this method was developed using the competent velocity approach and was based on data for fine silts to coarse sands. For all cases this approach gives the highest estimate of general scour. However this is highly dependent upon the choice of shape factor. If the shape factor as defined by Maza and Alfaro is used then the total scoured depth is less than the maximum flow depth, as seen in Figure 6 where the scour depth with this shape factor was plotted instead of the CIRIA shape factor. However, if the shape factor as defined by the CIRIA Manual is used then the scour depth can be almost three and a half times (e.g. Case 3) the deepest depth predicted by any of the other methods. The method of scaling the average and maximum scoured depths is therefore critical when applying this procedure.

CIRIA Manual (2002)

The CIRIA Manual provides a methodology for the analysis of channel response to flood conditions. Initially the HR Wallingford Regime Tables were used to assess the existing channel dimensions. However, any regime type formula/method could have been applied.

The use of a regime method as the basis of the analysis is a limitation of the methodology. Since if the channel system based on existing cross-sectional data and flow information cannot be matched to a regime dimensions then there is no way of estimating the effect of a higher flow regime. This could be seen to some degree in Case 3, where the match between the bank-full conditions and an equivalent regime channel was less clear than for the other two rivers. This may therefore have impacted upon the general scour depths predicted by the other formulas, especially those that strongly depend upon the channel width dimension.

One aspect of this approach that it not addressed by any of the other procedures is suspended sediment transport. When using the HR Wallingford Regime Tables the regime channel dimensions must be matched for sediment concentration as well as flow rate.

Comparison of Predicted Scour Depths for 100-year and 200-year Return Period Events

The resulting predicted scour depths for the 200-year return period events are provided in Figures 2, 4 and 6. General scour depths were also estimated for the 100-year return period event for each river.

For Case 1, all the prediction equations predicted smaller depths of general scour. Overall, the average predicted reduction in scour depth was around 12%. The formula of Mirtskhoulava (1967, 1991) gave the smallest reduction (8%) while that of Holmes (1974) gave the greatest (26%). These results are expected, as the flow rate for the 100-year event is 12.5% less than the 200-year event.

For Case 2 there was a wider range of changes in the predicted general scour depths. The method of Simons and Albertson (1963) predicted greater depths of general scour while all the other formulae predicted reductions in general scour ranging from 6% (Kellerhals, 1967) to 50% (Neill, 1973). The reduction in flow for the 100-year event compared to the 200-year event is 16%.

Case 3 produced the most interesting results. In many cases the general scour depths predicted for the 100-year event were in fact greater than for the 200-year event. This can be explained by examining the river cross-section. For the 100-year return period flow the highest proportion of the flow is concentrated in the main channel. However, as the flow rate increases the proportion of the total flow in the main channel actually decreases. This results in decreased velocities and decreased scour potential in the main channel.

What is shown by these results is that when considering the most critical case for general scour depths at a particular location consideration must be given to the flow and channel configurations over a range of flows. It is not necessarily the highest return period event that produces the greatest scour depths.

CONCLUSIONS

1. There is no clear pattern shown by any of the general scour prediction equations.
2. The type of river channel system has a significant effect on the performance of the various prediction equations. The most sensitive parameter appears to be the channel width. In the analysis presented here, the channel width was assumed to remain constant with no width adjustment occurring due to the short duration of the flood event. This assumption should be investigated further. It may be more realistic to relax the constant width constraint based on an estimate likely lateral movement of the channel. Any estimate of lateral channel movement should consider sediment and slope characteristics for the bed and banks as well as flow properties.
3. Many of the methods do not explicitly account for cases where there is more than one channel, or where floodplain flows occur.
4. The definition of scour depth varies between methods, some using an average depth, others applying a shape factor. This makes direct comparison of the predicted depths more difficult. The definition of shape factor and the effect of overbank flows on the shape factor should be investigated further.
5. Given the uncertainty in the general scour estimates the use of a safety factor is recommended.

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SYMBOLS

B	Channel width
d_{50}	Sediment size for which 50% by weight is finer than.
d_{90}	Sediment size for which 90% by weight is finer than.
f	Lacey's silt factor.
Q	Flow rate
q	Flow rate per unit width
S	Energy slope
y_s	Scoured flow depth; refer to individual formulae for further definition
σ_g	Geometric standard deviation of the sediment size.

Table 1: Summary of General Scour Depth Prediction Methods.

Method	Description
Lacey (1930) & (1933)	$y_{ms} = 0.47\left(\frac{Q}{f}\right)^{1/3}$ where mean scoured flow depth y_{ms} (m) is defined as the wetted area divided by the surface width; Q (m^3/s) is the design discharge; and *f* is the Lacey silt. This equation is applicable to uncontracted sandy alluvial channels.
Blench (1969)	For sand of $0.06 < d_{50}$ (mm) < 2: $y_{ms} = 1.20\left[\frac{q^{2/3}}{d_{50}^{1/6}}\right]$ For gravels of $S = 2.65$ and $d_{50} > 2$mm: $y_{ms} = 1.23\left[\frac{q^{2/3}}{d_{50}^{1/12}}\right]$ q ($m^3/s/m$) is the discharge per unit width, for the main channel if the channel has floodplains; and d_{50} (mm) is the sediment size for which 50% is finer than, and y_{ms} is the mean scoured flow depth below the free surface. The sand size sediment equation is derived for regime channels of steady discharge, steady sediment-transport rate, a dune sand bed of natural particle size distribution, suspended load too small to influence equations, and steep cohesive channel sides (hydraulically smooth). The gravel equation is derived from large gravel rivers.
Maza Alvarez and Echavarria Alfaro (1973)	$y_{ms} = 0.365\left(\frac{Q^{0.784}}{W^{0.784} d_{50}^{0.157}}\right)$ where y_{ms} (m) = flow depth from the design water level to the mean scoured bed level; Q (m^3/s) is flow rate; W (m) is water surface width; and d_{50} (m) is the median sediment size. For sands and gravels of $d_{75} < 6$mm
Kellarhals (1967)	$B = 3.26Q^{0.5}$ $y = 0.47q^{0.8}d_{90}^{-0.12}$ where B is the mean channel width, y is the mean depth of flow, and d_{90} is the size of bed material (m) such that 90% of the stones by number are smaller. This formula is based on work on gravel bed rivers.
Neill (1973)	Neill outlines four approaches to estimating the general scour depth in a river reach. Methods 1 to 3 rely on utilisation of field measurements, whereas method 4 (detailed here) is the approach to be adopted where no measurements of channel change are available. This method depends on the hypothesis that scouring will continue until the mean velocity is reduced to just above critical for bed material exposed at the scoured depth. It is considered conservative for high bed-load conditions.
	Procedure: Compute the mean velocity through the opening at the design discharge – assume no scour. Determine the corresponding depth of flow and median sediment diameter; Compare the computed velocity with the competent velocity (figure 4.12, Neill 1973). If the computed mean velocity > competent mean velocity, general scour occurs; Determine by trial the average general scour level, assuming an appropriate cross-sectional shape, so that the mean velocity is equal to the competent velocity for the material exposed at that level. The appropriate average depth of flow after scour should be used in selecting the competent velocity. For graded material armouring should be considered – perhaps by using a larger D_{50} value (but less than D_{80}); Redistribute the trapezoidal cross sectional area to give the worst expected cross-sectional shape and lowest elevation of general scour.

Method	Description
Charlton (1982)	Deep channels – for $3 \le y_s/d_{90} \le 80$ $B = 3.74 K_G Q^{0.45}$ $y_s = \left(0.114 K_G^{-1.82} Q^{0.42} d_{65}^{-0.38} d_{90}^{-0.24}\right) - d_{50Z}$ $S = 0.15 K_G^{-1} Q^{-0.76} B^{0.76} d_{65}^{1.38} d_{90}^{-0.24}$ B is the channel width; y_s is the scoured flow depth; S is the energy slope. The value of the non-dimensional factor K_G depends on the type of vegetation on the banks of the channel: for grass and light vegetation, $0.9 < K_G < 1.3$; for trees and heavy vegetation, $0.7 < K_G < 1.1$. Shallow channels – for $y_s/d_{90} < 3$ $B = 3.74 K_G Q^{0.45}$ $y_s = \left(0.477 K_G^{-1.82} Q^{0.25} d_{65}^{-0.22} d_{90}^{0.55}\right) - d_{50Z}$ $S = 0.068 K_G^{-1} Q^{-0.45} B^{0.45} d_{65}^{1.22} d_{90}^{-0.55}$ These formulae apply to gravel-bed rivers only. Refer to CIRIA (2002) for a full discussion of this method and the various sediment and channel factors.
Simons and Albertson (1963)	$P = J_1 Q^{1/2}$ $\qquad B = 0.98 P + 0.7$ $A = J_2 Q^{0.87}$ $\qquad R = J_3 Q^{0.36}$ $y_s = 1.21 R$ for $R < 2.1$ m $y_s = 0.93 R + 0.6$ for $R > 2.1$ m where P is the length of the wetted perimeter, A is the corresponding flow cross-sectional area, R is the hydraulic radius, B is the channel width, ν is the kinematic viscosity of water (= 1.14 × 10^{-6} m^2/s at temperature of 15° C). All quantities in the equations should be in SI units, as defined above. The values of the coefficients vary according to the type of channel. The J coefficients are then determined based on the channel type chosen. Refer to the CIRIA Manual for a complete listing of channel types and coefficients.
Holmes (1974)	Developed to estimate the total scour at a site. General scour is not estimated as an individual quantity. $y_s = \dfrac{y_r V_1 K}{\sqrt{A/W}}$ where y_s (m) is the scoured flow depth, and $V_1 = C\left(\dfrac{Q}{A}\right)\left(\dfrac{y}{A/W}\right)^{2/3}$ and $K = \sqrt{\dfrac{W}{4.83 Q^{0.5}}} \le 1$ y (m) is the unscoured flow depth; y_r (m) is the water level rise from low water to flood stage; A (m^2) is the flow area of the unscoured profile; W (m) is the waterway width allowing for berm flow; V_1 is the approach flow velocity; C is a coefficient related to channel type. This method was developed based on field data collected in New Zealand for a range of rivers covering a wide range of sediment sizes. It incorporates a safety factor. See Melville and Coleman (2000) for a detailed description.

Method	Description
Mirtskhoulava, Ts.E (1967, 1991) and further papers	$y_s = \left(\frac{1.25q\Delta^b}{em_1m_hv_n}\right)^{\frac{1}{b+1}}$ where y_s is the depth of flow after scour; e is a coefficient taking into account contraction of the flow and increasing specific discharge; v_n is the non-scour near bed velocity at the height of the roughness protrusion; q is the specific discharge; m_1 is the coefficient of conditions of performance; m_h is a coefficient taking into account a water layer in the flood plain in channels formed of cohesive as well as fine grained soils (n = 4 recommended); Δ is the protrusion height (taken as $0.75d_{95}$); and b is a calculated parameter. $v_n = 1.25\sqrt{\frac{2}{0.44\rho_o n}}\left[g(\rho_s - \rho_o)d_{50}\right]$ where ρ_s and ρ_o are the sediment and water densities respectively. $b = \frac{\log\log\left(\frac{8.8y}{d_{95}}\right)}{\log\left(\frac{y}{0.7d_{95}}\right)}$ where y is the average flow depth before scouring. These formulas are applicable to specific flow conditions, such as for the rivers in the present study. The river conditions should be checked against the methodology presented by Mirtskhoulava to ensure the most appropriate version of the scour prediction equation is used.
CIRIA Manual (2002)	This manual provides the following procedure for estimating the likely general scour depth due to a flood. *Procedure:* The existing cross-sectional shape of the main incised channel is checked against dimensions predicted by the HR Wallingford regime tables (or any other regime method) for the bank-full flow rate. Next the conveyance in the main channel due to the flood flow is calculated. Using a regime method assess the predicted dimensions of the incised channel if it were to reach equilibrium conditions for the flow. If the required area from (2) is greater then the available area then the channel is assumed to adjust its shape to provide the additional flow area. A shape factor is provided for use in redistributing this required area.

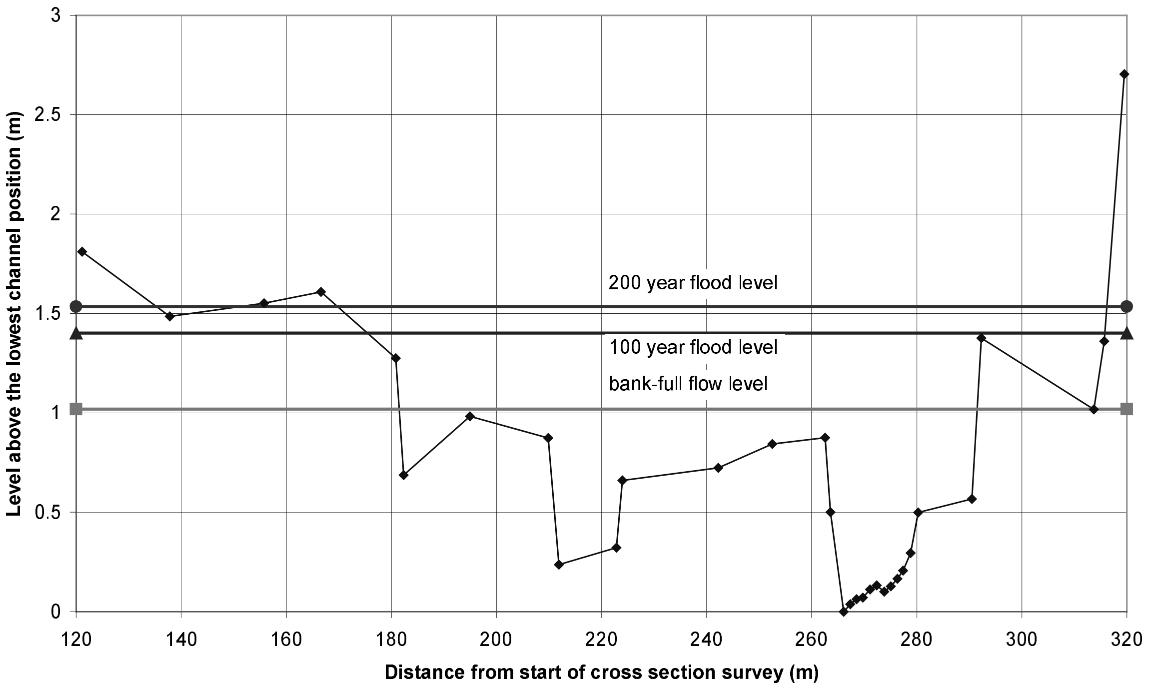

Figure 1. Cross-sectional view of Case Study 1 site.

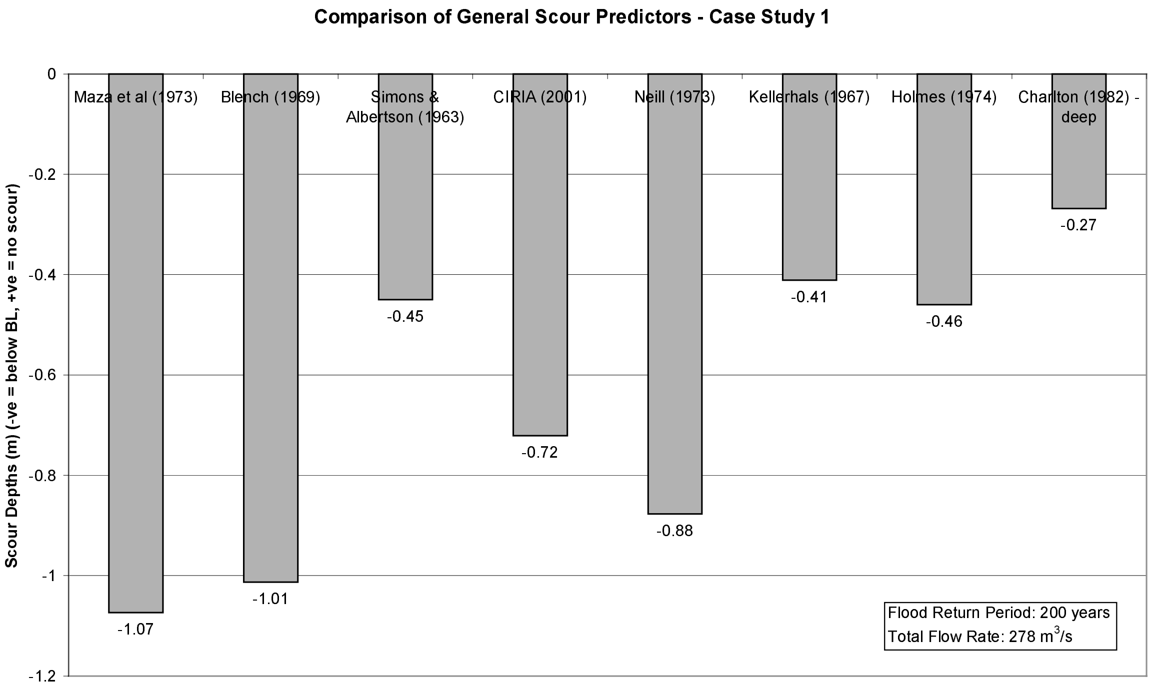

Figure 2. Comparison of General Scour Prediction Equations for Case Study 1 Site.

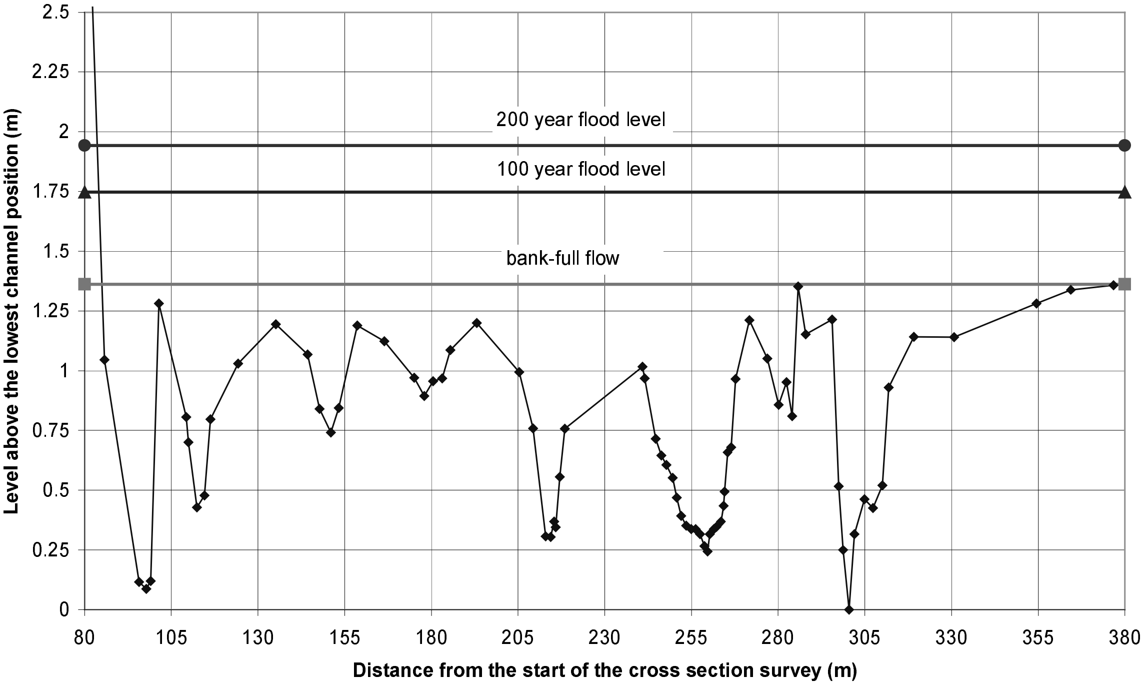

Figure 3. Cross-sectional view of Case Study 2 site.

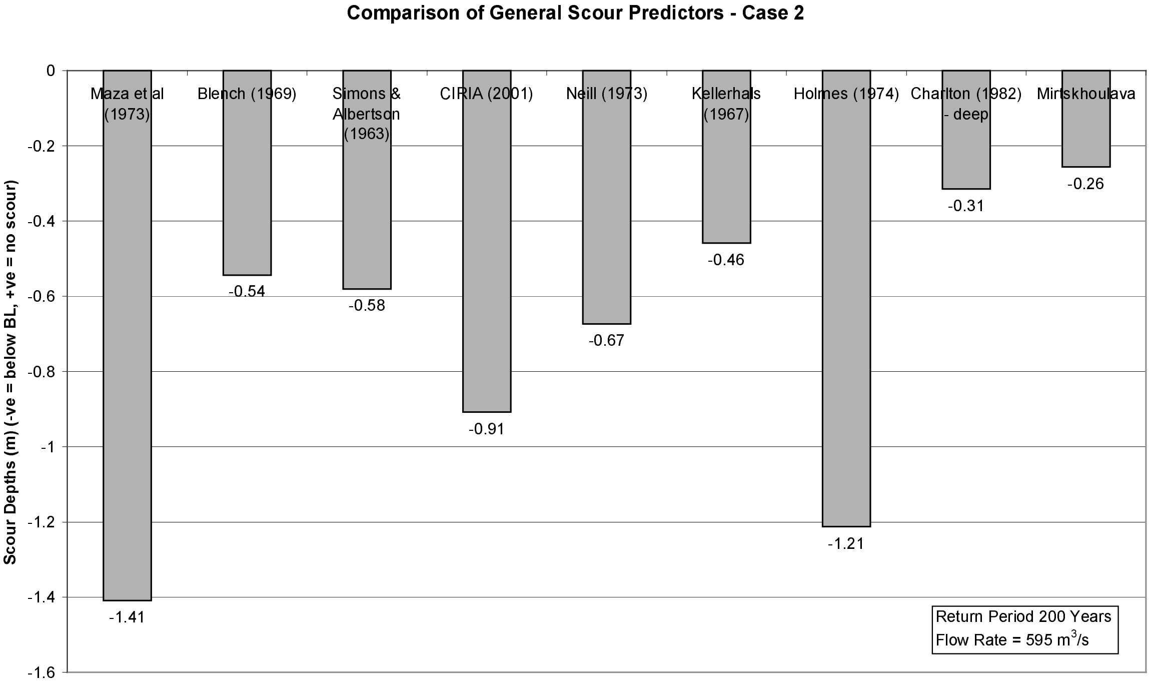

Figure 4. Comparison of General Scour Prediction Equations for Case Study 2 Site.

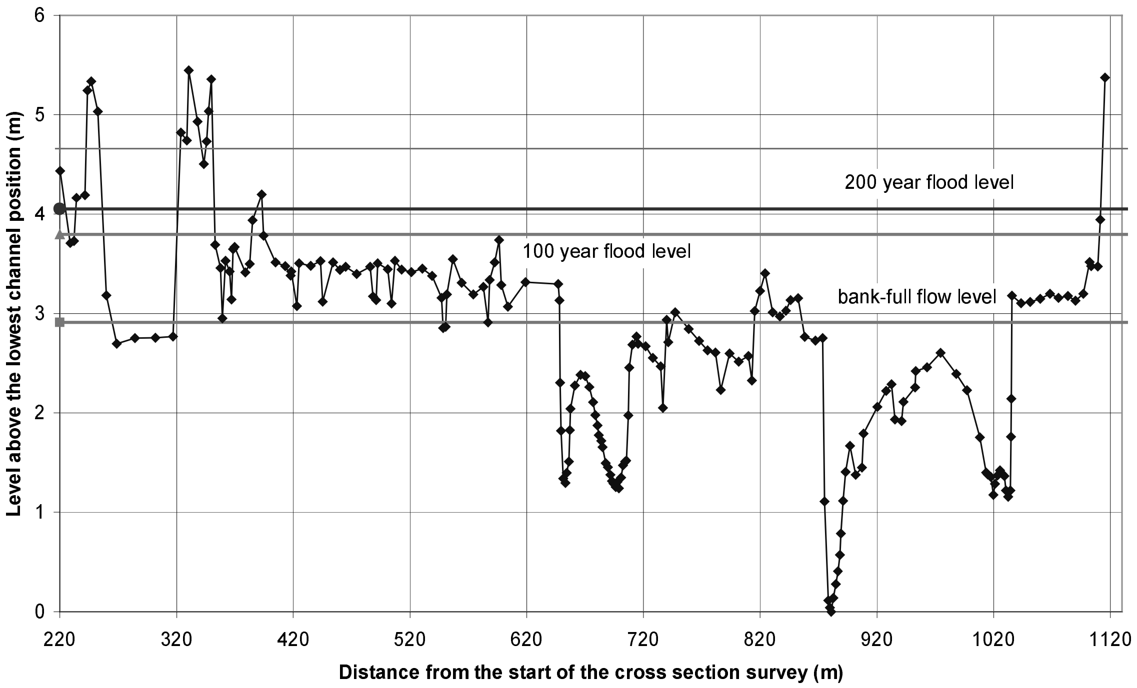

Figure 5. Cross-sectional view of Case Study 3 site.

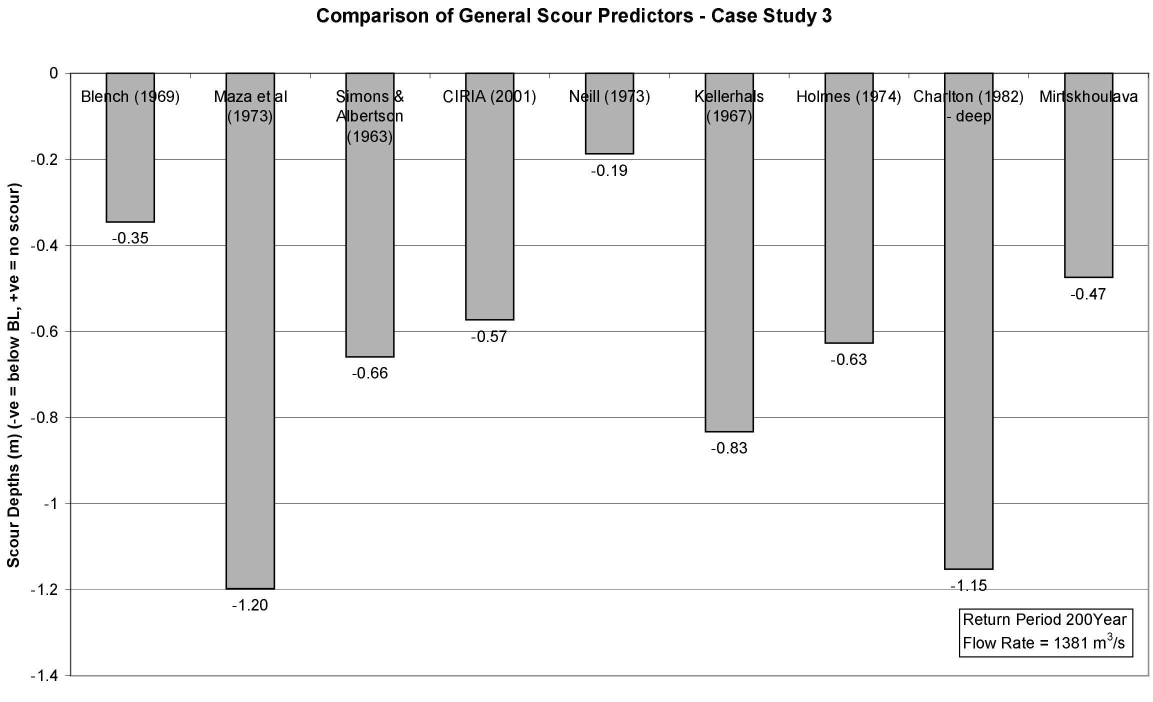

Figure 6. Comparison of General Scour Prediction Equations for Case Study 3 Site.