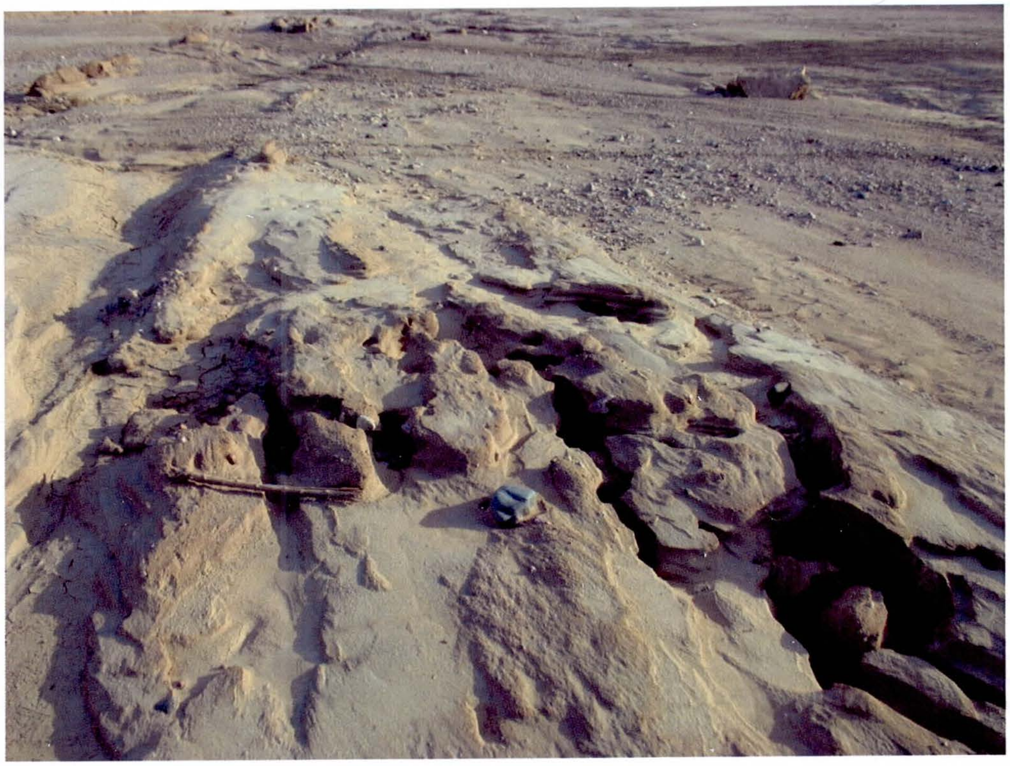
Sensitivity Analysis of HEC-6T for the Lower Hassayampa River Mining Pits

FINAL REPORT



Performed for

THE FLOOD CONTROL DISTRICT OF MARICOPA COUNTY

By

R₂D

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January 31, 2013

Registered Professional Engineer (Civil)
CERTIFICATE NO.
36225
GARY E.
FREEMAN
Date Signed 2/1/13
ARIZONA, U.S.A.
Expires 6/30/2013

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1.0 Executive Summary

A series of HEC-6T models were run for the Hassayampa River from approximately the Buckeye Road to Olive Avenue and included the I-10 crossing of the river. The reach includes three sand and gravel mining pits (Pioneer, CEMEX, and Hanson). This study investigated the impact of changes or inaccuracies in the input variables to the HEC-6T model when applied to sand and gravel pits. The Hassayampa is a sand bed river with limited gravels and no cobbles. The findings of this study may not be directly applicable to the gravel and cobble bed rivers and streams in Maricopa County but can be used for guidance for future studies on the Hassayampa River in this reach. This study also provides a basis to help understand the hydraulics of flow into sand and gravel pits.

Manning's N Value. The modeling effort found that the model is somewhat sensitive to the Manning's n value used for the channel but the headcut length and depth are not sensitive to the selected n value. The scour depths are very comparable for the headcut but vary within a range of approximately 1.2 ft for the actual values and 0.6 ft for the averaged maximum scour depths in the predicted headcut reach. The headcut was predicted to be 2112 ft long with one exception of 3960 ft. The observed headcut was on the order of 5,000 ft.

Peak Flow Rate. The sensitivity to changes in the full model is low. The maximum change in the averaged maximum scour depth over the range tested was approximately 0.7 ft. A change in the peak flow rate of 10,000 cfs resulted in a change in the average scour depth of 0.5 ft. The changes in scour depth were almost all due to headcuts or tailcuts at the three pits contained in the model. Changes in the headcut depth for the Pioneer Pit were about 1.5 ft compared with a maximum headcut depth of approximately 14 to 15 ft. The model predicted the headcut to be approximately 3,000 ft for the model with no bed smoothing and 1400 to 2500 for the model with bed smoothing turned on. The predictions were erratic with only a general pattern of increasing headcut length for increasing flows evident.

The flow rate from the 2010 flood event used in previous studies was again reviewed and found to be too high for the observed post-2010 event channel. Based on the observed post flood channel it is estimated that the flow above the Pioneer pit was on the order of 2-3,000 cfs and the peak flow rate between the Pioneer pit and the Hanson Pit was approximately 4,000 cfs. It appears that the east lobe of the Hanson pit breached rapidly during the 2010 event and produced the peak of 11,634 cfs which was observed at the I-10 Bridge.

Bed Gradation. It was found that the bed gradation used in the model did not impact the headcut length (2100 ft). The maximum depth variation was on the order of ±1.2 ft. This accounted for approximately 15% of the total headcut depth. The bed gradation did have an impact on scour depth but it was not extremely large with approximately a 0.9 ft difference in the average scour depth for the

model and about a 2 ft difference in the average scour depth for the headcut. The maximum headcut elevation varied by about 2.3 ft across the range of grain sizes used with the maximum headcut depth ranging from 12.4 to 14.7 ft in depth.

Inflowing Sediment Load. The inflowing sediment load had no impact other than at the first three to six cross sections. There was no impact in the model after the inflowing sediment load was allowed to adjust in the most upstream cross sections. The wide shallow floodplain allows the model to quickly regain sediment equilibrium in the first three cross sections for the most part.

Pit Width. The pit width was evaluated from half the original width to twice the original width. This change resulted in an increase in headcut depth of approximately one foot from 13.5 ft to 14.5 ft. The headcut length was constant at 2100 ft for all runs. The minimum headcut elevation (i.e. max scour depth) tracked within about 0.5 ft of the minimum *tailcut* elevation at the exit from the pit.

Pit Depth. The depth of the pit was modeled from a depth of 10 ft to a depth of 60 ft (2 x the original depth of 30 ft). The pit depth influenced the headcut depth but only to an elevation near that of the ending tailcut elevation. The maximum headcut depth was on the order of 14-15 ft with the exception of the 10 ft deep pit which was not deep enough to allow a 14 ft headcut. The headcut for the 10 ft deep pit was 10 ft in depth and the pit had mostly filled with sediment by the end of the simulation. It appears that for deep pits (> approx 20 ft) that are filled with water or those which fill quickly that the headcut depth is controlled by the elevation of pit outlet. For other pits that take a long time to fill this may not be true. The length of the headcut was again predicted at 2100 ft.

Pit Length. The length of the pit had a significant influence on the depth of the headcut. The maximum headcut depth (scour depth) varied by approximately 12 ft (9.9 ft to 21.6 ft) between the shortest (0.5x actual length = 1,000 ft) and the longest pit (2.0 x actual length = 4,000 ft) modeled in this study. The headcut elevation tracked the tailcut elevation until approximately 1.5 x the pit length when the minimum headcut elevation (maximum headcut scour depth) became approximately 2-3 ft higher than the minimum tailcut elevation. The change in the behavior of the headcut is likely due to deposition in the pit that interferes with the development of the headcut in the longer pits. The predicted headcut length was approximately 2100 ft and the averaged headcut scour depth varied by approximately 4.5 ft for the various runs .

Summary. The most important factor tested was the pit length. It appears that for the conditions modeled – a pit full of water with a sand bed channel - that the most important factor in determining the headcut depth is the difference in elevation between the bed at the upstream pit brink and the elevation of the bed at the pit outlet. This would likely not be true for very large pits that require significant amounts of time to fill. The maximum headcut depth under these conditions could very likely be well below the elevation of the downstream outlet prior to the pit filling. After the pit fills the top of the depositional delta inside the pit will be near the elevation of the pit outlet.

The HEC-6T model results are somewhat unstable in the headcut reach but the runs are repeatable so although the results are somewhat unstable the model does an adequate job of predicting the headcut depth and profile. The length of the predicted headcut is significantly shorter than that observed for the

Pioneer Pit but the area that was not predicted to be within the headcut consists of a relatively shallow portion of the headcut. Most of the data indicate an uncertainty band of approximately ±1.0 ft within the headcut reach. A summary of the data is shown in the following table.

Table 21. Summary of the Impact of Changes to Input Variables.

Variable	Modeled Impacts			
	Ave Bed Elevation	Headcut Depth	Headcut Length	Comments
Manning's n	Slight 21.74/Unit Increase (0.001 change = 0.02174 ft Ave)	Slight 0.5 to 0.75 ft Ave 2.5 ft max over full range	No	
Flow Rate	Some -5e-05/Unit	Some -5e-05 to -7.5e-05/Unit 3 ft Max	Yes but erratic predictions	
Bed Gradation	Some -0.334x+0.926 ft /Unit	Some -0.4536x+1.0348 /Unit 1.0 ft Total for Ave 2.3 ft Max	No	
Inflowing Sediment Load	No	No	No	
Pit Width	-	Some (1.5 ft diff)	No	
Pit Depth	-	Slight above 20 ft Depths 1.0 ft max diff > 20 ft	No	Significant headcut depth changes for pits shallower than 20 ft deep
Pit Length	-	Significant 10 to 22 ft	No	

2.0 INTRODUCTION

A number of sediment transport models of the Hassayampa River were developed to model a January 2010 flood event. These models include the river from approximately the Buckeye Road alignment to approximately the Olive Avenue Alignment (See Figure 1). This event caused significant headcuts and changes to the sand mining pits located in the reach. (River Research & Design (R_2D) 2011) The models applied in the earlier study included HEC-RAS, HEC-6T, and FLUVIAL-12. FLUVIAL-12 and HEC-6T both did good jobs of modeling the resulting scour although none of the models accurately predicted observed deposition within the pits. In consequence of the modeling effort it was desired to know how sensitive the Hassayampa River model was to changes in flow rates, inflowing loads, channel roughness, sediment size distribution, and pit dimensions. This project was funded by the Flood Control District of Maricopa County in order to determine how the models might be expected to vary based on changes to or inaccuracies in the model inputs.

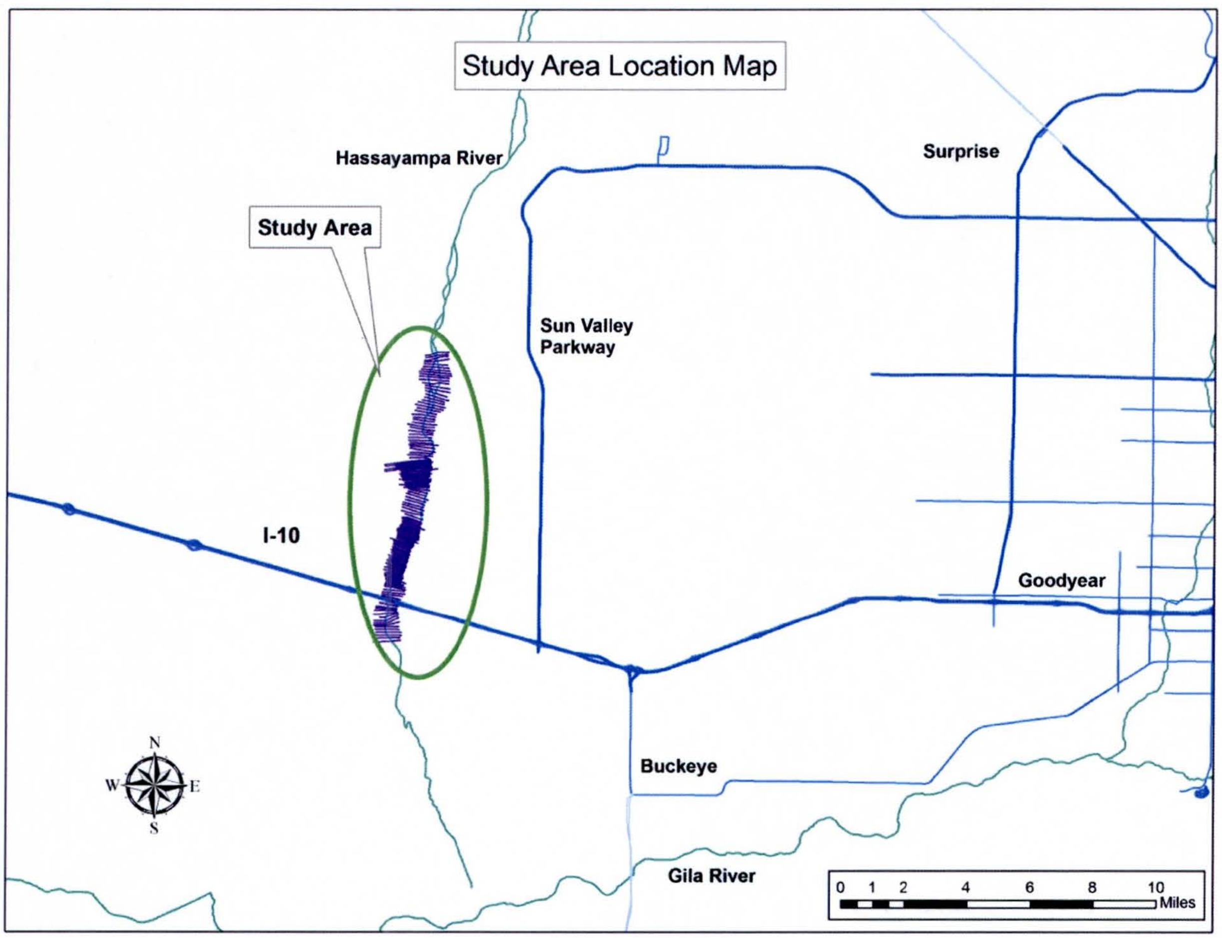


Figure 1. Location of Study Area on Hassayampa River.

This study focused on the HEC-6T model since it was one of the two best performing models used during the earlier study. This effort also included some coordination with HEC regarding features in the HEC-RAS sediment transport model that did not appear to be functioning as well as desired for this application. This report details the study methods and results obtained from the sensitivity analysis of the HEC-6T model of the reach of the Hassayampa from River Mile (RM) 9.64 to RM 19.01. The coordination effort is documented in Appendix II

The full model was from RM 9.64 to RM 19.52 but the initial six cross sections were eliminated from the analysis of the results since the sediment load was adjusting in this reach. The data is presented for the inflowing load analysis but not included in the bed change analysis since the impact of the inflowing load on the model further downstream was the focus of the analysis. Three mining pits are included in this reach (Figure 2) but only the headcut from the Pioneer (most upstream) pit was specifically evaluated for impacts. The other headcuts and all tailcuts were included in the full model results. The majority of the changes in the averaged minimum bed data are the result of changes in the headcut and tailcut reaches of the 3 pits. The cross section locations are shown in Figure 3.

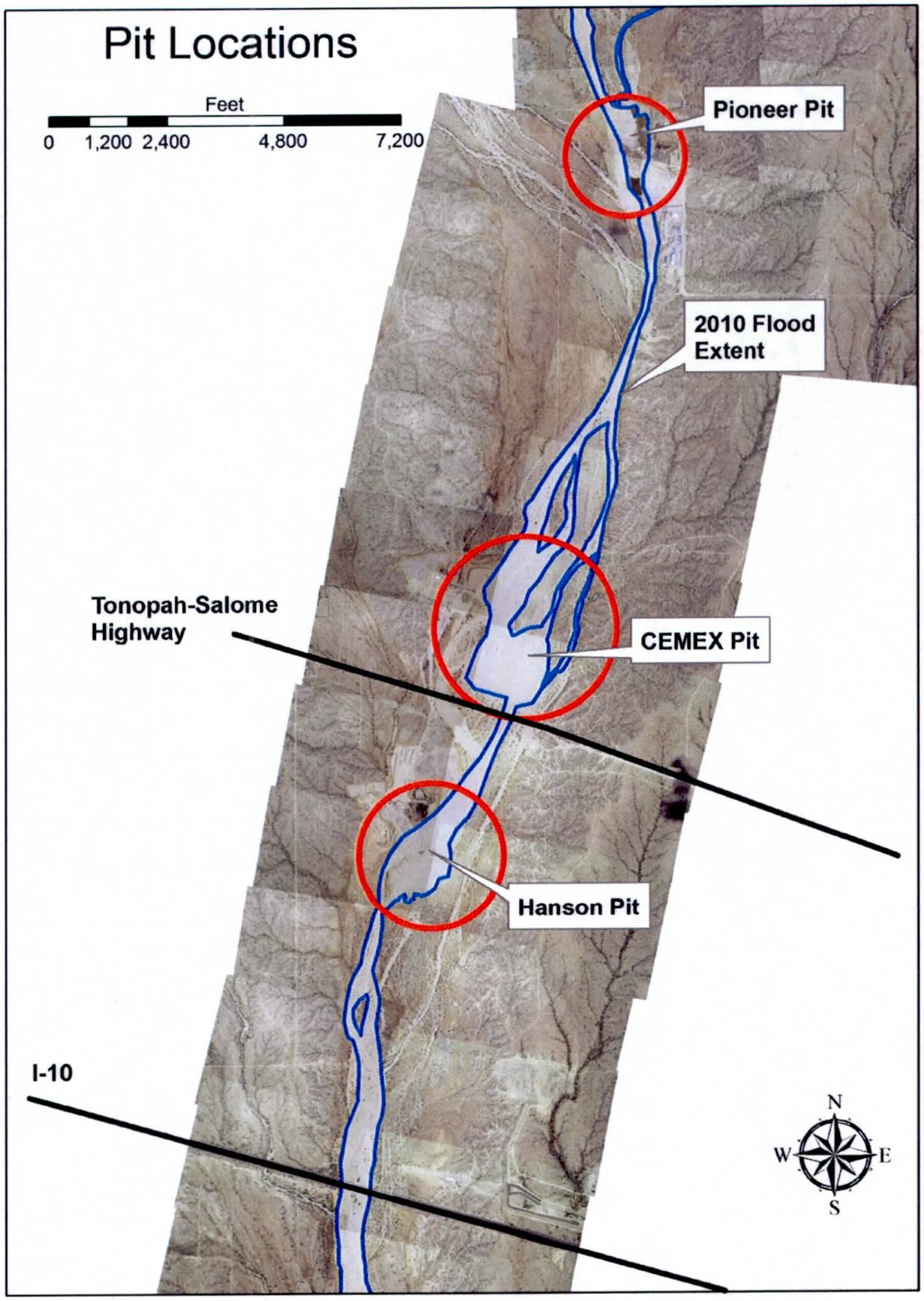


Figure 2. Location of Mining Pits along Hassayampa River. Blue lines are the extent of the 2010 flood event.

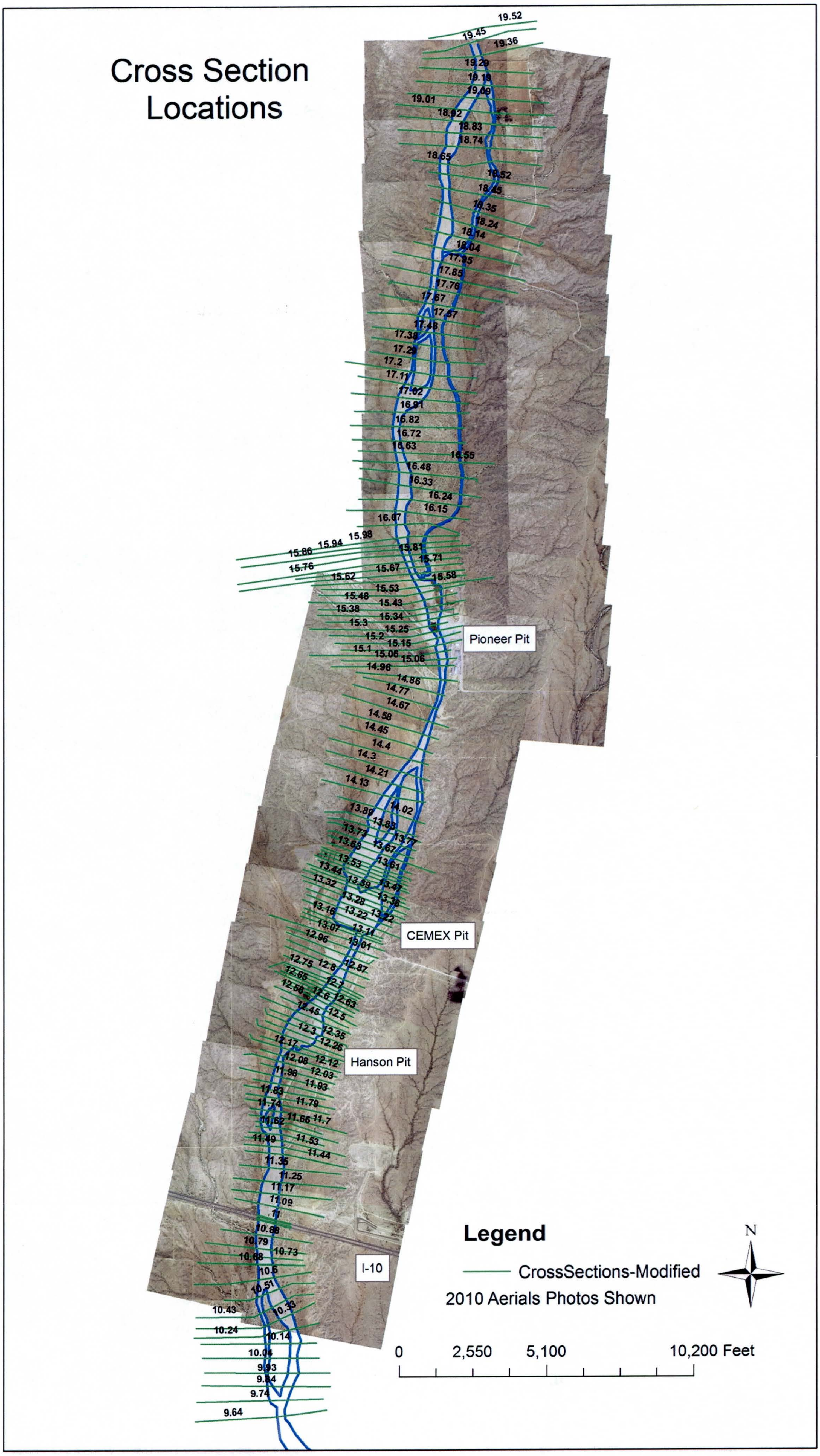


Figure 3. Location of Cross Sections in Relation to Pits and I-10.

3.0 STUDY OVERVIEW

3.1 MODEL DESCRIPTION

The model used for this analysis was the HEC-6T model from the previous modeling effort (R_2D 2011). The purpose of the previous effort was to compare models for the 2010 flood event on the Hassayampa River from approximately 1.3 miles below the I-10 bridges (RM 9.64) to approximately 4 miles above the Pioneer Pit (RM 19.52). The Pioneer pit is located from cross sections 15.25 to cross section 15.62.

The HEC-6T model used the Toffaleti equation combined with the Meyer Peter and Mueller sediment transport equation which produced results that were among the best obtained from previous modeling effort when using the HEC-6T model. The fewest changes possible were made to the model's input data although some changes were necessary to allow modeling of the various input ranges that were tested. The most substantial changes to the models are discussed below.

The major input variables for the HEC-6T model are given in Table 1 below. The input variables that were analyzed are discussed in more detail later in the report.

Table 1. HEC-6T Input Variables.

Variable	Base Values	Variation Modeled
Manning's n Value	Left Overbank 0.050 Channel 0.030 Right Overbank 0.050	Channel n – 0.020 to 0.050
Bed Sediment Reservoir	25 ft with 4 exceptions	15 ft to 30 ft
Peak Inflow	11,634 cfs	3,000 to 15,000 cfs
Sediment Gradation	D_{50} = 0.474 mm	D_{50} = 0.237 to 1.42 mm
Inflowing Sediment Load	Fuller Load	0 to 100 x Fuller Load
Bed Smoothing ($SMOOTH)	100 profiles per check	Smoothing off, 10 profiles/check and 100 profiles /check
Pit Width	Observed Pit	0.5 to 2.0 x actual width
Pit Depth	30 ft	10 ft to 60 ft deep
Pit Length	Observed Pit	0.5 to 2.0 x actual length

3.2 Changes to Models from Previous Study

1) The Manning's n value cards were changed from NX to NC cards to facilitate the effort since the Manning's n could be specified for the entire channel in one location. The average of the original n values as converted by HEC-RAS to left overbank, channel, and right overbank are 0.035, 0.028, and 0.036 from the WEST/Fuller model data (WEST 2006). The overbank n values for this test were raised to 0.05 to prevent water from preferring the overbank areas (i.e. those areas outside the observed flood extents for the 2010 flood) rather than the channel during high channel n value tests. The bank stations/flow limits in the original model were set to the width of the observed active channel so no

flow should have occurred outside of the main channel. No changes were made to the active channel limits / bank stations in this effort.

2) The first six cross sections of the model were eliminated from the average values for the channel due to large variations between runs. This was done to prevent the most upstream cross sections from adding additional variability to the average values since the sediment load was adjusting in this reach.

3) Cross Sections 18.35, 18.45, and 19.45 required the left side to be blocked to keep low flows in channel. Stations to left of 3340, 1191, and 2434 respectively (and lower than the main channel) were commented out (i.e. removed from the cross sections). The HEC-6T model was set up originally using X3 cards to block flow outside main channel to well above expected WS elevation for most cross sections – but it was not working for these three cross sections at low flows so additional measures were necessary to get the model to run successfully.

4) Removed single point pit section from cross section 15.20 to eliminate what appeared to be instability in the model. The value in question is not a model instability but the result of the very narrow pit section at a single point in a cross section that was eroding. This resulted in scour depths from the lowest point in the cross section appearing in the results which was misleading.

3.3 Data Evaluation Methodology

The data was evaluated with the goal of determining the rate of change in the bed elevation for changes in the following variables: Manning's n values, D_{50} sediment size, peak flows, inflowing sediment load, and pit size/configuration. Each variable was run for a wide range of values to ensure that results were applicable to a wide range of inputs. The values were selected based 1) what was used in the HEC-6 or HEC-6T models for the Hassayampa River during previous studies, and 2) the range of reasonable values that could be expected to be used in modeling this reach of the river.

The data was evaluated using several methods but the District preferred the results to be reported as the total scour depth based on the minimum bed elevation for the entire simulation. They also requested that any cross sections with deposition be eliminated from the calculations. It is acknowledged that this may tend to skew the results towards scour but the impacts of deposition in the areas away from the pits are relatively minor in comparison to the pits. The major concern was that deposition in the pits would tend to obscure scour resulting from the pits. The equation used to determine the results reported in this report is:

$$y = \frac{\sum_{n=1}^{N}(Z_{min,n} - Z_{0,n})}{N} \qquad (\text{for } Z_{min,n}\text{-}Z_{o,n} < 0) \qquad (1)$$

Where:

y = reach based averaged maximum scour depth from the original (pre-flood) elevation

$Z_{0,n}$ = thalweg elevation at beginning of simulation

$Z_{min,n}$ = minimum thalweg elevation for cross section n during entire simulation

N = the total number of cross sections

n = the cross section being evaluated

The equation was evaluated two ways – first with all of the values used (both fill and scour) and second with the values that indicated deposits (fill) removed from the calculations. This gave a good indication of the impact of pit sedimentation on the calculated averages. The removal of the fill values resulted in the calculation of values based solely on maximum scour depths (negative bed change). The impact of fill was not a problem for the headcut results since all of the values are negative (i.e. scour).

When testing was completed for each input variable (i.e. all of the Manning's n value adjustments) the scour depth data were then plotted and a best fit line drawn through the points. This results in an equation predicting averaged scour depth for the various values of each factor. The desired result was the rate of change of the scour depth for a unit change in the input variable (Manning's n, bed grain size, inflowing load, etc.). This was determined by two methods. The first method consisted of varying the input variable by a very small amount and viewing the results to see what the corresponding change was in the model output (averaged maximum scour depths). The second method was to make larger changes in the model input over the full range of the expected values of the variable and plot the results to see how the model responded over the full range of the results.

The first method involved determining a sensitivity coefficient to see how the change in averaged maximum scour depth varied as the input was varied. This is the difference in predicted scour depth between two points separated by a very small amount:

$$\frac{\partial y}{\partial x} = \frac{y2-y1}{x2-x1} \qquad (2)$$

where y1 is the averaged maximum scour depth obtained using the original model inputs (x1) and y2 is the averaged maximum scour depth from the model with an input of x2. The y2-y1 value was intended to be obtained by making very small change in the input variable and plotting how the results varied.

The second method used input values covering the full range of the anticipated range of input values – i.e. from the lowest to the highest input value that could be expected to be used in modeling of the river. The determination of the sensitivity coefficient for this data involved the determination of y for several x values within the full range of expected x values. A best fit curve was then plotted for these values and differentiated to obtain the sensitivity coefficient. This is described as follows:

$$\frac{\partial y}{\partial x} = \frac{\partial f(y)}{\partial x} \qquad (3)$$

where f(y) is the best fit line describing the data obtained from equation 1. Since each relationship is a function of only one set of variables (x,y) the partial derivative is identical to the full derivative.

Model Reach Utilized in Results

The cross sections used for the full model average (labeled as Model in the figures) are 9.64 to 19.01 or the entire model with the exception of the most upstream six cross sections which showed some erratic behavior while the inflowing sediment load was adjusting. The cross sections used for the observed Pioneer Pit headcut (Pit HC) are from 15.67 to 16.72 (17 cross sections) while those used for the predicted or modeled headcut are 15.67 to 16.07 (9 cross sections).

Sand and gravel mining pits are located at 12.21 to 12.45 (Hanson pit), 13.14 to 13.49 (CEMEX pit), and 15.25 to 15.62 (Pioneer pit) (See Figure 2 and Figure 3). It should be remembered that the Hanson and CMEX pits each has an associated head cut and tailcut that were not evaluated separately. The impact of varying input variables for these headcuts and tailcuts are included in the data for the full model. Analysis was not performed for the Hanson and CEMEX pits individually since the data was not as accurate as that for the Pioneer pit. The Hanson and CEMEX pits had experience multiple flows with differing pit configurations and headcuts were not as easily defined or as accurately modeled.

Preliminary Analysis of data

Initial efforts concentrated on the final thalweg elevation data. This produced reasonable results for most of the range of input variables. After consideration the District indicated that they would prefer to have the analysis based on the minimum thalweg depth predicted by the model rather than the elevation predicted at the end of run. The concern was that the maximum scour depths might be obscured by deposition during later portions of the flow event.

Data was originally obtained from the .t6 output file for use in the analysis but based on the data evaluated for the inflowing sediment load analysis it was not clear if the data from the .t6 file were accurate or not. The minimum thalweg elevation data obtained from the .t6 file appeared to contain some cross section values with excessive scour as compared with other data available. The problem became evident when data being used for analysis was compared between the .t6 file and the .t98 (plot) file data. The data from the plot file (.t98 file) did not appear to contain the anomalies seen in the .t6 files. No data could data be found to support the apparently anomalous data seen in the .t6 files. After serious investigation and consideration the data from the .t98 plot file was used for analysis.

This finding was followed up by discussions with Mr. Tony Thomas the developer of HEC-6T. The model with the largest anomalies was sent to Mr. Thomas for review. These discussions indicated that problems had occurred with the $SMOOTH card turned on in some of the older versions of the model but the new version of the model produced accurate results in both the .t6 and .t98 files. Unfortunately this was not discovered until nearly all of the modeling had been completed. The problems that led to this discovery occurred during the analysis of inflowing load sensitivity runs very near the end of the modeling effort and are discussed later in the report. The result was that the older versions of HEC-6T may produce results when using the $SMOOTH card that may not be as accurate as results with the $SMOOTH card not used (or turned off) for the version of HEC-6T used in this study. The most current version of HEC-6T produces results that do not exhibit this erratic behavior.

In an attempt to understand this anomaly the impact of the bed sediment reservoir was investigated since this seemed to have an impact on the anomalies. The anomalous data is shown in Figure 4 and will be discussed further in the section presenting the results for the bed sediment reservoir depth analysis. The various lines represent model minimum bed elevations using differing bed sediment reservoir depths and different a different number of iterations between the smoothing calculations. One of the runs contained 501 warnings regarding bed sediment reservoir depth but did not exhibit the anomalies found in the other runs so the anomalies did not relate to errors or even the maximum error values reported at the end of the output data.

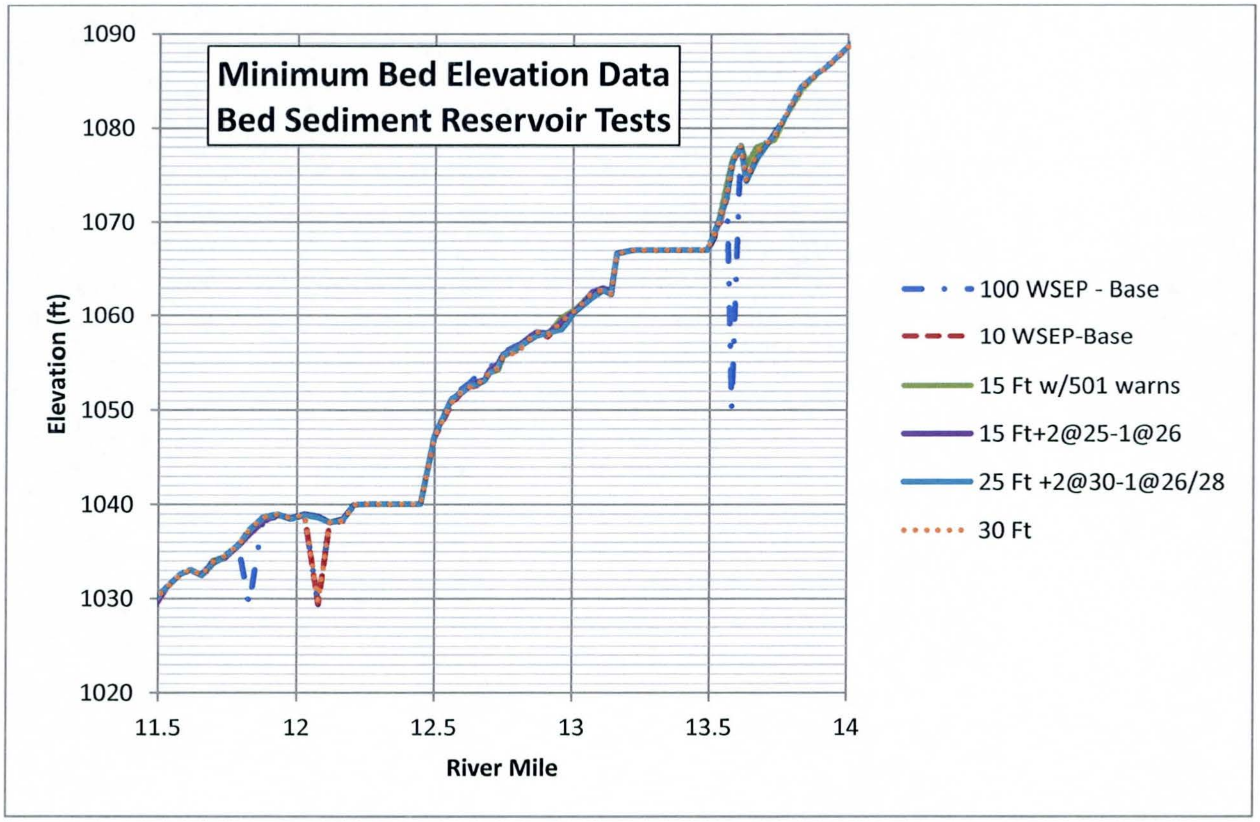


Figure 4. Minimum Bed Depth Results for the Bed Sediment Reservoir sensitivity evaluation for the Hanson and CEMEX pit reach. WSEP = Water Surface Elevation Profiles between smoothing calculations. With exception of 100 WSEP data all models have 10 WSEP between smoothing calculations. The notes after the bed sediment reservoir depth indicate how many cross sections were deeper than the test depth and the depths they were set to. For example 25 ft+2@30=1@26/28 indicates the bed sediment reservoir was set at 25 ft with two cross sections set to 30 and one cross section set to 26 ft and one set to 28 ft in depth.

Based on the results of the various studies it is recommended that analysis of data from older versions of HEC-6T be based on the data contained in the .t98 or .t12 files rather than the minimum bed elevation data contained in the .t6 file. The only values where significant problems were noted were for the minimum bed elevations in the .t6 file. The data regarding this observation are presented in graph form in the main report and in tabular form in the Appendix. The problem was only noted at four cross sections and varied with changes in the input variables.

4.0 HEC-6T SEDIMENT TRANSPORT SENSTIVITITY ANALYSIS

The sensitivity of the HEC-6T model to input variables consisted of two efforts. The first effort was to vary the input variables for the Manning's n value, peak flow, bed D50 grain size, and the inflowing sediment load by small values and determine the change in the model output. The second effort was to vary the input variables between limits that were thought to be reasonable for the upper and lower bounds of the model.

4.1 Sensitivity Coefficient Computation

In the original scope of work it was anticipated that one set of runs would be made with small changes in the test variables and another set would be run using a broad range of input values. During the early stages of the analysis it was determined that very small changes from the base condition were inconsistent and did not produce useable results. This can be seen in Figure 5 near the 0.0 change in the Manning's n value. The output values varied widely for very small changes in the Manning's n values used in the channel.

As a result of the inconsistencies and instabilities[1] found in the Manning's n value runs the two series of tests (subtask 1.1 and 1.2 in the scope using equations 2 and 3) were combined such that a larger number of runs were made for each main variable (flow, n value, bed gradation, and inflowing load) over the full reasonable range of the tested variables. This produced results that could be evaluated and allowed the runs with very small changes from the base value that were not predictable to be either eliminated or ignored if desired. The results for very small changes from the base values can be seen in the n value results that follow. Very small changes were not evaluated for the other input variables.

The findings of this task indicate that very small changes in the model input can result in relatively large changes in averaged output whereas larger changes can result in relatively smaller changes in the averaged output. Changes on the order of 0.001 in Manning's n values, for example, resulted in more reasonable changes in the averaged output whereas changes on the order of 0.0001 resulted in wide variations in the averaged output as can be seen in Figure 5.

4.2 Parameter Range Sensitivity Analysis

4.2.1 Variation of Manning's n Values

The Manning's n values for the river channel were originally set so that they varied by cross section and location within the cross section as was discussed earlier. The original n values were based on vegetation and other factors in the earlier River Research & Design (R_2D) and WEST/Fuller studies. The model was adjusted in the earlier study (R_2D 2011) to set the channel n value to 0.025 to facilitate the running of scenario where the 2005 flood was modeled followed by the 2010 flood event. The use of a single set of NC cards with an n value of 0.025 for the channel and 0.050 for overbank was also used as the base condition for the channel and overbanks in this study. The use of the single NC card greatly facilitated changes to the channel n value. The 0.025 value was set at what appeared to be a reasonable

[1] The HEC-6T model was not unstable in the traditional sense that it produced differing results for identical input values but in sense that a very small change in the input value produced a relatively large change in model output that was not consistent as the input was varied by additional similar amounts. The model did produce the same results each time the model was run for a specific set of input values.

value and accounted for grain size roughness in channels where the vegetation was removed during the 2010 event. The 0.025 value is similar to the 0.026 used by Howard Chang in his Fluvial 12 model in the earlier study (R_2D 2011) and similar to many of the bare channel values used by WEST/Fuller in their earlier study (WEST 2006). It was observed that the channel areas were almost void of vegetation so the use of the low value appeared justified once significant flow had begun in the channel.

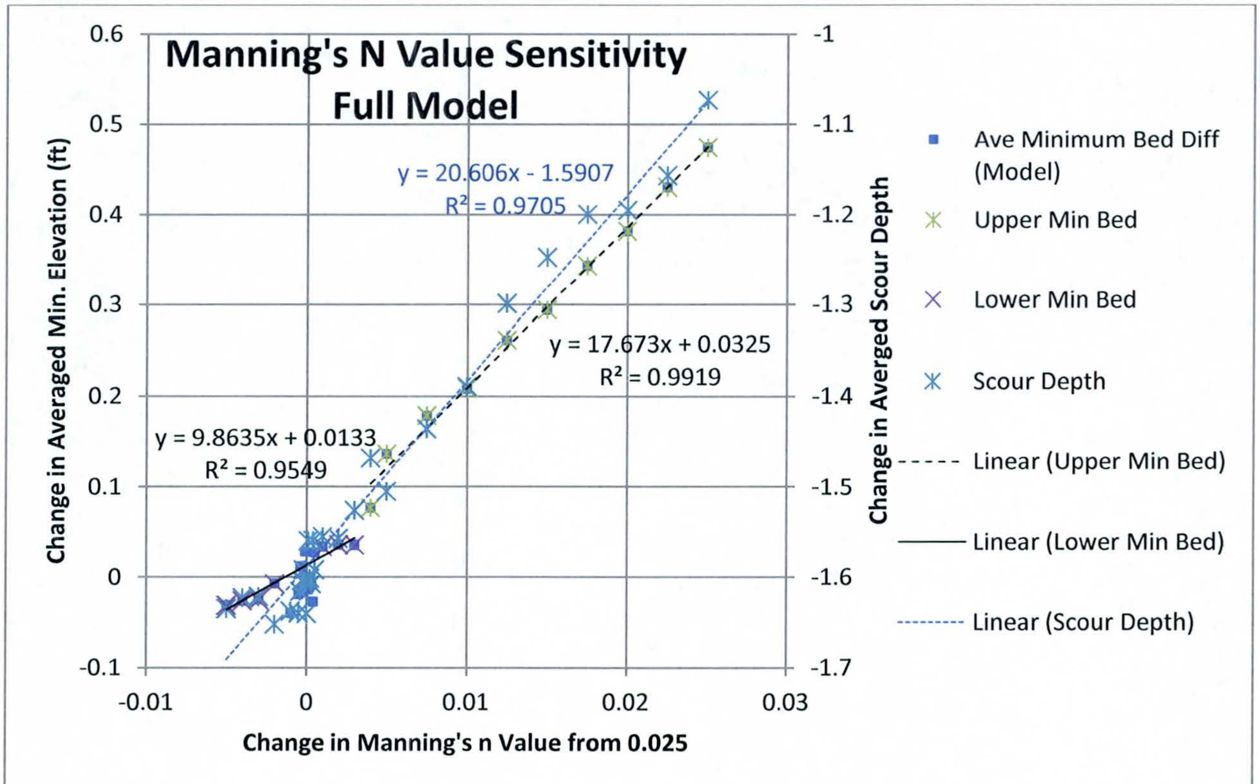


Figure 5. Change in Minimum Bed Elevation and Maximum Scour Depth for Changes in Manning's n Value. The Best Fit Line for the Lower Minimum Bed Data is based on ignoring values between -0.001 and +0.001 which show large instabilities.

In order to view the impact of changes in the Manning's n value on channel elevation the base n value (0.025) was modified and the maximum bed change observed at each cross section averaged to directly calculate the change that occurred between the two n values. Originally this was done by modifying the original n value by a very small amount (0.0001) and comparing output from one run to the next (i.e. results for n=0.0252 to 0.0251, etc). In the runs very near the base value of 0.025, however; the values - while repeatable - were so erratic that no trend could be determined. In order to see if any trend was possible the data from the various runs were compared to the original model (channel n = 0.025) rather than to an intermediate model. This provided more consistent data as can be seen in Figure 5 and was the method used as the basis for the study. Based on the results using very small changes the decision was made to use larger changes in Manning's n values (0.001) than were used in the earlier runs (0.0001). The district desired to know the relationship between the maximum scour depths and the changes in Manning's n value rather than just the change between runs so the basis of the analysis was then changed to be the beginning thalweg elevation rather than the change in thalweg elevation from the base run with a Manning's n of 0.025. The maximum scour depth data is also shown in Figure 5 and is associated with the right axis.

The data indicates that the two values (averaged maximum scour depth and averaged minimum bed elevation) produce very similar trends and either relationship could be used to predict changes for long reaches similar to that modeled herein.

The range of n values analyzed ranged from 0.020 to 0.050 (-0.005 to +0.025) for the channel values. The lower limit of 0.020 is very smooth and is likely the lower limit of roughness values for this stream. Some channels do have lower n values but given the grain size and the tendency of sand bed streams to develop bedforms a lower limit of 0.020 was thought to be reasonable. The upper limit for this reach of the river is likely in the 0.035 to 0.040 range based on prior studies but the range was extended to 0.050 to ensure that the full range of reasonable values were considered.

The data shown in Figure 5 and Figure 6 show that the there is a good relationship between changes in the Manning's n value for the channel and changes in the averaged minimum bed for the Hassayampa River model. The exception is the data between approximately -.001 (0.024) and +0.001 (0.026) as discussed previously. Figure 5 shows all of the data obtained while Figure 6 shows the data with the exception of the range between -0.001 and +0.001. The data between these values resulted in much larger changes in the averaged bed change per unit of change than any of the data outside this range and was eliminated from analysis as shown in Figure 6.

Also included in Figure 6 are the results from the ending bed data. This figure shows the impacts of looking at the ending bed elevation rather than the minimum bed elevation during the entire simulation. The change in the ending bed elevation is substantially lower in the portion of the headcut near the pit since it fills significantly as the upstream portion of the pit fills with sediment.

Based on the results shown in Figure 5 it appears that the model becomes less stable at the lower Manning's n values tested and at an value of approximately 0.030 (change of +0.005) the model begins to behave somewhat differently. The change is not drastic and when the data very near the base n of 0.025 is eliminated the best fit line for the combined minimum bed data set (R^2 = 0.9894) (Figure 6) is perhaps better than the best fit lines when the data is split at 0.0275 (R^2 = 0.9919 for the upper data set and 0.9549 for the lower data set as shown in Figure 5).

The data for the minimum bed elevation, maximum scour depth, and final bed elevation are shown in Figure 6 for reference although the primary analysis will focus on the maximum scour depth data as requested by the District. The data for the plots are contained in Table 2.

It can be seen in Figure 6 that there is a slightly differing slope between the lines for the averaged minimum thalweg elevation and the maximum scour depth but the behavior of the data sets are similar.

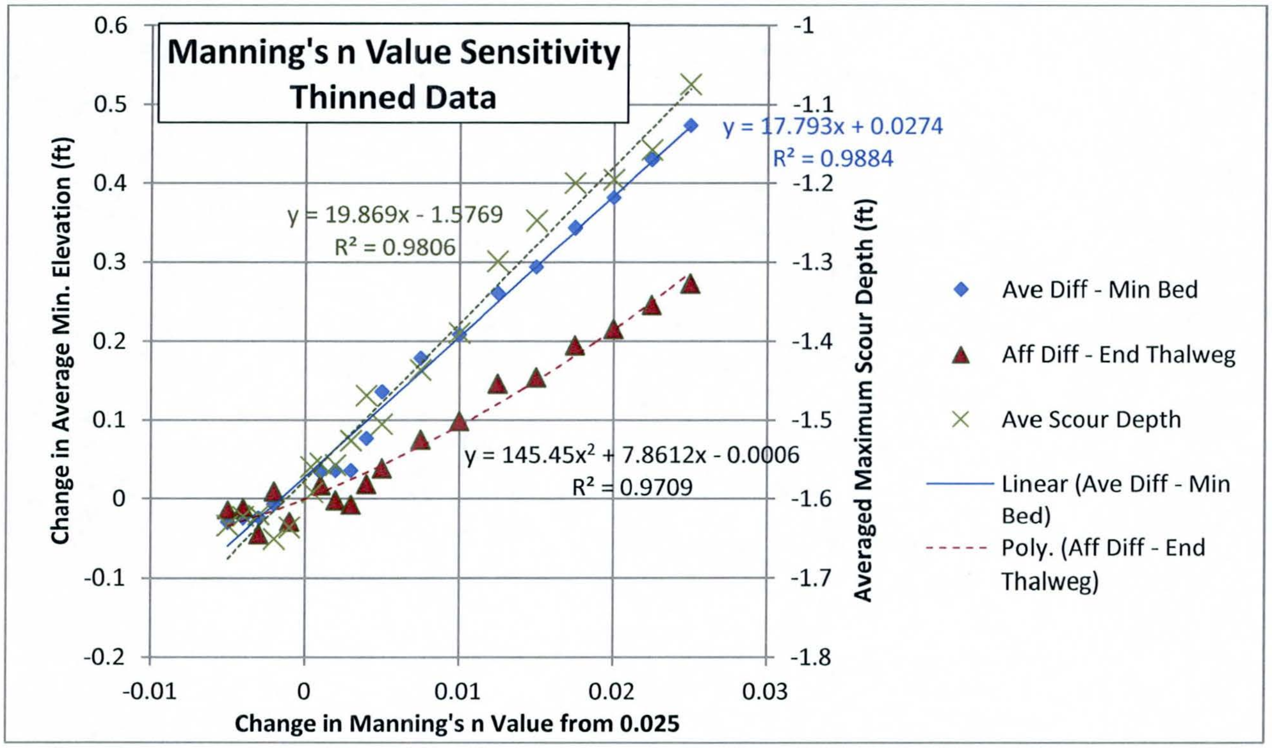


Figure 6. Change in Average Change in Minimum Bed, Average Bed, and Ending Thalweg Elevations for Changes in Manning's n Value for the Full Model not Considering Data Points Between -0.001 and +0.001.

Since problems were noted in HEC-6T related to the use of bed smoothing ($SMOOTH card) the data for the model with bed smoothing turned on and off is presented in Figure 7. It can be seen that there is some difference between the two sets of runs but the equations and fits are similar. For this application the impact of problems in the implementation of the $SMOOTH card are not extreme although noticeable. The data for the models with bed smoothing turned on results in a smoother plot down to a Manning's n of 0.030 (+0.005 from the base condition). Below the 0.030 value both sets of results are more erratic – especially near an n value of 0.025. The data for the plots with bed smoothing turned on are contained in Table 2 while those with bed smoothing turned off are contained in Table 3. The slopes of these lines correspond closely to the slope of the averaged maximum scour depth line in Figure 6.

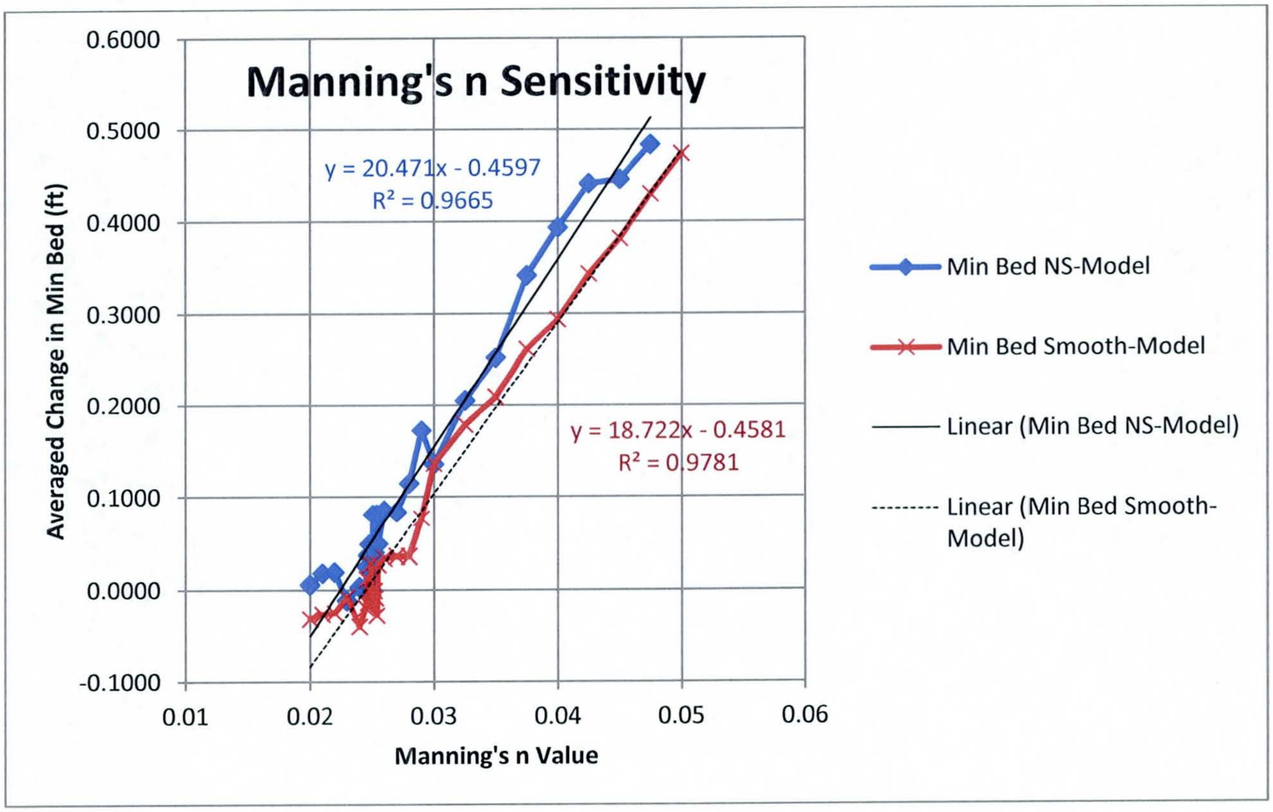


Figure 7. Full Model Sensitivity to Manning's n Value for Minimum Bed with bed smoothing (Smooth) and without (NS) bed smoothing. Data is calculated as change from the results for a Manning's n value of 0.025.

Table 2. Model Sensitivity Data for Manning's n for Runs with Bed Smoothing on. Data from .t98 files.

Delta n value	Actual n Value	Maximum Headcut Depth Pioneer Pit		Averaged Change in Bed Elevation Full Model		Averaged Change HC Elevation Modeled HC	
		Final Bed	Minimum Bed	Min	Ave	Min	Ave
-0.0050	0.0200	-11.34	-14.17	-0.03141	-0.08835	0.24264	-0.067958
-0.0040	0.0210	-12.5	-14.06	-0.02633	-0.08713	-0.04565	-0.844288
-0.0030	0.0220	-12.5	-14.25	-0.02507	-0.13023	0.12217	-0.655189
-0.0020	0.0230	-11.28	-14.19	-0.00747	-0.0279	0.30278	0.2507112
-0.0010	0.0240	-11.98	-14.12	-0.03984	-0.05283	0.10582	0.0907271
-0.0005	0.0245	-12.11	-15.37	-0.01948	-0.03935	-0.03731	-0.03051
-0.0004	0.0246	-12.02	-14.72	0.011547	-0.01952	0.26596	0.0796494
-0.0003	0.0247	-13.14	-15.24	-0.01358	-0.03084	-0.31448	-0.300057
-0.0002	0.0248	-11.62	-14.21	-0.01716	-0.024	-0.12732	-0.021657
-0.0001	0.0249	-12	-14.28	0.027836	0.008068	0.18180	0.0159828
0	0.0250	-11.91	-14.16	0	0	0	0
0.0001	0.0251	-12.09	-14.99	-0.01415	-0.03748	-0.08848	0.003804
0.0002	0.0252	-12.08	-14.64	-0.00121	0.000845	0.12819	0.0379646
0.0003	0.0253	-12.49	-15.32	-0.00857	-0.01559	-0.27944	-0.24331
0.0004	0.0254	-12.29	-15.21	-0.02754	-0.07352	-0.40713	-0.929121
0.0005	0.0255	-12.95	-15.27	0.026979	-0.04262	-0.21616	-0.863733
0.0010	0.0260	-12.12	-14.18	0.033648	0.005809	-0.02214	-0.065106
0.0020	0.0270	-12.07	-14.16	0.035629	-0.00918	-0.0392	-0.170472
0.0030	0.0280	-13.38	-15.29	0.035509	-0.02139	-0.22258	-0.906108
0.0040	0.0290	-12.82	-14.92	0.076313	-0.00849	0.15004	-0.674554
0.0050	0.0300	-13.49	-15.29	0.135967	-0.00758	-0.01385	-0.822989
0.0075	0.0325	-11.09	-14.02	0.178422	0.05993	0.3575	-0.18771
0.0100	0.0350	-11.7	-14.26	0.208549	0.069171	0.2125	-0.504715
0.0125	0.0375	-10.83	-14.32	0.261077	0.112621	0.2757	-0.668261
0.0150	0.0400	-11.59	-14.55*	0.29367	0.119269	-0.3132	-1.257152
0.0175	0.0425	-12.24	-14.74**	0.3432	0.16261	-0.4121	-1.247596
0.0200	0.0450	-12.01	-14.14	0.38143	0.184249	-0.0334	-1.266769
0.0225	0.0475	-12.11	-13.75	0.429794	0.201203	0.0481	-1.386424
0.0250	0.0500	-12.32	-12.55	0.473572	0.228268	0.2878	-1.241475

* Max Value at second cross section upstream from pit = - 13.70 at end of HC

** Max Value at second cross section upstream from pit = - 14.31 at end of HC

Table 3. Model Sensitivity Data for Manning's n for Runs with Bed Smoothing Turned Off.

N Value Adjustment	Modeled N Value	Model Values		HC-Model		Max HC Depth (ft)	Modeled Headcut Length (ft)
		<-----------Data from .t98 Files------------->					
		Min Bed	Ave Bed	Min Bed	Ave Bed		
-0.005	0.020	0.0053	-0.0636	0.1857	-0.3085	13.51	2112.00
-0.004	0.021	0.0175	-0.0810	-0.1147	-0.8421	13.92	2112.00
-0.003	0.022	0.0188	-0.0531	0.1257	-0.7563	12.94	3960.00
-0.002	0.023	-0.0118	-0.0812	-0.4105	-1.3617	14.20	2112.00
-0.001	0.024	0.0027	-0.3380	-0.0484	-1.3334	13.85	2112.00
-0.0005	0.0245	0.0006	-0.0037	-0.0581	0.0451	13.89	2112.00
-0.0004	0.0246	0.0245	-0.0133	-0.2469	-0.2046	13.92	2112.00
-0.0003	0.0247	0.0363	0.0246	-0.2792	-0.0642	13.95	2112.00
-0.0002	0.0248	0.0482	-0.1371	0.0001	-0.1831	14.12	2112.00
-0.0001	0.0249	0.0346	0.0117	-0.0617	0.0894	14.06	2112.00
0	0.0250	0.0000	0.0000	0.0000	0.0000	14.04	2112.00
0.0001	0.0251	0.0806	0.0342	0.0308	0.1192	14.24	2112.00
0.0002	0.0252	0.0390	0.0265	-0.2989	-0.1977	13.87	2112.00
0.0003	0.0253	0.0328	0.0237	-0.3141	-0.2100	13.93	2112.00
0.0004	0.0254	0.0808	0.0282	-0.1889	-0.2041	14.06	2112.00
0.0005	0.0255	0.0485	0.0202	-0.3507	-0.2606	13.98	2112.00
0.001	0.0260	0.0851	0.0293	-0.3357	-0.2706	13.80	2112.00
0.002	0.0270	0.0831	0.0351	-0.2446	-0.1512	13.95	2112.00
0.003	0.0280	0.1142	-0.0153	-0.2627	-1.4104	13.81	2112.00
0.004	0.0290	0.1719	0.0366	0.1332	-0.6482	13.19	2112.00
0.005	0.030	0.1352	0.0145	-0.7365	-1.3190	14.06*	2112.00
0.0075	0.0325	0.2043	0.0597	0.1218	-1.2438	14.02	2112.00
0.01	0.0350	0.2512	0.1132	-0.2281	-0.8638	14.30**	2112.00
0.0125	0.0375	0.3413	0.1678	-0.3385	-0.9127	14.01	2112.00
0.015	0.040	0.3931	0.1749	0.1164	-1.1688	13.57	2112.00
0.0175	0.0425	0.4407	0.2150	-0.0746	-1.3853	13.26***	2112.00
0.02	0.0450	0.4451	0.2459	-0.2531	-1.1944	13.25	2112.00
0.0225	0.0475	0.4831	0.2603	-0.0315	-1.3635	12.07	2112.00
0.025	0.050	0.5664	0.2930	0.0167	-1.3407	11.88	2112.00

* Max HC Depth occurs at 2^{nd} cross section – end cross section was 13.70

** Max HC Depth occurs at 2^{nd} cross section – end cross section was 12.40

*** Max HC Depth occurs at 2^{nd} cross section – end cross section was 12.21

4.2.2 Results based on Negative Values Only

The removal of values indicating fill (located most predominately within the mining pits) resulted in greater scour depths but all four data sets have a very similar slope (20.5 to 21.7) as can be seen in Figure 8. These slopes are slightly higher than that noted with all of the data considered (17.8 to 19.9) as shown in Figures 5 and 6. The data were plotted on differing axis as shown in Figure 9. The scales in Figure 9 include the same range but are shifted to plot the data approximately on top of one another. It can be again noted that there is a slight slope difference but that the difference in predicted slope values between the two methods are small. The data for the plots is presented in Table 4.

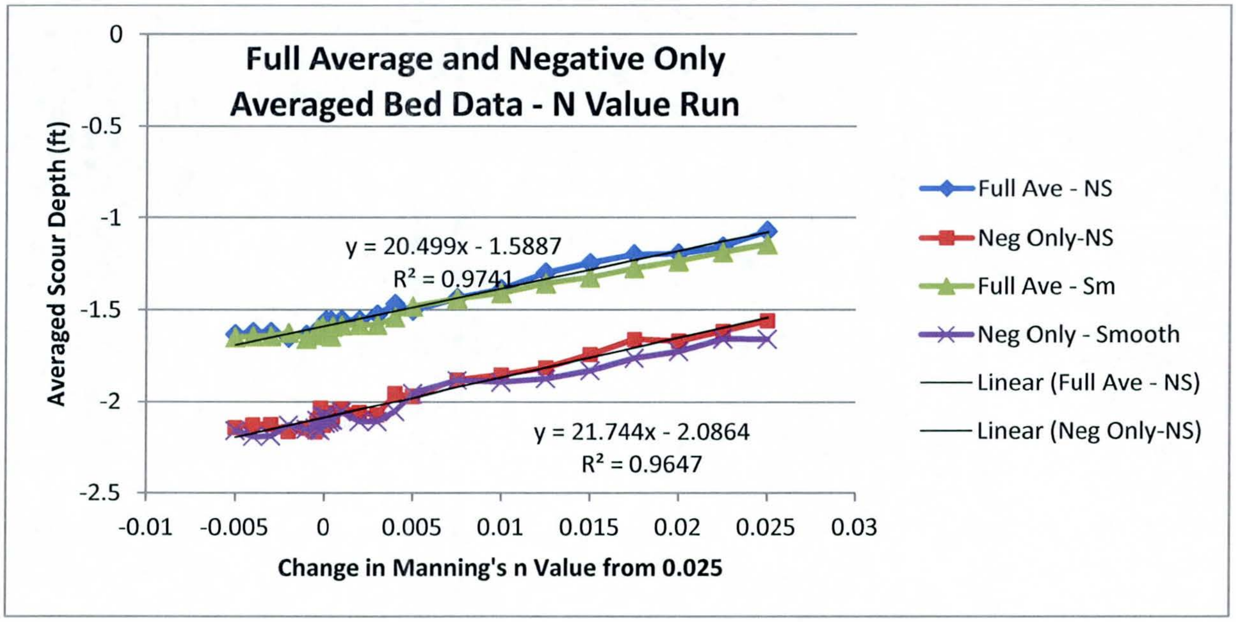


Figure 8. Averaged Bed Elevation Data for N value Sensitivity for Full Model with all Data and only the Scour Values with and without Bed Smoothing.

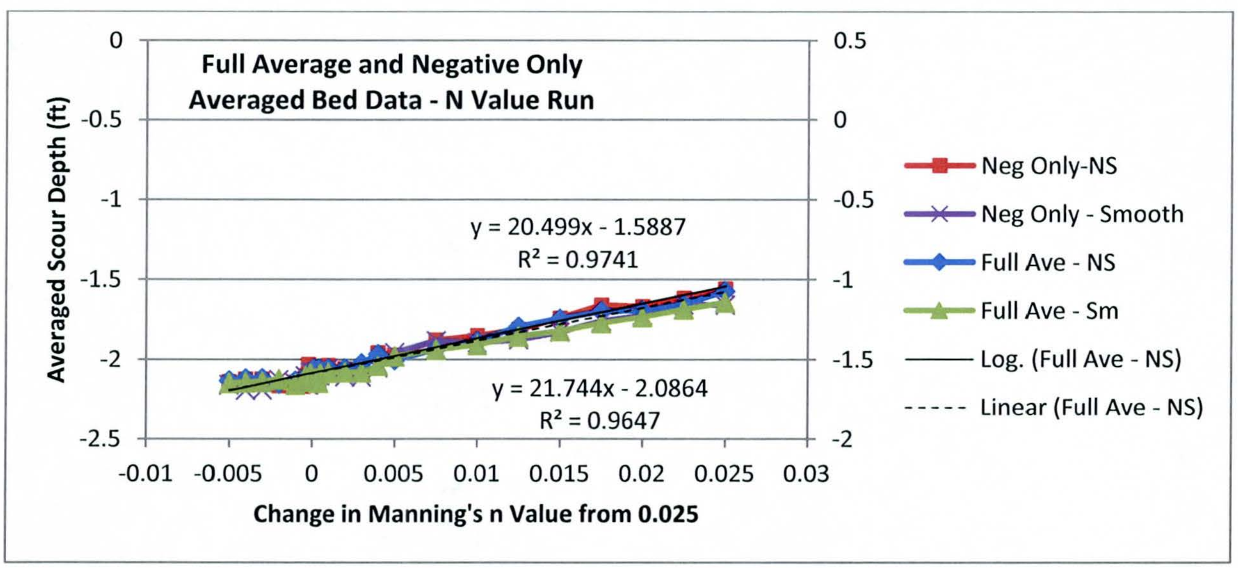


Figure 9. Averaged Bed Data for Manning's n Values showing all Data and Only the Negative Data on a Separate Axis.

Table 4. Data for Full Model Average and Negative Only Average for Manning's n Value Sensitivity.

Averaged Maximum Scour Depths from Original Bed Elevation in Feet							
Change in Manning's n Value 0.025 base	Bed Smoothing Off (NS)			Smoothed Bed (Sm)			
	Full Average	Negative Only	Delta		Full Average	Negative Only	Delta
-0.05	-1.63534	-2.14195	-0.5066	-0.05	-1.6497	-2.16075	-0.51105
-0.04	-1.62316	-2.12598	-0.50283	-0.04	-1.64462	-2.19291	-0.54829
-0.03	-1.62187	-2.1243	-0.50243	-0.03	-1.64336	-2.19123	-0.54787
-0.02	-1.65245	-2.16435	-0.5119	-0.02	-1.62576	-2.12939	-0.50363
-0.01	-1.63801	-2.14543	-0.50742	-0.01	-1.65813	-2.15274	-0.4946
-0.005	-1.64014	-2.1674	-0.52726	-0.005	-1.63777	-2.14511	-0.50735
-0.004	-1.61615	-2.1168	-0.50065	-0.004	-1.60674	-2.10448	-0.49774
-0.003	-1.60438	-2.10138	-0.497	-0.003	-1.63187	-2.15648	-0.5246
-0.002	-1.5925	-2.03187	-0.43938	-0.002	-1.63545	-2.16121	-0.52575
-0.001	-1.60605	-2.12235	-0.5163	-0.001	-1.59045	-2.08314	-0.49269
0 =0.025	-1.64069	-2.1301	-0.4894	0	-1.61829	-2.08274	-0.46445
0.001	-1.56009	-2.06162	-0.50153	0.001	-1.63244	-2.11937	-0.48694
0.002	-1.60169	-2.09786	-0.49617	0.002	-1.6195	-2.0843	-0.4648
0.003	-1.60785	-2.10592	-0.49808	0.003	-1.62686	-2.11214	-0.48527
0.004	-1.55985	-2.06131	-0.50145	0.004	-1.64583	-2.09992	-0.45409
0.005	-1.59222	-2.08546	-0.49324	0.005	-1.59131	-2.10288	-0.51156
0.01	-1.55564	-2.03755	-0.48191	0.01	-1.58464	-2.05732	-0.47268
0.02	-1.55759	-2.05831	-0.50072	0.02	-1.58266	-2.11029	-0.52762
0.03	-1.52654	-2.0728	-0.54626	0.03	-1.58278	-2.11044	-0.52766
0.04	-1.46879	-1.95846	-0.48967	0.04	-1.54198	-2.05604	-0.51406
0.05	-1.5055	-1.97187	-0.46637	0.05	-1.48232	-1.95885	-0.47653
0.075	-1.43635	-1.88131	-0.44495	0.075	-1.43987	-1.88591	-0.44604
0.1	-1.38947	-1.85269	-0.46322	0.1	-1.40974	-1.89681	-0.48706
0.125	-1.2994	-1.81432	-0.51492	0.125	-1.35721	-1.87733	-0.52012
0.15	-1.24762	-1.74202	-0.4944	0.15	-1.32462	-1.83225	-0.50763
0.175	-1.20001	-1.65989	-0.45988	0.175	-1.27509	-1.76374	-0.48865
0.2	-1.19556	-1.66933	-0.47377	0.2	-1.23686	-1.727	-0.49014
0.225	-1.15761	-1.61635	-0.45874	0.225	-1.1885	-1.65947	-0.47097
0.25	-1.0743	-1.55885	-0.48455	0.25	-1.14472	-1.66102	-0.51631
Average	-1.49679	-1.98889	-0.4921	Average	-1.52445	-2.02328	-0.49883
Min	-1.0743	-1.55885	-0.43938	Min	-1.14472	-1.65947	-0.44604
Max	-1.65245	-2.1674	-0.54626	Max	-1.65813	-2.19291	-0.54829
Range	0.578149	0.608544	0.106883	Range	0.513416	0.533438	0.102247

Full Data

$$y = 20.499x - 1.5887 \qquad R^2 = 0.9741 \qquad \frac{dy}{dx} = 20.50 \qquad (4)$$

Negative Date Only

$$y = 21.744x - 2.0864 \qquad R^2 = 0.9647 \qquad \frac{dy}{dx} = 21.74 \qquad (5)$$

4.2.3 Headcut Data for N Value Runs

The data for the headcut modeling shows that the averaged minimum thalweg elevation change and average scour depths results are erratic for the entire range of n values used. This can be observed in Figure 10. The difference between runs with the $SMOOTH card on and off are also shown in the figure. The scatter for the headcut reach is much greater than the full model data which is somewhat unstable for values below about 0.030 (change of +0.005). The scatter, while not extremely large, is significant but none of the data shows a trend towards decreasing or increasing elevations or depths for the range modeled. The headcut data is based on data from cross section 15.67 to cross section 16.07.

It is suspected that the erratic behavior found in the headcut modeling is because the model hydraulic calculations are defaulting to critical depth for various cross sections and, depending on which cross section defaults, the results vary. The model, however; produces the same results for runs with identical inputs so the model is not unstable in the traditional sense. The impact of this erratic behavior, while problematic on the charts shown in Figure 10 does not greatly impact model results as can be seen in Figure 11. The maximum variation is on the order of 2 ft or less at one or two cross sections and all of the runs give a good estimate of the headcut formed by the 2010 flood event (labeled Observed in the Figure).

The minimum bed elevation data show about the same amount of variation as the scour depth data. Neither data set shows any trend towards a lower or higher bed due to the changes in the Manning's n value. The averaged change in the minimum headcut bed elevations within the calculated headcut appears to be insensitive to the Manning's n value used.

4.2.3 Headcut Length and Maximum Depth

The length of the headcut did not vary from a length of 2112 ft when changes were made to the Manning's n value for the channel with the exception of a single run with bed smoothing turned off (Table 3) where the length was 3960 ft. The length of the predicted headcut is significantly shorter (2112 ft) than the observed headcut length of approximately 5,100 ft. The headcut depth and length data are shown in Table 2 for the model with smoothing turned on and Table 3 for smoothing turned off. The maximum depth varied slightly but no pattern was evident and no relationship between n value and the maximum depth of the headcut could be determined (see Figure 12 and Figure 13). Based on this data it appears that the maximum depth of the headcut (Figure 12) and averaged change in headcut depth (Figure 13) are not dependent on the n value used in the channel.

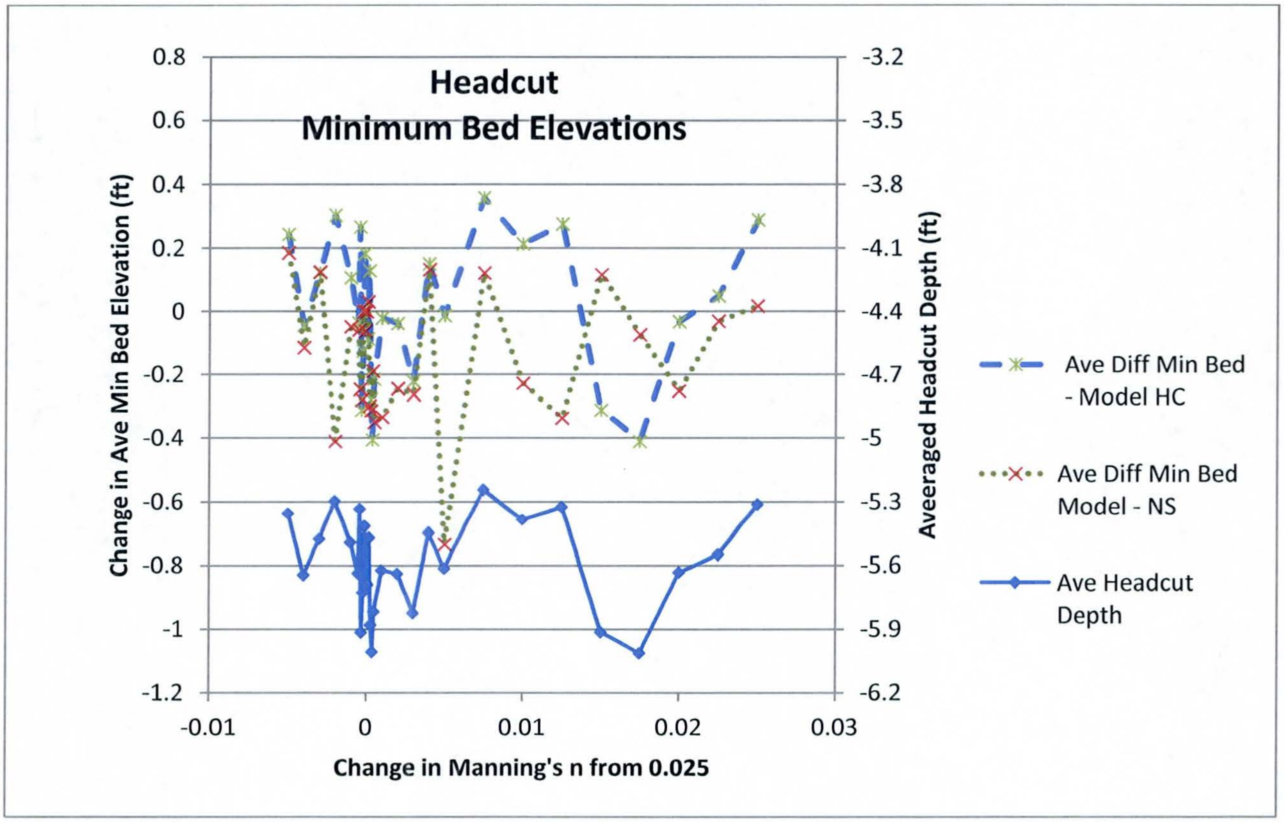


Figure 10. Averaged Elevation Change for Average Bed Elevation Data (above) and Minimum Bed Elevation for Modeled Headcut (below). Lower figure shows impact of the $SMOOTH option on results.

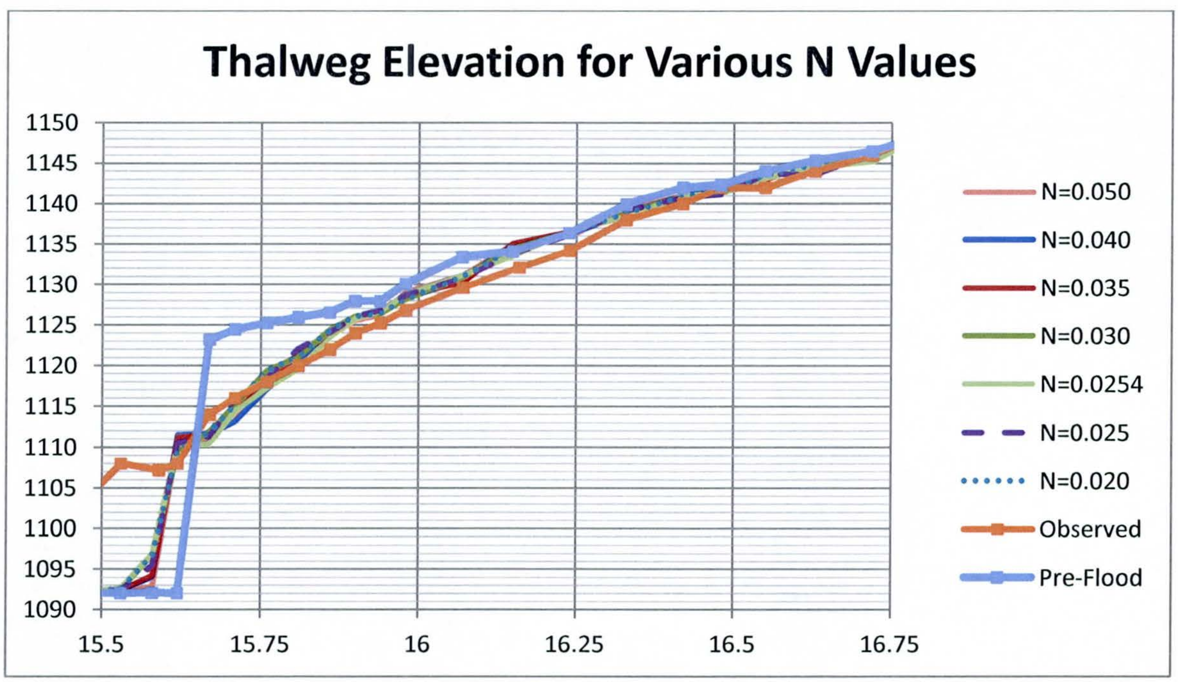


Figure 11. Thalweg Elevations for HEC-6T at the Pioneer Pit Headcut for Various Manning's N Values.

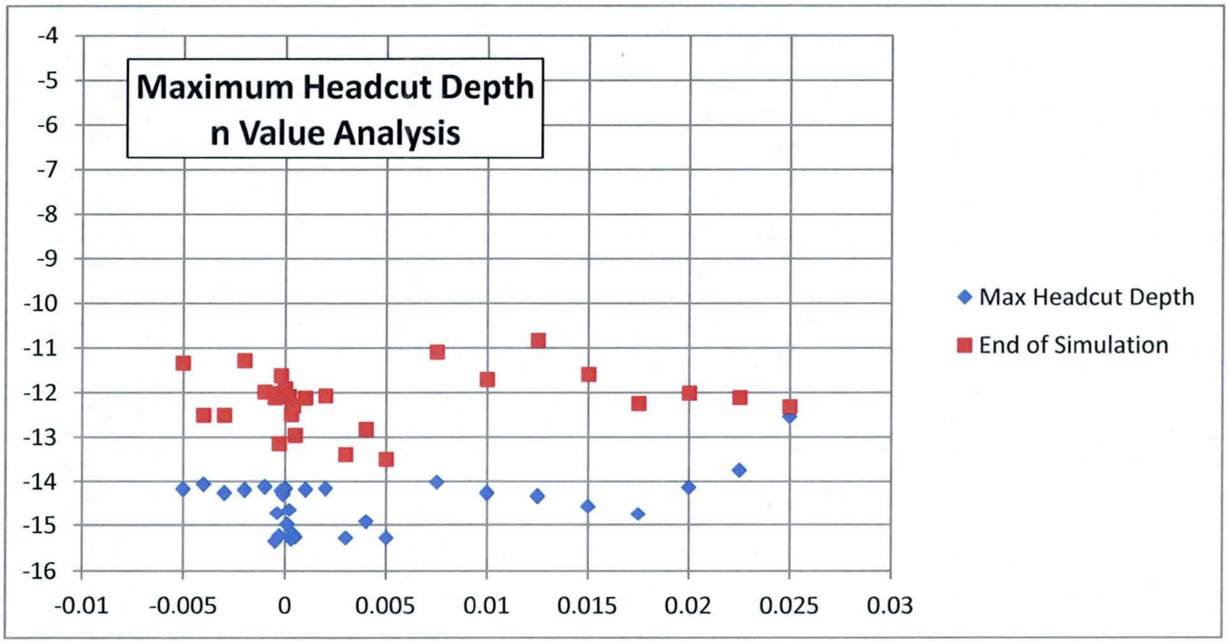


Figure 12. Maximum Headcut Depths for End of Run and Minimum Bed Elevation Data.

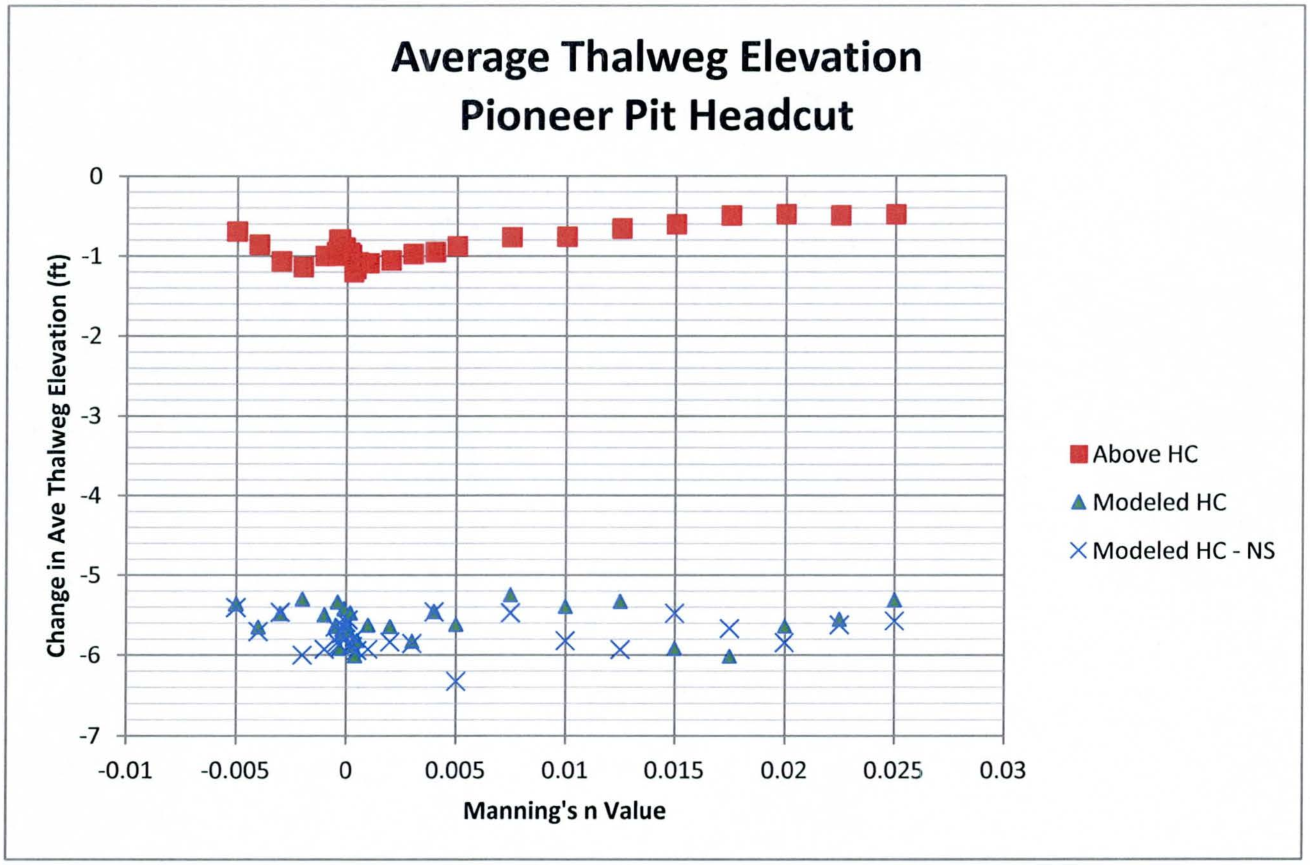


Figure 13. Averaged Thalweg Elevation Change for Upper (Observed) Headcut and Lower (Modeled) Headcut.

An additional approach was taken to view the average headcut depth for the calculated headcut length (2112 ft). The bed change data for the area immediately above the headcut (Xsect 16.15 to 16.72 or upper headcut reach) was averaged in addition to the modeled headcut length (Xsect 15.67 to 16.07) for both the smoothed and non-smoothed bed runs. This data is shown in Figure 13. It can be seen that the averaged headcut depths (average of original model thalweg minus minimum thalweg) varies but no trend is evident in the data and this trend is similar both above the headcut as well as within the modeled headcut. The difference between the maximum and minimum values for the average thalweg data is given in Table 5. It can be noted that the range increases slightly with bed smoothing turned off but the range is similar for all of the conditions run. It is also apparent from Figure 13 and Table 5 that the values are not especially dependent on Manning's n value.

Table 5. Average Minimum Thalweg Data for Pioneer Headcut showing Range of Values.

Description	Deepest Average	Shallowest Average	Maximum Difference
Area Above HC	-1.20	-0.48	-0.72
HC – Smoothing On	-6.01	-5.24	-0.77
HC – No Smoothing	-6.33	-5.41	-0.92

4.2.3 N Value Sensitivity Results

Full Model Results. The HEC-6T model of the Hassayampa indicates that equation for the best fit line for the **ending thalweg** elevation (neglecting the values very close to 0.025) is:

$$y = 145.45x^2 + 7.8612x - 0.0006 \qquad R^2 = 0.9709 \qquad (6)$$

The equation for the rate of change of the **ending thalweg** with respect to the change in Manning's n is:

$$\frac{dy}{dx} = 290.9x + 7.8612 \qquad (7)$$

The equation for the change in the **averaged maximum scour depth** due to changes in the Manning's n value can be estimated by an equation for the entire model length as:

$$y = 21.744x - 2.0864 \qquad R^2 = 0.9647 \qquad (5)$$

and the rate of change of the change in **averaged maximum scour depth** with respect to the change in Manning's n is:

$$\frac{dy}{dx} = 21.74 \qquad (5)$$

where:

y = the change in averaged minimum bed elevation and

x = the change in Manning' n from 0.025 (between -0.005 to +0.025)

The rate of change in the averaged maximum scour depth for the model reach is 21.74 ft per unit change in Manning's n value over the range evaluated (0.020 to 0.050). This data ignores the values between 0.0245 and 0.0255

The headcut reach did not produce consistent enough data so as to lend the data to accurate analysis. There does not appear to be any discernible trend towards changes in the averaged minimum bed elevations for changes in Manning's n values. The uncertainty (range of the data) for the headcut reach was about 1.2 ft. This is likely due to the model defaulting to critical depth in the headcut calculations.

4.3 Additional Investigation of Channel Flow Rates

The sensitivity to the water flow in the channel was scoped to include the FEMA uncertainty for the 2010 event based on a flow rate of approximately 11,634 cfs coming into the Pioneer pit. This is something less than a 10 year event at the I-10 gage. During an investigation to determine the impacts of overbank n values in the models developed in the earlier study (R_2D 2011) it was found (during this study) that the 11,634 cfs observed at the I-10 gage did not fit within the 2006 channel upstream of the Pioneer Pit nor in the 2010 post flood topography upstream from the Pioneer Pit. This raised serious concerns regarding the flows used in the previous study even though they were based on the observed flow rate in the lower reach of the model. Extensive review was performed in the earlier study to determine if the flow used was accurate but the analysis was focused on the values at the downstream gages where data was more readily available to estimate flows.

4.3.1 Investigation of Channel Flow based on I-10 Gage Data

Since the flow was not contained within the aerial limits of the 2010 event in the model based on the 2006 topography (WEST/Fuller model) an HEC-RAS model was developed based on the 2010 topography obtained by the District. A review of the flow observed at the I-10 gage when applied to a newly developed Hassayampa River model using the 2010 topography clearly indicated that there was a problem with using the flow rate observed at the I-10 gage in the upper portion of the model (above the Pioneer pit). This finding led to an additional review of the flow data for the model and the gage information as described below.

Since Jackrabbit Wash enters the Hassayampa River in the immediate vicinity of the Pioneer pit it was expected that a change in flow rate in the main stem occurred during the 2010 event. Given the lag between Jackrabbit Wash and the Hassayampa River, the Jackrabbit flow was ignored since it was expected that the larger flow from the Hassayampa River (something on the order of 10,000 cfs) would more than make up for the inflow from Jackrabbit wash. It was also observed that the flow from Jackrabbit wash entered the Hassayampa River at the downstream end of the Pioneer pit. From the aerial photos and from site visits after the flood it did not appear that the 2010 flood on Jackrabbit wash had entered the Pioneer pit to any significant degree. If any deposition occurred from the Jackrabbit flow it would have been at the very downstream end of the pit. Since the flow of 11,634 cfs at I-10 was significantly larger than the observed flow of 4,570 cfs in Jackrabbit Wash it was expected that the main stem flow would account for any flows from Jackrabbit wash.

The investigation using the model based on the 2010 post flood topography also revealed that the 11,634 cfs flow could not be contained in the 2010 observed channel immediately downstream of the CEMEX pit. This indicated that the I-10 gage reading was too high for the channel upstream from the Hanson pit. The maximum capacity for the river channel immediately below the CEMEX pit is something less than 4,000 cfs based on an HEC-RAS model using the 2010 post flood topography. This is in line with the maximum observed flow on Jackrabbit wash of 4,570 cfs assuming some attenuation occurred while flow was passing across the alluvial fan at the mouth of the wash, down the main channel of the Hassayampa and through the CEMEX pit.

Further analysis indicated that upstream of the Pioneer pit the maximum channel flow rate was on the order of 2-3,000 cfs rather than the 11,634 cfs observed at the I-10 gage. This discovery created a dilemma since both the gage observations and two dimensional modeling of the gage site based on high water marks indicate that the flow at I-10 was on the order of 11-12,000 cfs. The question of where the extra water came from thus became important to current modeling efforts.

Based on the available data and observations by District personnel it was originally (during the previous study) thought that the CEMEX pit had breached its downstream sill and produced a surge. A review of the historical aerial photos indicated that flow was exiting the pit at the current location after the 2005 event and that no apparent large new breach of the downstream sill occurred. The downstream pit brink was lowered significantly in the 2010 event but did not appear to have failed suddenly. The occurrence of a surge was then discounted and not investigated further. The new data developed as a part of this study showing the limited capacity of the channel downstream from the CEMEX pit (approx. 4,000 cfs) further supports the conclusion that no surge occurred at this location since the channel cannot convey a flow similar to that observed at the I-10 gage. The lack of capacity below the CEMEX pit turned attention to the Hanson pit. The Hanson pit is the most downstream pit of the three pits being modeled.

The aerial photos of the Hanson pit revealed that the property had been mined extensively to the east of the existing channel to a depth below the 2006 river channel. A careful review of the 2009-10 photos shows no channel connecting this eastern pit lobe with the river downstream - rather the pre-existent channel bypasses the pit to the west. The 2010 aerial photos, however; show that the downstream wall of this eastern pit lobe has breached and the topography shows the new channel through the pit that is lower than the former channel to the west. It is now postulated that the downstream pit wall of the eastern lobe was overtopped during the 2010 event – likely during the peak from Jackrabbit Wash - and breached catastrophically causing a much larger peak downstream of the pit than was flowing into the pit. This higher flow (estimated to be almost three times the inflow based on channel capacities) occurred for a very limited time while the pit was draining. Once the pit had drained the flow continued through the pit and the breach leaving the original channel to the west perched slightly above the new (eastern) river channel. This is consistent with a vague general feeling present at the I-10 gage site during initial field visits that the flow patterns and debris were more consistent with an outwash event than with the pattern of a normal river flood event.

The breach of the Hanson pit would also explain why peak flows at the old US 80 bridge near Arlington were only on the order of 5,880 (measured by USGS) rather than something more similar to the 11,634 measured at the I-10 gage. The higher peak from the Hanson pit breach would have been relatively short and without a large enough volume to sustain the high flows for the 8+ miles to the Arlington gage. It does appear that the breach did impact flows downstream at the Arlington gage since the flow upstream from the Hanson pit is now estimated to be on the order of 4,000 cfs and no other significant inflow sources were noted between I-10 and the Arlington gage for the 2010 event.

4.3.2 Conclusion. Based on the modeling and field data it would thus appear that flows below the Hanson pit were on the order of 11,600 cfs as measured at the I-10 gage, flows between the CEMEX and Hanson pit in the 4,000 cfs range and flows above the Pioneer pit in the 2-3,000 cfs range.

4.4 Modeling of Flow Sensitivity

Based on the investigation into flow rates described above the lower limit of flow to be tested under this task was reduced from the lower limit of the expected values (4,700 cfs) to 3,000 cfs. The 100 year flood at the I-10 gage from the original FIS study shows the flow to be 75,164 cfs. Values for the other floods were obtained from the FIS study and are shown in Table 6. The range of values used in the sensitivity analysis to determine the impact of flow errors ranges from 3,000 cfs to 15,000 cfs. Flows larger than 15,000 cfs were not used since the model was initially set to prevent flows on the overbank. Significant changes to the model geometry and input parameters would have been necessary to model flows in excess of 15,000 cfs. These modifications were later performed to the model but since indications are that the flow being modeled was at the low end of the modeled flow range it was decided that extending the range to higher flows would not be advantageous to the current study. The use of the higher flows would have likely required rerunning some of the previous work to gage the impact of the changes on work completed in the previous study.

Additionally if the peak flow was estimated to be similar to the 4,500 cfs peak from Jackrabbit wash based on the channel capacity and the upstream and downstream of the CEMEX pit the peak at the I-10 gage would have been less than a 5 year event and the 90% upper limit (which can be estimated from Table 6) would have been in the 15-20,000 cfs range. The 15,000 cfs upper limit was thus taken to be reasonable based on the available data.

Table 6. Flow Values for the I-10 Hassayampa River Gage.

Return Period	2 Year	2.8 Yr 2010	3.4 Yr	5 Year	2010 Meas.	10 Year	20 Year	50 Year	100 Year
90% Upper Limit	9,700	15,535	19,420	31,100	44,200	58,300	124,400	198,200	288,000
Expected Value	2,500	4,000	5,000	8,000	11,364	15,000	32,000	51,000	74,100
10% Lower Limit	1,035	1,655	2,070	3,310	4,700	6,210	13,250	21,100	30,700

The Manning's n value for the channel in the flow analysis and later efforts was set to 0.030 to avoid problems with instabilities near an n value of 0.025 that were noticed in the n value tests described earlier in this report.

The various flows used in this modeling were scaled from the 2010 event as observed at the I-10 gage for simplicity. The use of the I-10 data as the basis for the various tests does introduce some errors as discussed above but no other data was available that would provide a better set of data for the tests.

After initial runs were performed to determine the impact of the range of values used, the blocked areas from the previous studies were removed for most areas. Exceptions were the Hanson off-channel pit and a section of the Hanson pit on the east bank that is included in cross section 12.3 that does not have flow under any condition modeled in this exercise. The ineffective areas in HEC-6T originally specified an elevation several feet above the over bank using ELLEA and ELREA on the X3 card. Ineffective areas were removed for most of the areas in the model or, if not removed, lowered to represent normal flow conditions rather than the 2010 channel constraints which were determined to be too narrow for flows above perhaps 3 - 5,000 cfs. The files with the modified cross sections to remove the channel constraints are indicated as NC for non-constrained channel (i.e. Hass2010-NCxxk.t5).

The constraints for cross section 16.24 were removed with some raising of dry low flow channels, 16.33 and 16.42 were left blocked (i.e. low flow areas commented out) since the low flow areas were very large in comparison to the active channel. Low off-channel areas in cross sections 16.07 and 16.15 were raised (i.e. low elevations commented out) to keep flow in main channel for the lower flows. Overbank areas with elevations lower than the main channel were moved in one space in the HEC-6T input (.t5) files to comment out the points. The bed sediment reservoir for section 12.6 was lowered from 25 ft to 30 ft for 6,000 cfs or larger flows for the non-constrained case due to warnings about the active bed layer being greater than the bed sediment reservoir. The bed sediment reservoir depth was increased to 32 ft for cross section 15.67 for the non-constrained case with smoothing turned off to avoid warnings regarding the active bed layer depth. (The sensitivity to changes in the depth of the bed sediment reservoir will be discussed later.) Cross Section 18.35 was blocked for non-channel areas below approx. elevation 1184. The channel erosion limits were not adjusted from the 2010 event channel limits used in the previous study (R_2D 2011).

4.4.1 Averaged maximum scour Depth for Varying Flow Rates

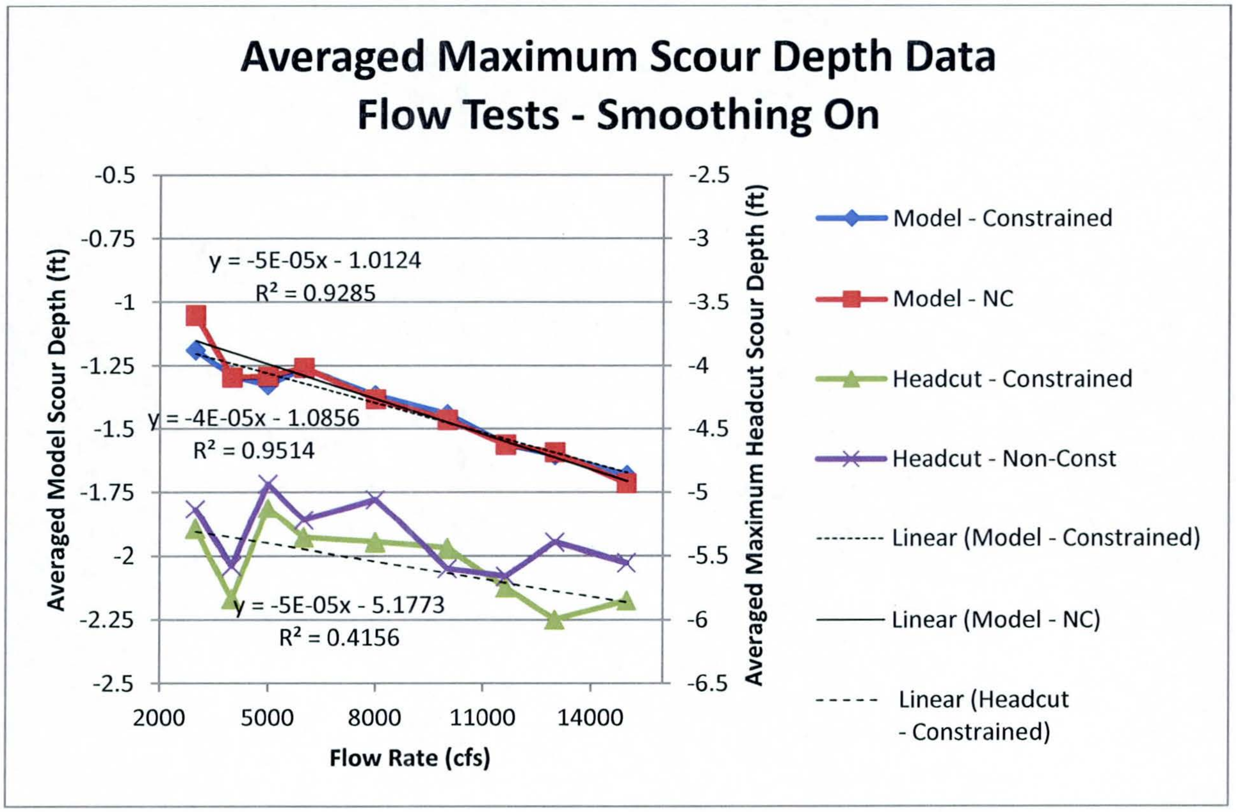
The HEC-6T model shows a relatively smooth response to changes in the flow rates with the averaged maximum scour depth increasing slightly as flow increased. There was still some variation but the relationships were much better defined than the results for n values tests. The averaged maximum scour depth varied as shown in Figure 14. The figure shows results for both the constrained (i.e. all flow confined to the observed 2010 channel - approximately between the bank stations) and unconstrained models with bed smoothing on (upper figure) and bed smoothing off (lower figure). It can be seen that there is a difference in the headcut values with smoothing on and off but only a very slight change in the averaged model scour depths between the smoothed and non-smoothed conditions. All of the runs show a general trend that the averaged maximum scour depth increases slightly with increasing flow rates. The change in the headcut values is not smooth but does still show an increasing scour depth with increasing flow rate.

The averaged maximum scour depth in the non-constrained model for the full model is fairly accurately represented by the upper equation shown in Figure 14. The line is also a good fit for the change in the averaged maximum scour depth for the non-constrained case and the difference between the lines for the constrained and unconstrained runs are not that great with bed smoothing on or off. Again the full model results do not include the first (upstream) six cross sections where the sediment is adjusting to the inflowing load.

The full model averaged maximum scour depth data based on the minimum bed elevation are all plotted together in Figure 15 for easier reference. It can be noted that the scour data is very close and that the constrained channel and smoothing do not have large impacts on the full model results. The data from the four runs are shown include with and without channel constraints (C and NC) and smoothing on (SM) and off (NS). The data all show a slight trend towards decreasing averaged maximum scour depth with increasing flows. The variation between the full model averaged maximum scour depth for the condition with smoothing on and off is about 0.1 ft with more scour indicated for the case with smoothing turned off than for the models with smoothing turned on.

The data using only the negative values is shown in Figure 16. It can be seen that these data, while lower due to the elimination of fill data, show an identical slope but have a lower R^2 value than for the full data set. The plots of the two data sets were adjusted to overlay on another and are plotted in Figure 17. It can be noted that the data sets overlay very well with the no smoothing cases for the constrained channel case being slightly lower than the other data. The slopes are identical between the two plots.

The decrease in the averaged maximum scour depths is primarily due to changes in the headcut and tailcut reaches for the 3 pits in the model. This can be seen in Figure 18 which shows the data for the modeled reach for the runs with an unconstrained channel and smoothing turned off. It can be seen that while some minor differences may occur away from the pits, the vast majority of the differences occur near the various pits.



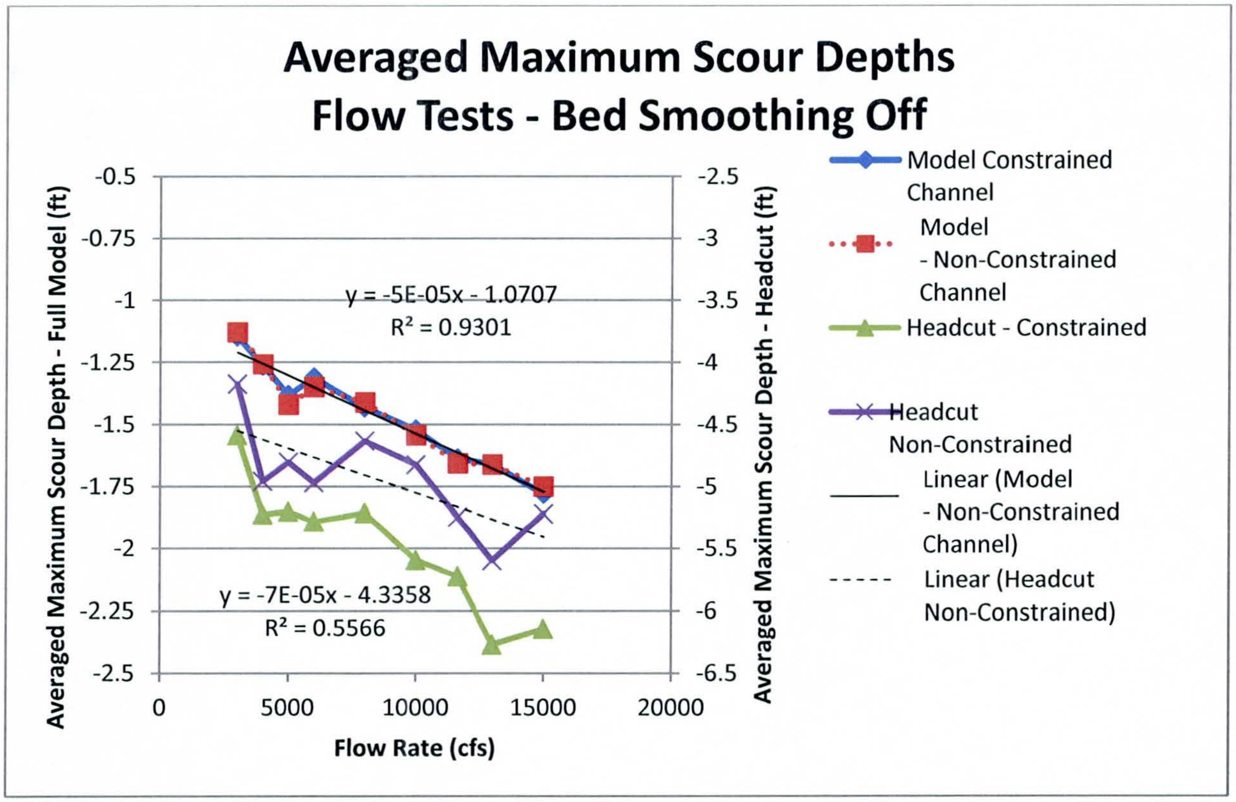


Figure 14. Averaged maximum scour Depths for Full Hassayampa River HEC-6T Model and for the Pioneer Pit Headcut. Upper Plot is with $SMOOTH Card set to 10 and Lower Plot is with $SMOOTH Card set to Disable Bed Smoothing.

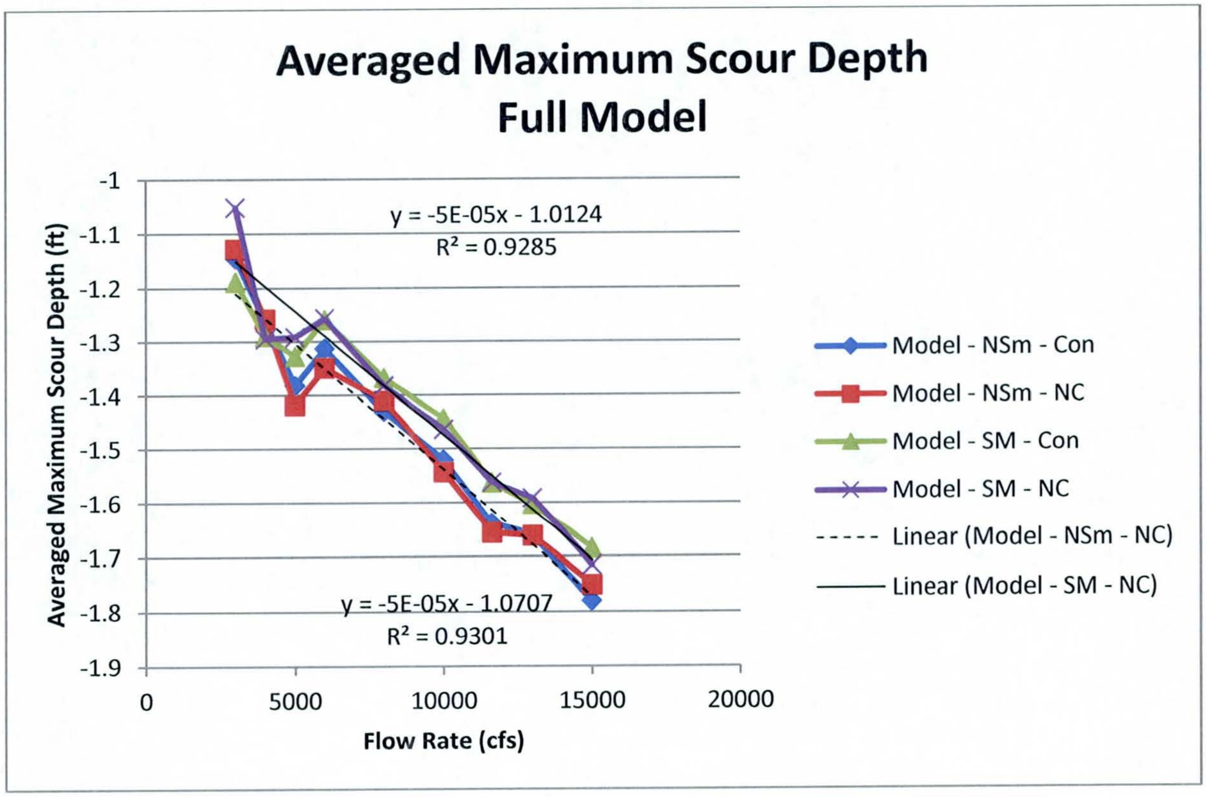


Figure 15. Averaged Maximum Scour Depth Based on Minimum Bed Elevation for Various Flow Rates. Best Fit Lines are based on Model with Unconstrained Channel.

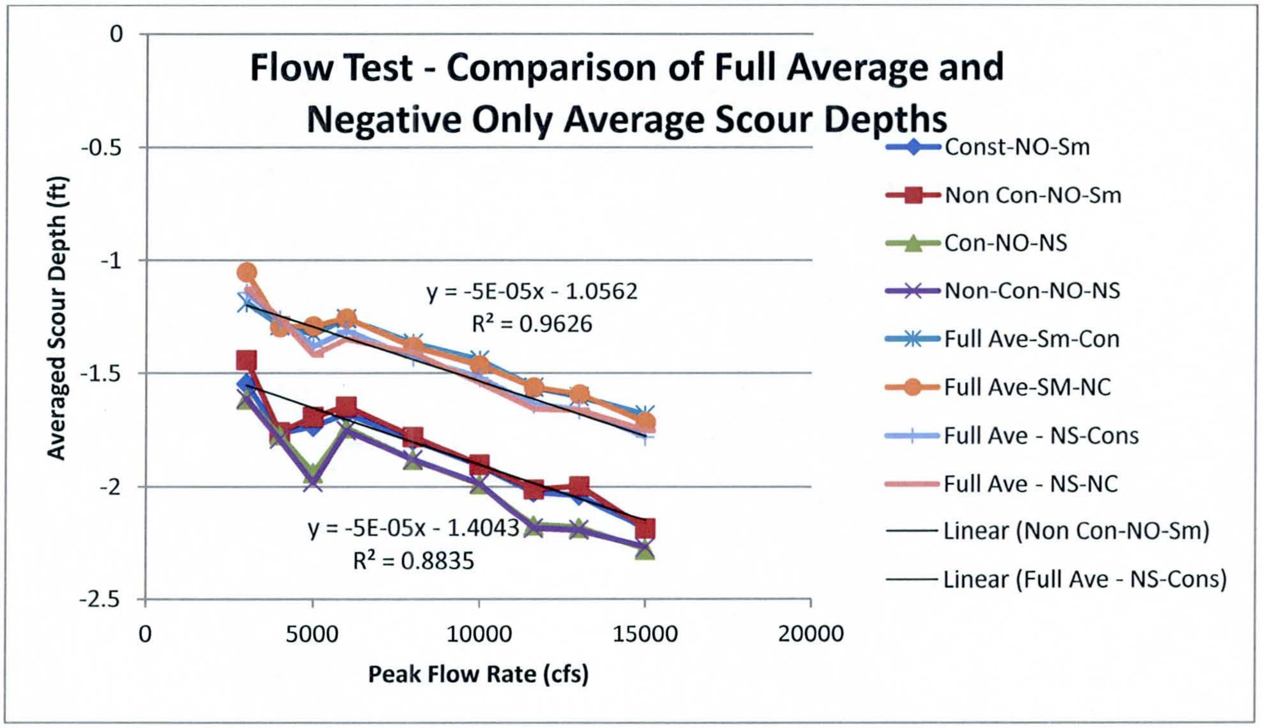


Figure 16. Comparison of Maximum Scour Depths for Full Average Data and only Negative Values all cases. (NO = Neg. Only)

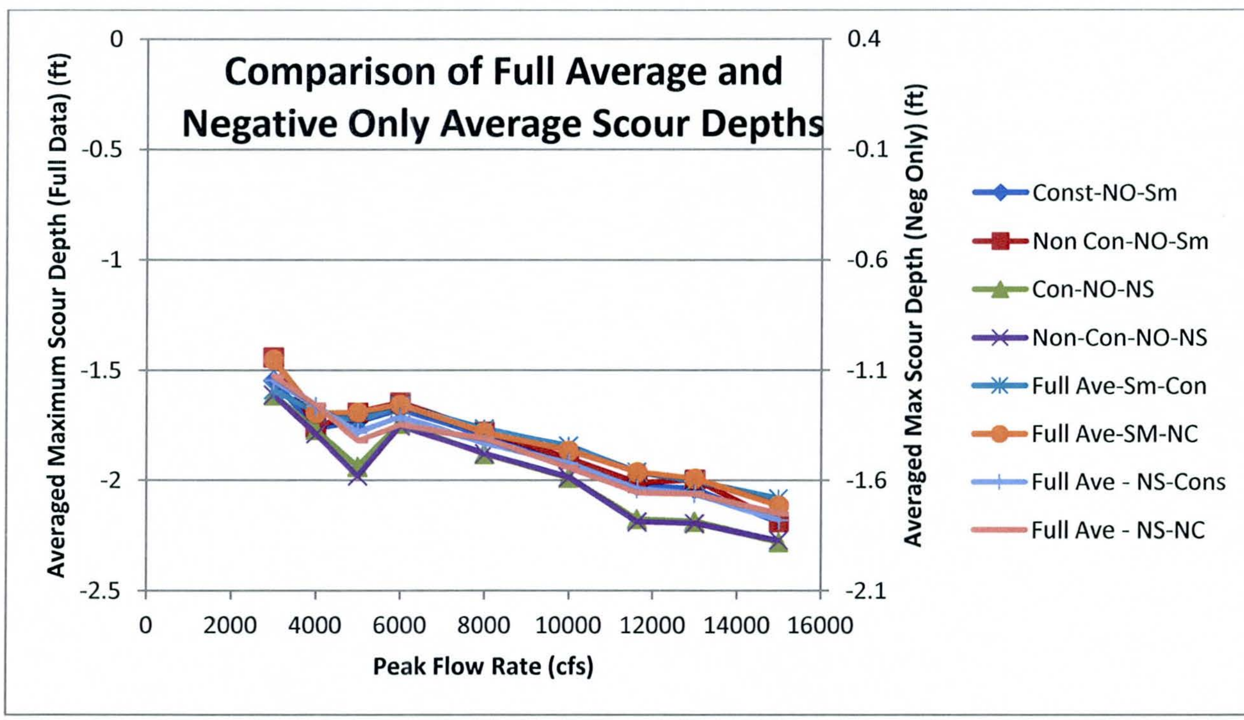
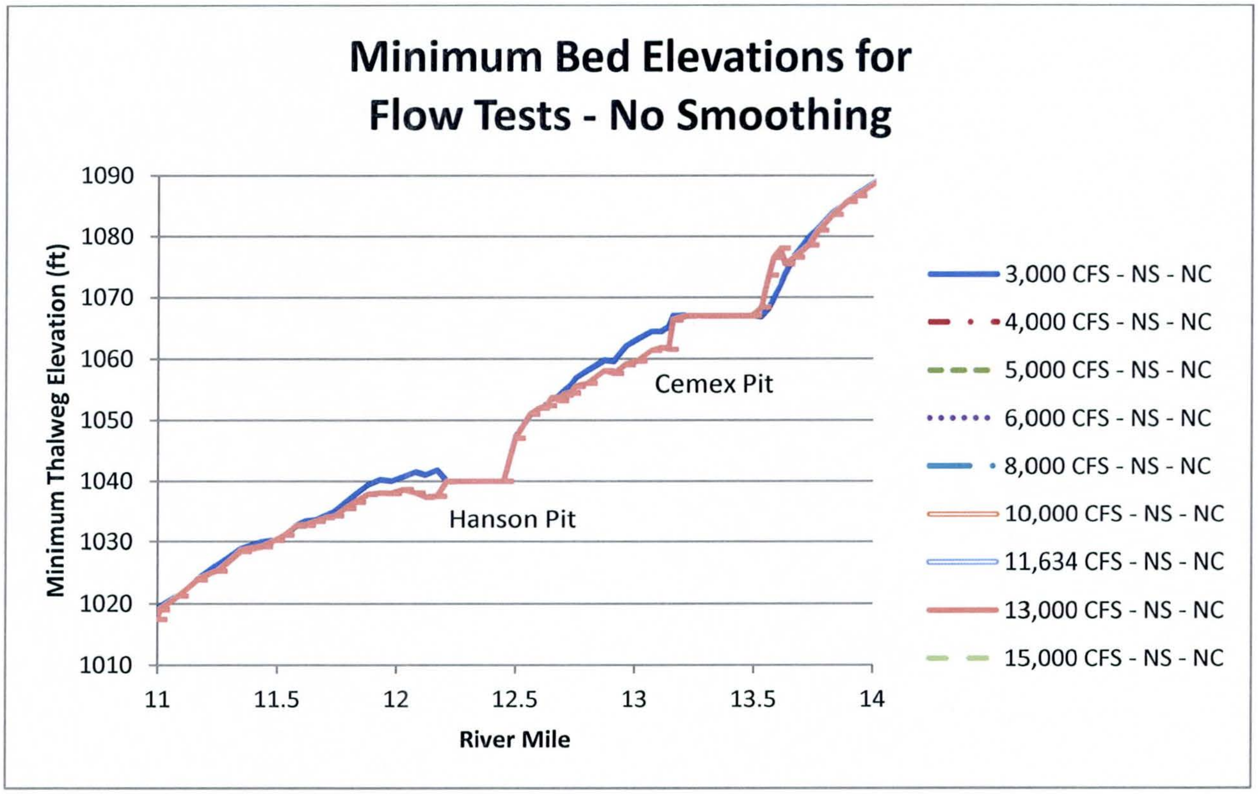


Figure 17. Negative Only Data Overlaid on Full Data Set for Comparison.



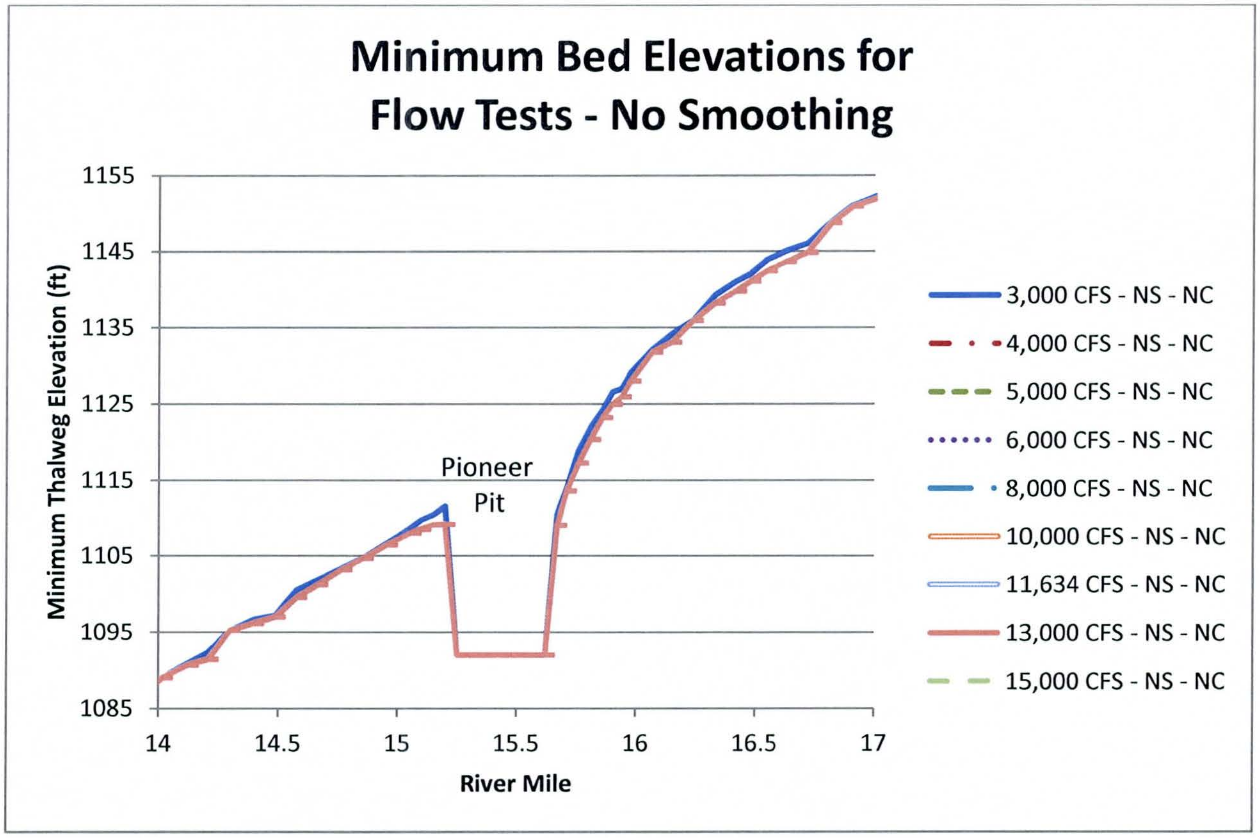


Figure 18. Minimum Bed Elevations for Flow Tests with Bed Smoothing ($SMOOTH Card) turned off.

The averaged maximum scour depth data used for the plots in this section are shown in Table 7.

Table 7. Averaged Thalweg Change Data for Flow Tests. Headcut Lengths are based on Distance to 1st Cross Section with less than 1.0 ft scour depth.

No Bed Smoothing (NS)								
	Constrained				Non-constrained (NC)			
	Ave Scour Depth		Headcut Length		Ave Scour Depth		Headcut Length	
Flow Rate	Full Model	Headcut	Upstrm Sect	Distance	Full Model	Headcut	Upstrm Sect	Distance
3000	-1.146	-4.58687	15.94	1426	-1.12806	-4.17568	15.94	1426
4000	-1.26348	-5.22832	16.15	2534	-1.25743	-4.95798	16.24	3010
5000	-1.38284	-5.20391	16.15	2534	-1.41891	-4.80353	16.24	3010
6000	-1.31337	-5.2858	15.98	1637	-1.3486	-4.9695	16.24	3010
8000	-1.4313	-5.21594	15.98	1637	-1.41019	-4.63374	15.98	1637
10000	-1.52134	-5.596	16.24	3010	-1.54297	-4.82572	16.24	3010
11634	-1.63875	-5.72631	16.24	3010	-1.65606	-5.25023	16.24	3010
13000	-1.6614	-6.27327	16.33	3385	-1.66189	-5.60207	16.24	3010
15000	-1.78082	-6.14679	16.24	3010	-1.75079	-5.22312	16.24	3010
Bed Smoothing On								
	Constrained				Non-Constrained (NC)			
	Aver Scour Depth		Headcut Length		Ave Scour Depth		Headcut Length	
Flow	Full Model	Headcut	Upstrm Sect	Dist (ft)	Full Model	Headcut	Upstrm Sect	Dist (ft)
3000	-1.18934	-5.29266	15.94	1426	-1.05171	-5.13603	15.94	1426
4000	-1.29066	-5.83431	15.94	1426	-1.29528	-5.57952	15.94	1426
5000	-1.32805	-5.1308	15.94	1426	-1.29171	-4.93561	15.94	1426
6000	-1.25939	-5.36071	15.94	1426	-1.25674	-5.22337	16.15	2534
8000	-1.36789	-5.39533	15.98	1637	-1.38213	-5.05985	15.94	1426
10000	-1.4433	-5.44271	15.98	1637	-1.46429	-5.59951	16.15	2534
11634	-1.56277	-5.74556	15.98	2534	-1.56237	-5.65874	16.15	2534
13000	-1.60394	-5.99857	16.15	2534	-1.59179	-5.3988	16.15	2534
15000	-1.68426	-5.84631	16.15	2534	-1.71501	-5.5567	16.24	3010

4.4.2 Actual Headcut Length, Depth, and Cross Section

The headcut length and maximum depths were also collected from the HEC-6T model and are tabulated in Table 7. The headcut length obtained from the model is the length from the edge of the pit to first cross section where the model predicts less than 1.0 ft of maximum scour depth during the simulation.

The averaged maximum headcut scour depths for the models with the $SMOOTH card turned on and off (commented out) for the various flow rates tested are shown in Figure 18. The data show a significantly greater variation in the data for the headcut than for the full model but the slope of the data (dy/dx) are similar between the data sets. The data with a constrained channel and no smoothing show significantly great scour depths for all of the flow rates. None of the headcut data is smooth – likely due to instabilities in the model near or below critical depth. The model results are again repeatable when using identical input values.

The headcut depths, profiles, and cross sections for the predicted (modeled) and the observed data were also examined to see how they compared. The thalweg data can be seen in Figure 19. The data show that thalweg results are similar for all of the flow rates used. The thalweg data is all contained within a band with approximately a 2.0 ft depth variation. The only location where the variation exceeds 2 ft is at the brink of the pit. This similarity also appeared to be true for the tailcut from the pit.

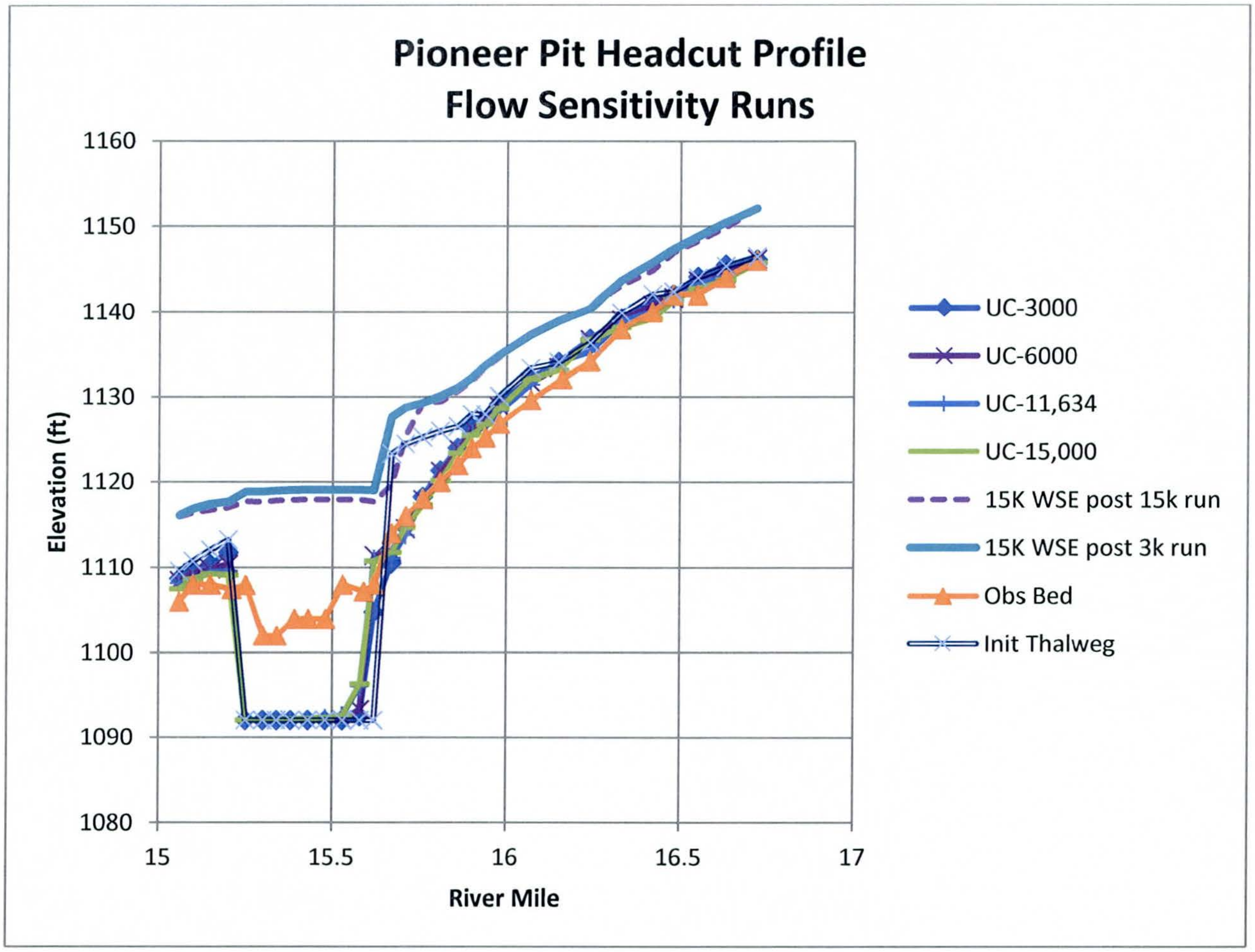
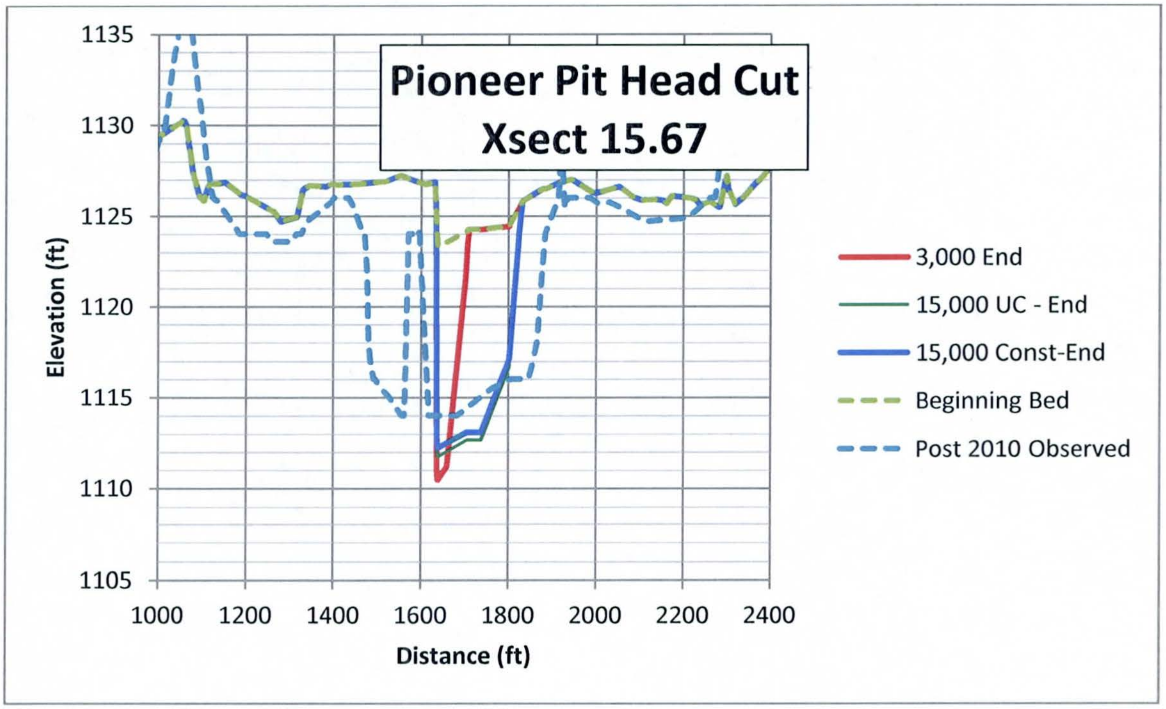


Figure 19. Modeled Headcut and Tailcut for Pioneer Pit for Various Flow Rates. Data includes water surface elevations for 15,000 cfs after the highest and lowest modeled flow events. Observed data is post-2010 bed data.

The water surface elevations are shown in Figure 19 for a 15,000 flow after the 3,000 cfs run and after the 15,000 cfs run. The flows, while identical, produce significantly differing results in the headcut reach and slight differences in the pit and for a short distance downstream from the pit. The water surface elevations away from the pit impact as shown in Figure 19 both upstream and downstream of the Pioneer Pit are very nearly identical. This difference can be explained by comparing the cross sections immediately upstream from the pit as shown in Figure 20. It can be seen that the width of the headcut varies dramatically between the 15,000 cfs run and the 3,000 cfs run but that the depth of the headcut is very similar. It can also be seen that the depth of the erosion is slightly deeper for the unconstrained case than for the constrained case as was discussed earlier.

The difference in water surface elevations for the tailcut downstream of the pit for the 3,000 cfs run and the 15,000 cfs run are also somewhat different as can be seen in Figure 19. This is again due to the cross section changes as can be seen in Figure 21. It can be seen that while the thalweg elevations are similar between the runs, a comparison of the model data and the observed data that the volume of material removed by the headcut is not similar.

The length of the predicted headcut varied from a minimum of 1214 ft to a maximum of 3010 ft for the data using the distance to the first cross section with a scour depth less than 1.0 ft (See Table 7 and Figure 19). The most consistent prediction (for the single cross section data) was with no bed smoothing (NS) and an unconstrained channel which predicted a 3010 ft headcut for all flow rates with the exception of the 3,000 and 6,000 cfs flows which predicted a headcut length of 1426 and 1637 ft respectively. The other model variations produced a wide range of values with most values being in the 1,400 to 3,000 ft range.



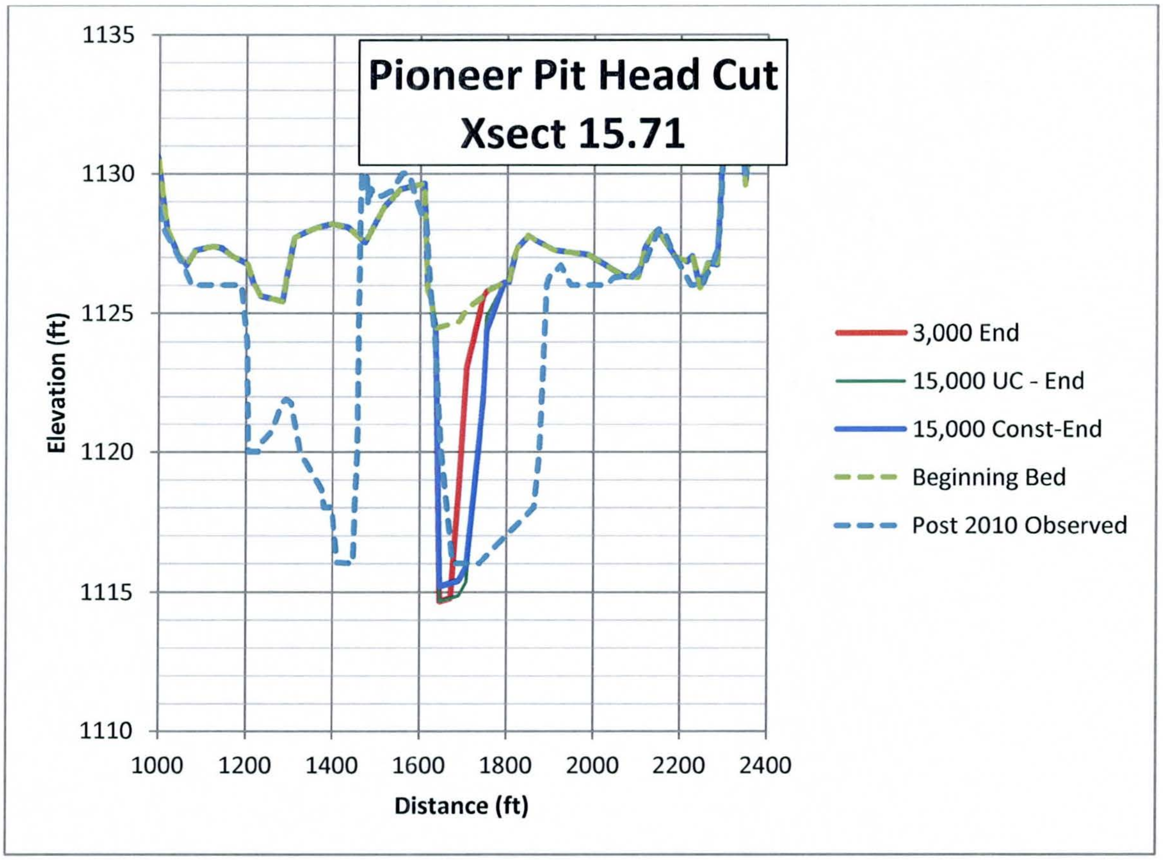
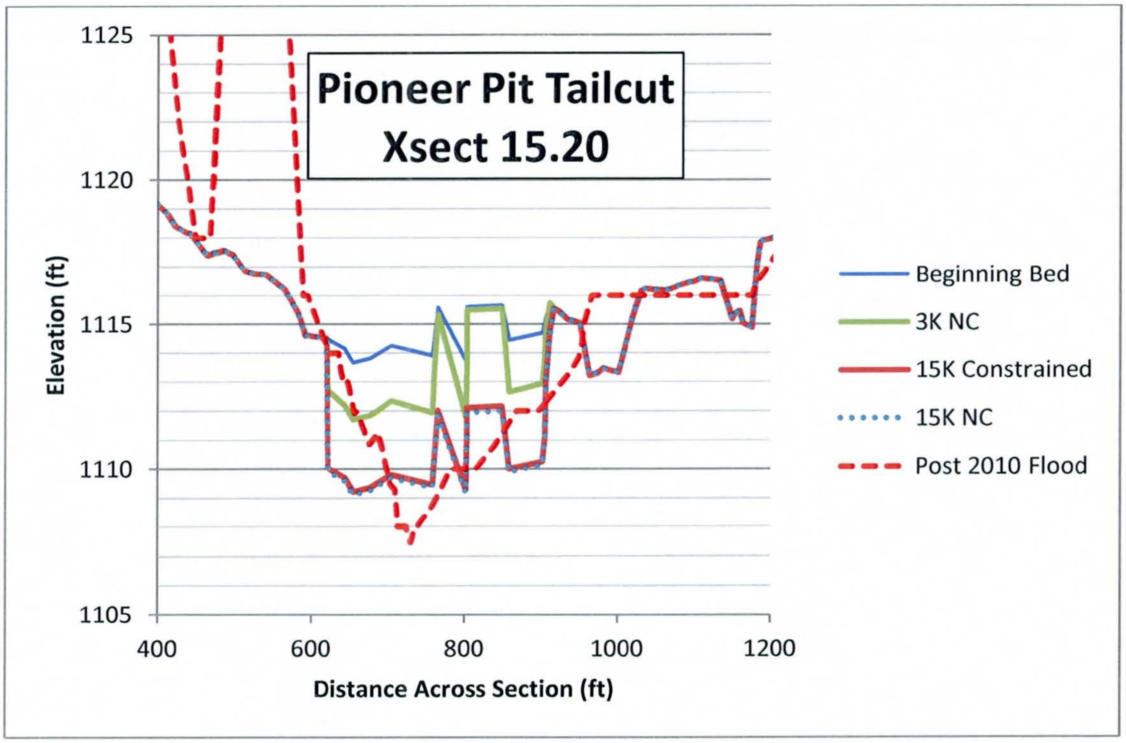


Figure 20. Cross Section Data for First Two Cross Sections above Pioneer Pit. Erosion to left in observed data is erosion from east channel that was not modeled in this exercise.



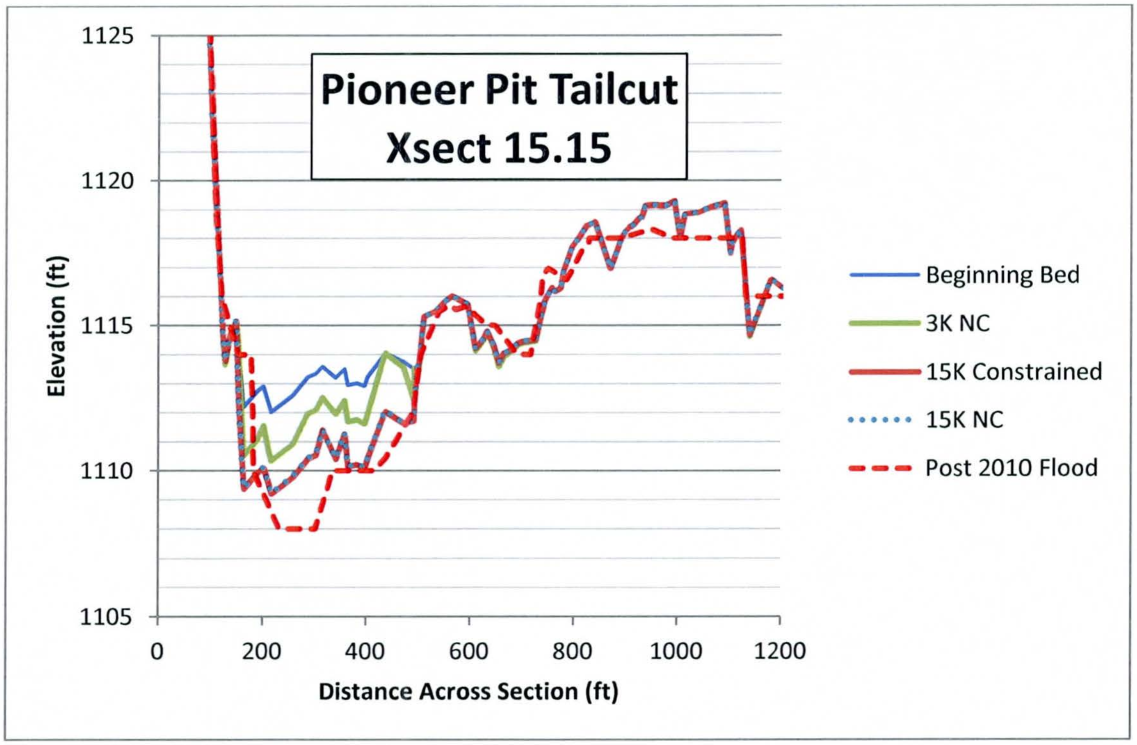


Figure 21. Pioneer Pit Tailcut for Cross Section 15.20 (Immediately Downstream from Pit) and 15.15 (2nd Cross Section Downstream).

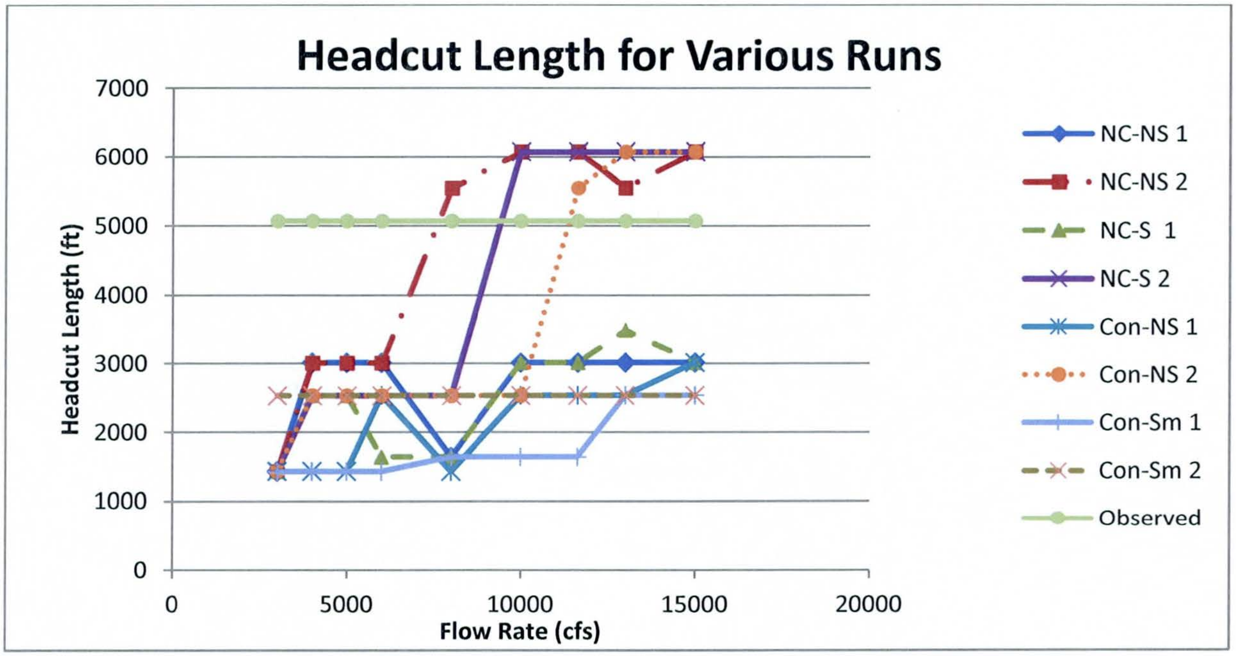


Figure 22. Headcut Lengths for Flow Rate Tests with Smoothing (Sm), and No Smoothing (NS) combined with Constrained (Con) and Non-Constrained (NC) Channel conditions. The number extension (1 or 2) indicates how many consecutive cross sections with scour below 1.0 ft were necessary to locate the upper end of the headcut.

The impact of two options for the determination of headcut length can be seen in Figure 22. The figure shows the impact of using the first cross section where the scour depth is below 1.0 ft versus using the first two consecutive cross sections where scour is less than 1.0 ft. Obviously neither of the methods is especially accurate in predicting the observed headcut length. The results of the headcut length predictions can be seen in Figure 23 and shows a general increase in headcut length for increasing flows.

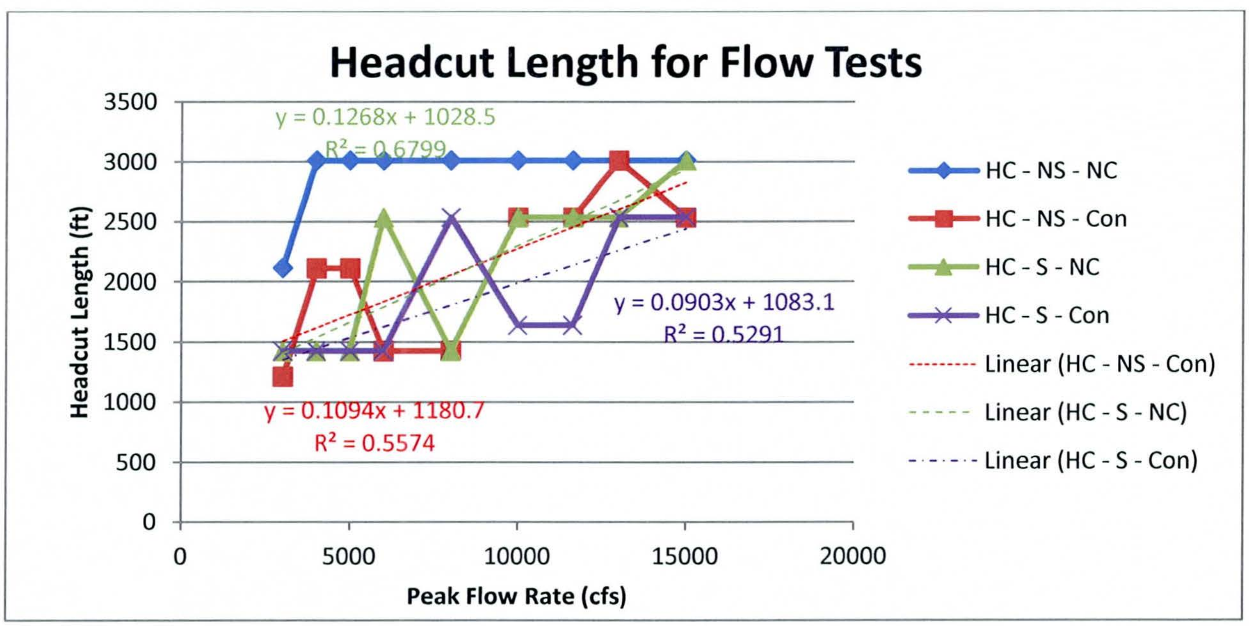


Figure 23. Headcut Length Data Using Distance to First Cross Section with a Scour Depth of less than 1.0 ft.

The equations, while all having very low R2 values, primarily show a trend towards an increasing headcut length of approximately 10% of the increase in flow rate. This would indicate that a 5,000 cfs increase in flow would produce approximately a 500 ft increase in the predicted headcut length.

Impact of Bed Smoothing Checks. Additional tests were run in an earlier iteration of the Hassayampa River model (constrained channel elevations were lower in the region of the Pioneer pit and some other minor modifications above the headcut area) to view the impact of bed smoothing on the results. The impact of how often the smoothing algorithm was implemented was varied so that the number of water surface profiles between bed smoothing checks being changed from 100 to 10 as a part of the flow sensitivity. The results of the various runs with the earlier iteration of the models are shown in Table 8. It can be seen that the headcut length was impacted by the changes made to the model as well as the maximum depths and both varied between the runs. When the values from Figure 22 are compared with the older models above (see Table 8) it can be seen that the modifications to the model caused significant changes in the head cut length. Also from Figure 22 it can be seen that none of the models do a good job of predicting the observed headcut length. It appears that for the flow tests the maximum headcut length is relatively sensitive to flow rate as well to channel constraints and the use of bed smoothing. The results are, however; so variable that no pattern could be discerned or relationship determined. The observed headcut length was 5,068 ft and is shown in Figure 22 for reference.

The calculated maximum headcut depth is shown in Figure 24. It can be seen that the differences are less than 2.0 ft with the exception of headcuts for the low flow conditions with a constrained channel. There is a trend towards increasing headcut depth with increasing peak flow rates. The maximum difference is approximately 2 ft with the exception of the constrained channel cases with flows of 4,000 cfs or less which result in significantly deeper maximum headcut depths.

Table 8. Headcut Length & Maximum Depths for Flow Sensitivity Runs. Length is determined by distance to two Consecutive Cross Sections with Scour less than 1.0 ft in depth.

	No Smoothing Constrained Chan.		Smoothed (100) Constrained Chan.		Smoothed (100) Non-Constrained		Smoothed (10) Constrained Chan.	
Flow	Length	Max Depth	Length	Max Depth	Length	Max Depth	Length	Max Depth
3000	2112	-13.14	2112	-16.18	1214	-16.21	2112	-16.28
4000	2112	-13.47	2112	-15.70	2112	-15.43	2112	-17.23
5000	2112	-13.34	2112	-12.91	2112	-13.21	2112	-13.08
6000	2112	-12.95	2112	-13.29	2112	-13.38	2112	-13.43
8000	2112	-13.05	2112	-13.99	2112	-14.37	2112	-14.42
10000	2112	-13.78	2112	-14.79	3010	-9.96	2112	-14.52
11634	2112	-13.95	2112	-14.32	3010	-10.36	2112	-15.04
13000	2112	-14.23	5070	-15.06	3010	-10.16	5070	-14.90
15000	2534	-14.54*	2112	-14.99	3010	-11.59	2112	-15.39

** 12.5 at last cross section – 14.54 at 2nd cross section above pit brink*

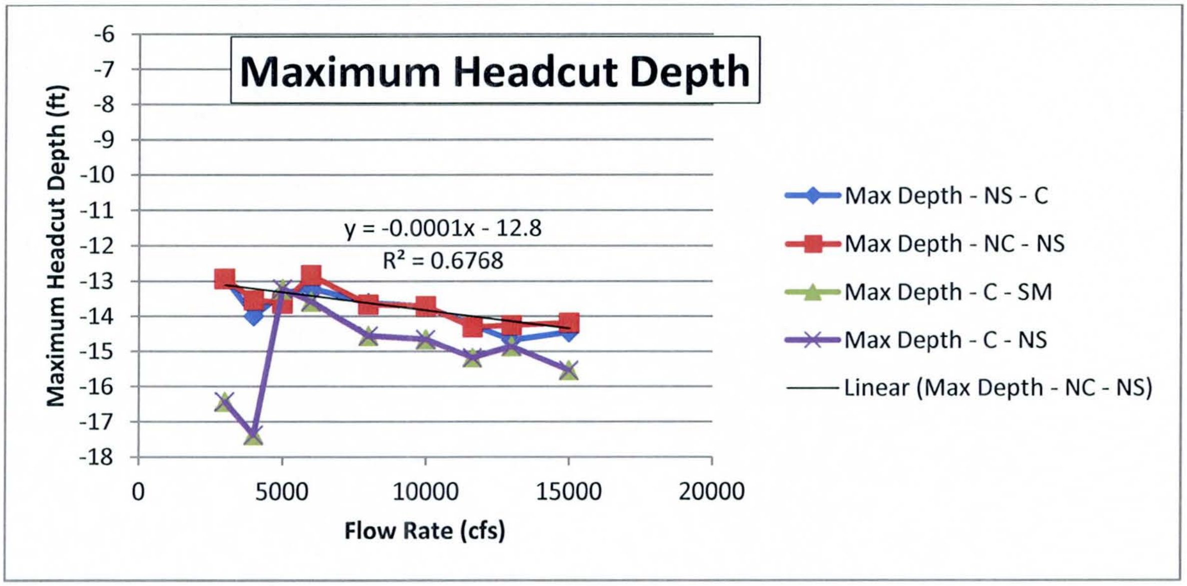
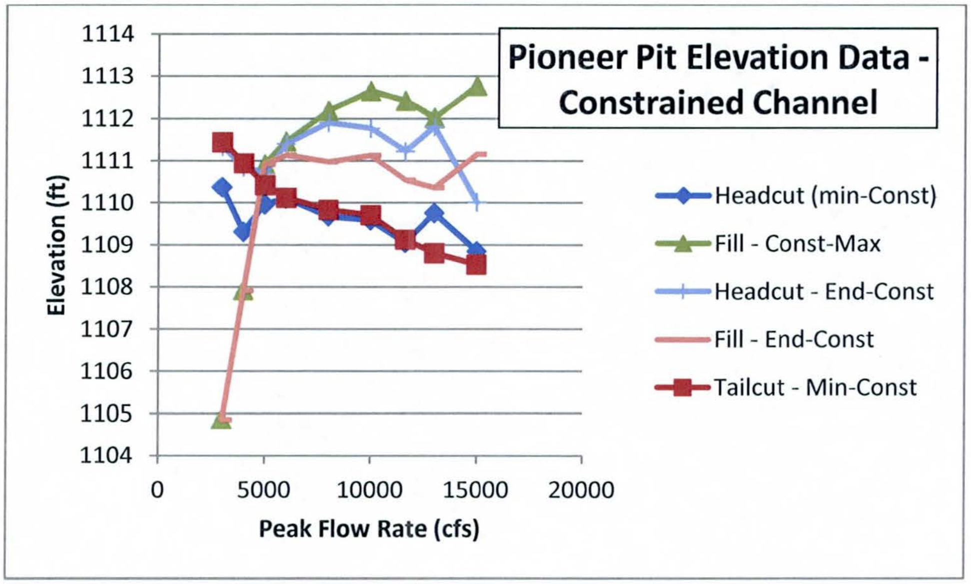


Figure 24. Maximum Headcut Depth for Flow Tests showing Impact of Smoothing. The best fit line is for Max Depth NC-NS.

The relationship between the headcut and the tailcut elevations was also investigated briefly to help shed light on the behavior of the headcut. It can be seen from Figure 25 that the minimum headcut elevation approximates the elevation of the tailcut – especially after the top of the depositional delta inside the pit builds to the level of the headcut. Prior to that time the headcut may be up to 2 ft below the level of the tailcut for this model. The figure also shows that the minimum bed elevation for the headcut can be from one to two feet lower than the ending bed elevation for this situation. The top of the delta also appears to be limited by the original elevation at the downstream end of the pit (the outlet elevation) – an elevation of 1113 ft. This seems reasonable since the water level in the pit will be approximately the elevation of the outlet once the pit fills. It should be noted that the HEC-6T model assumes the pit is full of water at the beginning of the simulation. The data for the plots are contained in Table 9.

Table 9. Minimum/Maximum Elevation Data for Flow Test Runs.

Bed Smoothing On						
	Constrained Channel			Non-Constrained Channel		
	Headcut	Fill	Tailcut	Headcut	Fill	Tailcut
3000	1106.67	1104.83	1111.71	1106.877	1104.259	1111.75
4000	1106.679	1107.345	1111.31	1105.925	1107.119	1111.32
5000	1110.13	1110.63	1110.82	1110.08	1110.70	1110.817
6000	1109.75	1111.497	1110.305	1109.725	1111.51	1110.319
8000	1108.77	1112.057	1109.92	1108.74	1112.094	1110.069
10000	1108.526	1112.457	1109.945	1108.64	1111.882	1109.957
11634	1108.23	1112.56	1109.7	1108.12	1112.186	1109.69
13000	1108.358	1111.96	1109.4	1108.437	1112.434	1109.407
15000	1107.64	1112.065	1109.179	1107.766	1112.161	1109.03
No Bed Smoothing (NS)						
	Constrained Channel			Non-Constrained Channel		
	Headcut	Fill	Tailcut	Headcut	Fill	Tailcut
3000	1110.36	1104.87	1111.447	1110.366	1104.838	1111.449
4000	1109.306	1107.92	1110.946	1109.76	1108.549	1110.94
5000	1109.957	1110.915	1110.42	1109.668	1110.98	1110.426
6000	1110.097	1111.46	1110.12	1110.477	1111.446	1110.127
8000	1109.67	1112.184	1109.837	1109.646	1112.259	1109.84
10000	1109.587	1112.645	1109.71	1109.59	1112.45	1109.658
11634	1109.046	1112.41	1109.129	1108.995	1112.44	1109.125
13000	1109.75	1112.016	1108.806	1109.049	1112.249	1108.807
15000	1108.84	1112.77	1108.53	1109.118	1112.04	1108.535



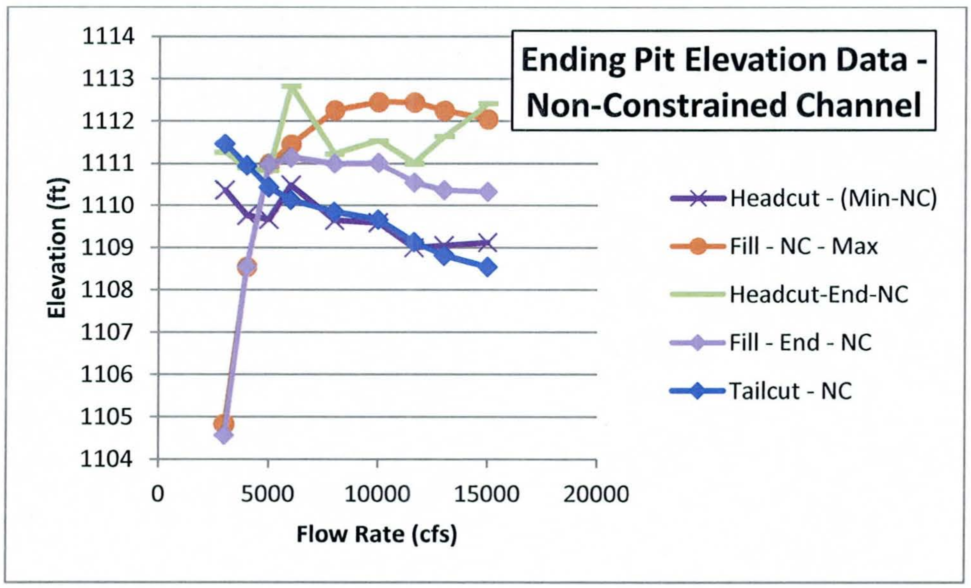


Figure 25. Minimum and Ending Bed Elevations and Maximum Delta Elevations for Flow Tests with No Bed Smoothing.

4.4.3 Flow Sensitivity Results

The averaged maximum scour depth values for the model were found to be sensitive to changes in the peak flow used in the modeling effort but variations were not large. The majority of the change occurred in areas near the Pioneer, CEMEX and Hanson pits where flows were constrained to relatively narrow channels. The changes were not large for any of the flows used although some variability was evident from using the $SMOOTH option in the model. The maximum range for the averaged maximum scour depth in the full model was approximately 0.8 to 0.85 ft. The equations for the change in averaged maximum scour depth for the models are as follow:

FULL MODEL: Non-constrained channel and smoothing on:

$$y = -5E\text{-}05x - 1.0124 \text{ (NC - Sm)} \qquad R^2 = 0.9285 \qquad (8)$$

Constrained channel and smoothing off

$$y = -5E\text{-}05x - 1.0707 \text{ (Con-NS)} \qquad R^2 = 0.9301 \qquad (9)$$

The slope of the averaged maximum scour depth with respect to the flow rate is:

$$\frac{dy}{dx} = -5E\text{-}05 \qquad (10)$$

where x is the flow rate in cfs and y is the averaged maximum scour depth for the full model.

The best fit line for the averaged maximum scour depth when bed smoothing is on with a constrained channel is:

$$y = -4E\text{-}05x - 1.0856 \text{ (Con-SM)} \qquad R^2 = 0.9514 \qquad (11)$$

$$\frac{dy}{dx} = -4E\text{-}05 \text{ w/Smoothing} \qquad (12)$$

HEADCUT: When bed smoothing is off the best fit line for the **averaged maximum headcut scour depth (NS)** is (see Figure 14):

$$y = -7E\text{-}05x - 4.3358 \text{ (NC-NS)} \qquad R^2 = 0.5566 \qquad (13)$$

The slope of this line is:

$$\frac{dy}{dx} = -7E\text{-}05 \text{ No Smoothing} \qquad (14)$$

When bed smoothing is on the equation for the **averaged maximum headcut scour depth (S)** with a constrained channel is (Figure 14):

$$y = -5E\text{-}05x - 5.1773 \text{ (Con-Sm)} \qquad R^2 = 0.4156 \qquad (15)$$

The slope of this line is:

$$\frac{dy}{dx} = -5E\text{-}05 \text{ w/Smoothing} \qquad (16)$$

The calculated headcut lengths vary from 1425 ft to 3485 ft with the headcut length generally increasing with increasing peak flow rates.

The predicted length of the headcut for a non-constrained channel is approximately:

$$y = 0.1094x + 1180.7 \text{ (Con-NS)} \qquad R^2 = 0.5574 \qquad (17)$$

and the slope of the line is:

$$\frac{dy}{dx} = 0.1 \quad (18)$$

4.5 SENSITIVITY TO GRAIN SIZE VARIATIONS IN THE BED

The grain size distribution used in the modeling was identical to that used by the WEST/Fuller sediment transport model for their earlier study. Only one size distribution for the bed sediment reservoir was used for the entire reach following the approach used by the WEST/Fuller model. In order to test the sensitivity of the model to changes in grain size distribution the distribution was both increased and decreased. No other changes to the models were made for this test with the exception of some additional runs to view the impact of the $SMOOTH card which was turned on in the early portion of the study. The Manning's n value for the channel was kept at 0.030

The grain size distribution was varied by multiplying the original grain size for each point on the distribution curve by a predetermined value. The values ranged from 0.5 to 3.0. This gave a wide range of variation in the grain size for the model and bracketed the possible distributions. The finest concentration (0.5 x WEST/Fuller data) consisted of approximately 10% silts or finer materials (< 0.067 mm) while the coarser distributions (2.0 and 3.0 x WEST/Fuller data) consisted of 36% gravels (> 2.0 mm) with no particles less than about 0.1 mm in diameter. The largest class to be transported in the HEC-6T model was left at 64 mm in the HEC-6T model and the largest amount of material larger than 64 mm was 1% or less for the coarsest distribution. The distributions used in modeling can be seen in Figure 26.

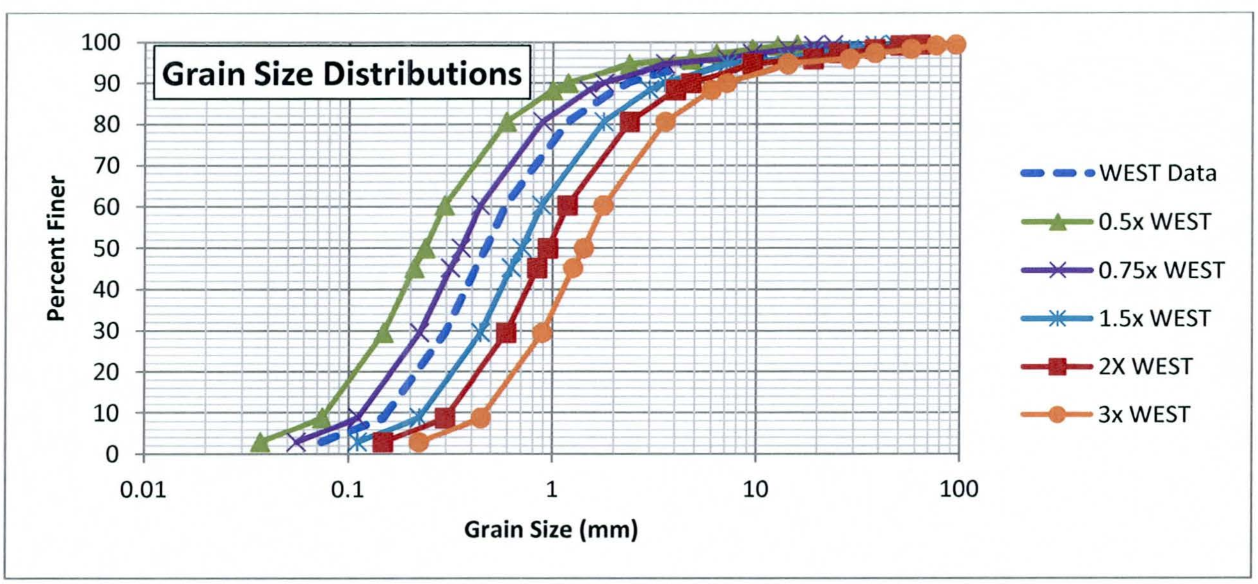


Figure 26. Range of Grain Size Distributions Used in Sensitivity Modeling. Original Study was by WEST for Fuller.

The modeling revealed a relatively smooth change in the full model averaged maximum scour depth for results with bed smoothing on and off. It appears that increasing grain size results in a reducing impact on scour up to about 2.25 times the Fuller/WEST gradation after which the impact of further increasing grain size is very limited for the case with no bed smoothing. The results with bed smoothing turned on continue to reduce scour depths up to approximately 2.5 time the Fuller/WEST gradation before the impact of further increasing the grain size becomes almost insignificant. These data can be seen in Figure 27. A best fit curve was determined for the data with no smoothing and is shown in the same figure. The lines are slightly different and the R^2 for both of the fits are better than 0.99.

There is also a difference in the values for the case using only the negative values. The average value is lower but the slope is nearly the same (ranging from -0.169x+0.9287 to -0.212x+1.1536) for all of the conditions. The main differences are due to the variation between the smoothed case and the non-smoothed case.

The data for the Pioneer headcut showed an instability below about 1.25 times the base grain size distribution as shown in Figure 28. Additional modeling was performed to investigate this instability once it was noticed resulting in additional points near the 1.0 point (WEST/Fuller distribution). The additional runs were concentrated in the 0.95 to 1.25 range and verified that an instability was occurring in this range. This instability is not major in terms of the actual results (see Figure 29) and is approximately 0.5 ft to 0.8 ft for the ending headcut data. The variation in results is shown in Figure 29 and it can be seen that even though the averages vary the actual bed elevations are within a fairly narrow band. The tabular data is contained in Table 11.

A best fit line for the change in the thalweg elevation data for the Pioneer pit headcut was determined using a polynomial fit. This resulted in the lines shown in Figure 28. The fit of the line is good away from the instability near the location of the WEST/Fuller sediment distribution. The impact of bed smoothing in this version of the HEC-6T model can be seen in the values below approximately 1.25 times the Fuller/WEST gradation. When bed smoothing is turned off the R^2 increases from 0.68 to 0.81 for the headcut data.

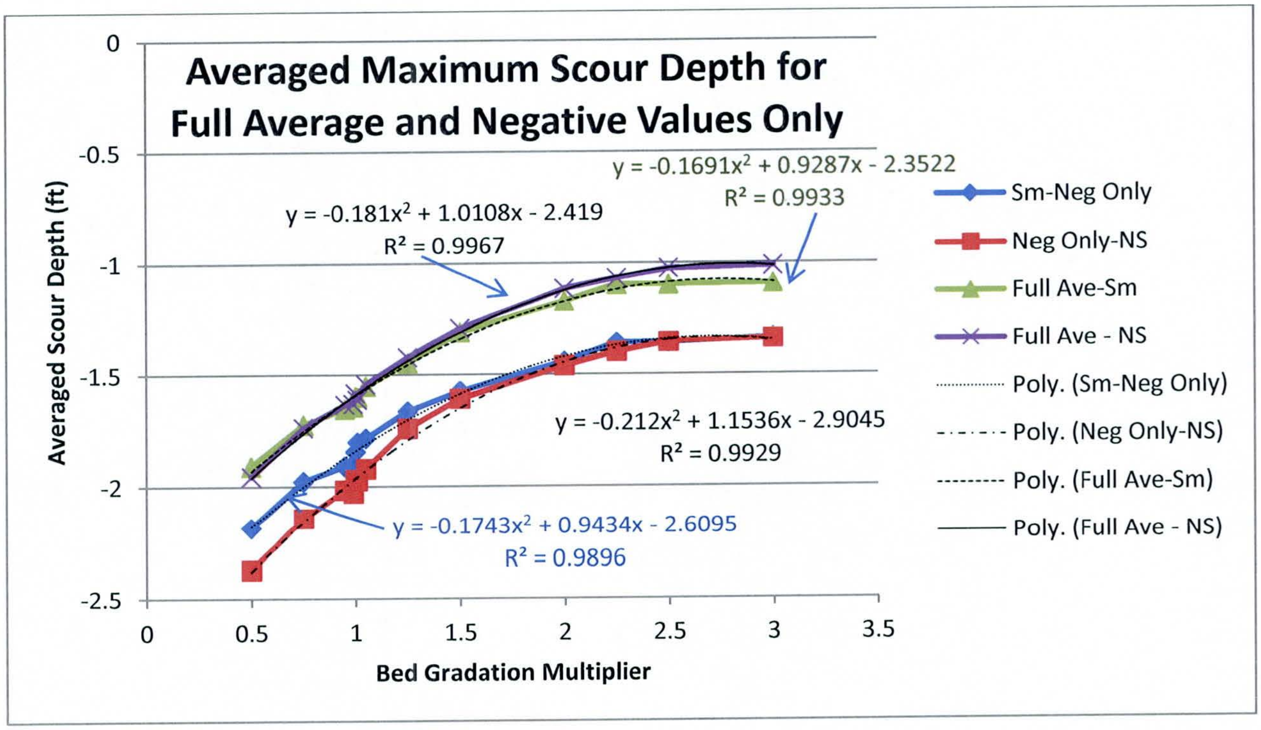


Figure 27. Comparison of Averaged Maximum Scour Depths with and without Smoothing for Full Model for Bed Gradation Tests.

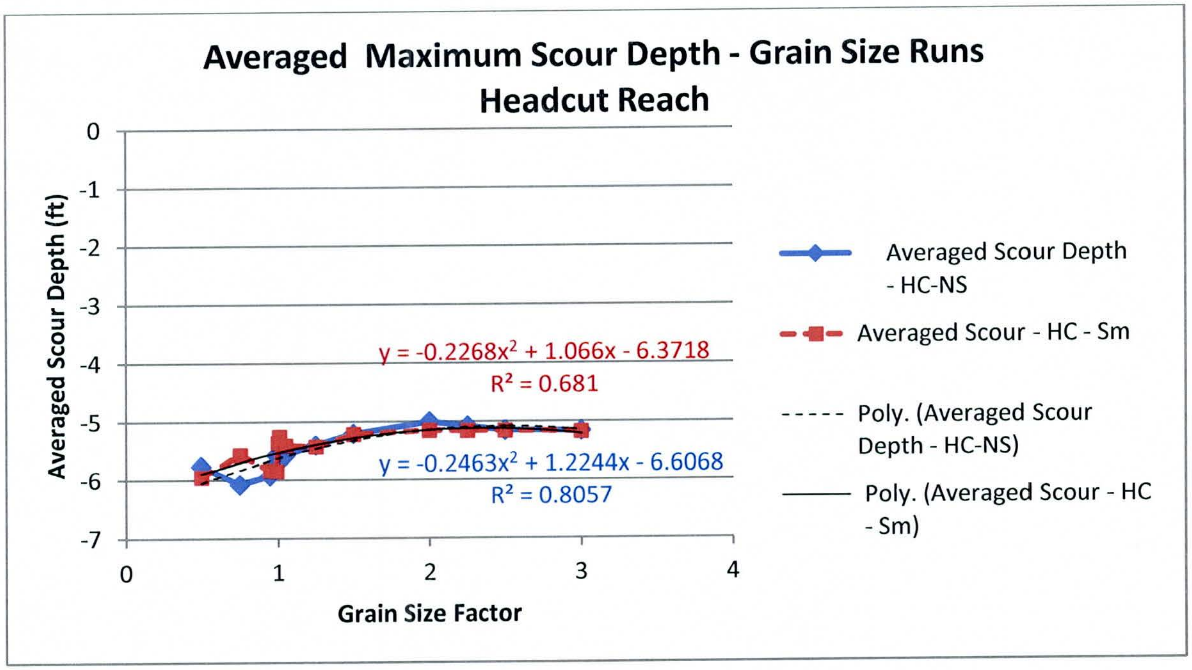


Figure 28. Averaged Maximum Scour Depth for Pioneer Pit Headcut for Grain Size Sensitivity runs.

Table 10. Averaged Maximum Scour Depth Data for Grain Size Runs.

Averaged Maximum Scour Depth					
	Smoothed Bed		No Smoothing		Headcut Length
Grain Size Factor	Model	Headcut	Model	Headcut	(ft)
0.5	-1.78199	-5.95009	-1.8404	-5.76519	2112
0.75	-1.59715	-5.56641	-1.62326	-6.08292	2112
0.95	-1.52655	-5.84228	-1.51909	-5.93203	2112
0.99	-1.51701	-5.85331	-1.51563	-5.57789	2112
1 (Base)	-1.46965	-5.36316	-1.46836	-5.70003	2112
1.01	-1.47237	-5.2539	-1.49727	-5.60491	2112
1.05	-1.4247	-5.40713	-1.42934	-5.58039	2112
1.25	-1.32174	-5.43129	-1.30896	-5.4088	2112
1.5	-1.18353	-5.21913	-1.17812	-5.21234	2112
2	-1.04308	-5.15531	-1.00069	-5.0127	2112
2.25	-0.97046	-5.16272	-0.95348	-5.08757	2112
2.5	-0.97057	-5.16085	-0.91109	-5.16085	2112
3	-0.9655	-5.17835	-0.8994	-5.16756	2112

Since the instability in the averaged maximum scour depth values for the Pioneer pit headcut appeared to be significant the variation of the actual data was reviewed. The thalweg elevations were plotted directly to observe how large the variations were in the original data. The thalweg plot for the headcut is shown in Figure 29. It can be noted that while the data does show some variation at individual cross sections, the differences between the runs are not large when compared with the beginning and observed data. The beginning and observed headcut are also shown in Figure 29 for the ending bed and in Figure 30 for the minimum bed data. The maximum referred to in Figure 30 refers to the minimum scour reported in the various runs while the minimum elevation is the result of the maximum scour reported from all of the model runs at a particular cross section. The data for Figure 30 are reported in Table 11 for closer evaluation.

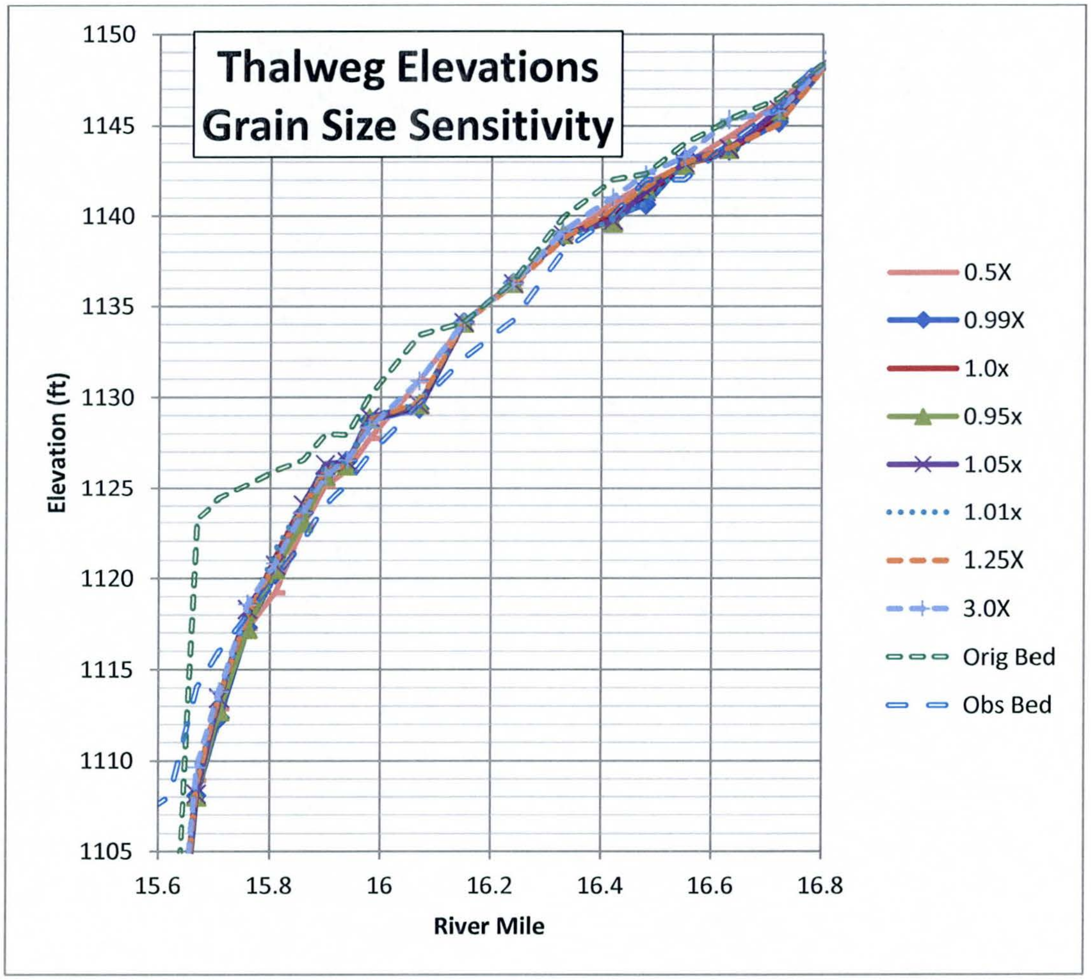


Figure 29. Thalweg Data for Pioneer Pit Headcut based on Varying Bed Sediment Gradations.

The instability[2] that occurs at and near the gradation used in the WEST/Fuller model causes some concern in the results. While this difference is not large as can be seen in Figure 30 it does show that the gradation can have an effect on the model results in this particular model at specific cross sections. The overall impact, however; does not appear to be extremely significant in terms of modeling results. This was further investigated by plotting the first two cross sections upstream from the Pioneer pit. These cross sections are plotted in Figure 31. The cross sections show that the bed elevation of the headcut varies from run to run with no clear pattern for the combined data. The shallowest scour occurs with the largest grain size input but the deepest scour occurs at a grain size distribution of 1.05 for cross section 15.71 and 0.95 for cross section 15.67. The differences between all of the runs is not large given the depth of the scour – approximately ±1.2 ft in the 14.75 ft deep headcut at cross section 15.67 and ±0.9 ft for the 13 ft deep headcut at cross section 15.71. (See Table 11). These values are in line with the uncertainty found during other tests.

[2] It should again be noted that the model was not unstable in but the results were unstable –i.e. the model produced consistent results for each set of input data but the results did not show consistent trends in this region.

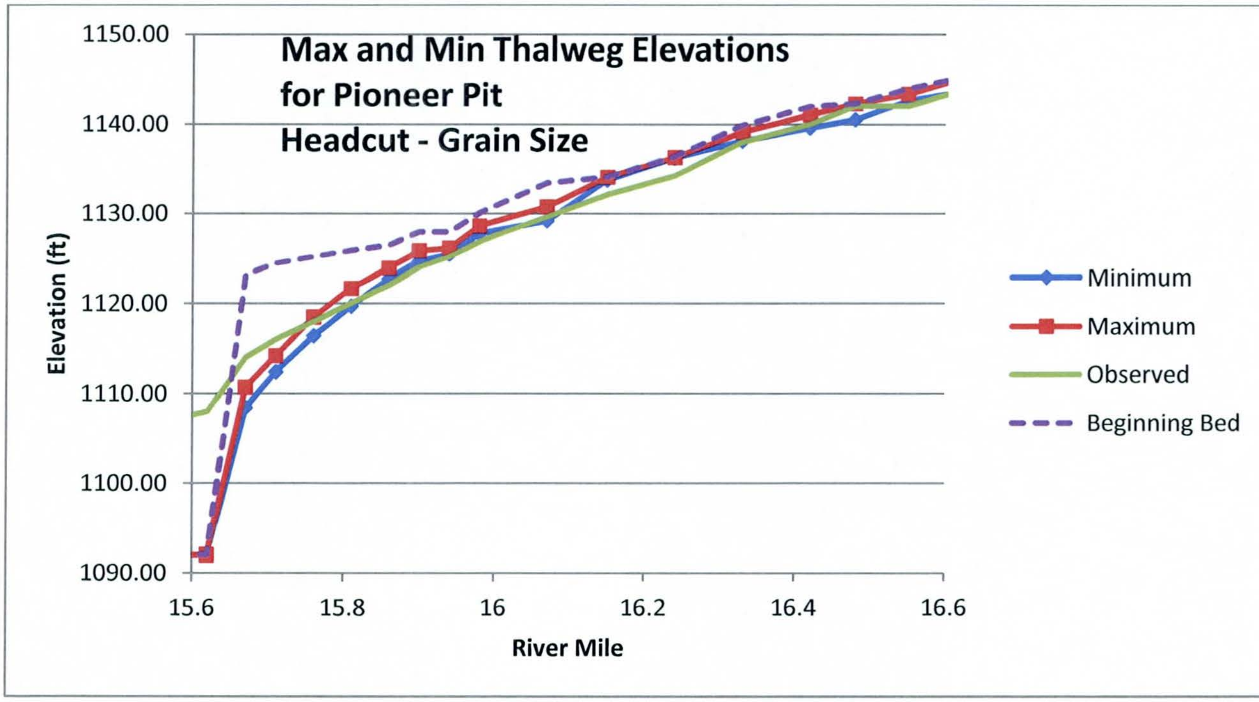
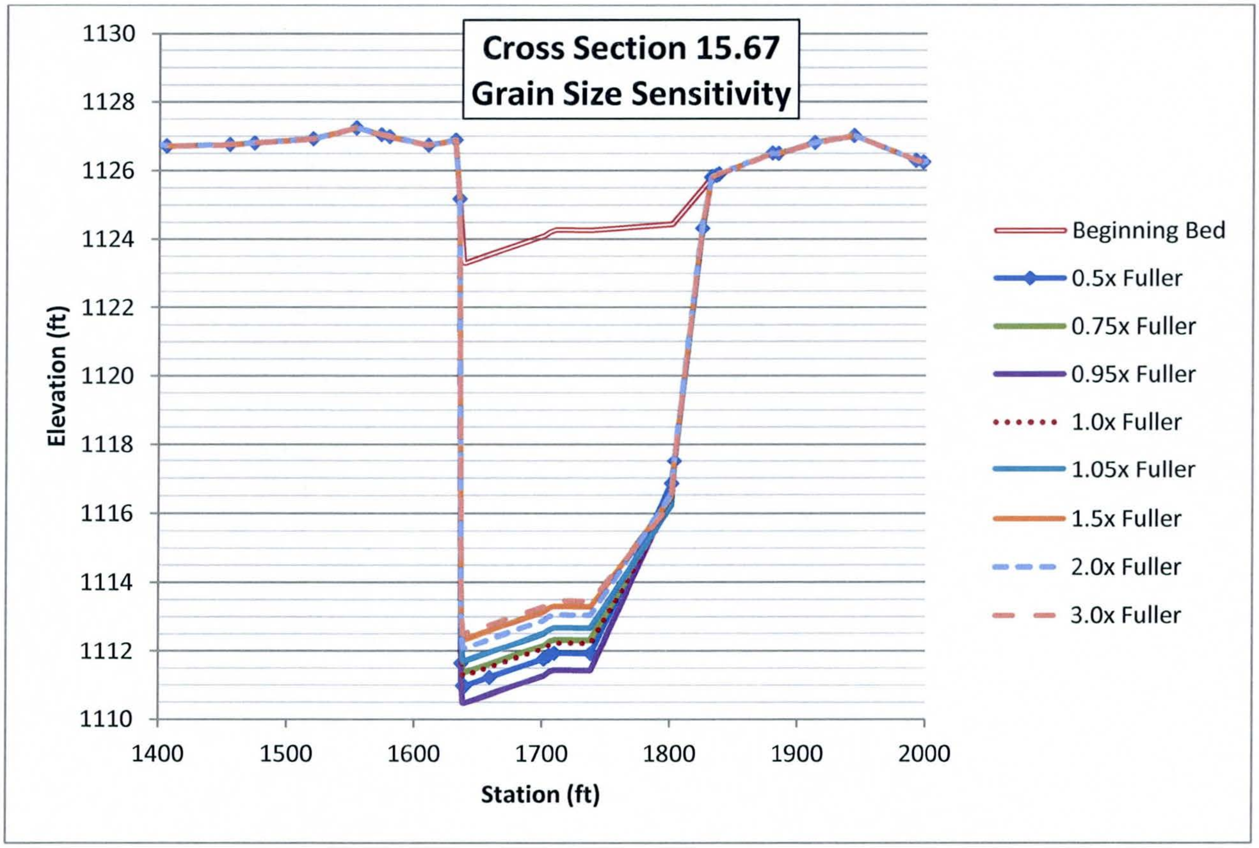


Figure 30. Maximum and Minimum Thalweg Elevations for Pioneer Pit headcut for Bed Gradation Variations.

The model results are also given in Table 11 along with the difference between the deepest scour (min) and shallowest scour (max) observed in the model results for all of the runs evaluating sensitivity due to flow. It can be seen that the maximum difference between the runs is 2.3 ft between the maximum and minimum scour depths at cross section 15.67. The average for the modeled headcut is -1.56 ft while the difference in the area just upstream from the headcut is -0.95 ft. This compares with the average change from the beginning bed elevations of -1.21 ft for the upstream (non-headcut reach) and -6.44 ft for the headcut reach. The variation in bed elevation (uncertainty if you will) accounts for 78% of the average change in bed from the beginning of the run for the non-headcut region but only 24% of the change in the headcut region. This indicates that uncertainty accounts for a much smaller percentage of the bed change in the headcut region than in the non-headcut region. It also shows that the uncertainty while larger than in the non-headcut reach is not unreasonable in terms of the depth of the headcut. The maximum variation (-2.3 ft) is 15.6% of the total headcut scour (2.3/14.74) at a single cross section and only 24% of the averaged maximum bed change. The largest uncertainty value occurred at the pit brink with the values generally trending lower as one moved away from the pit.

The actual scour depths, based on the minimum bed values with no smoothing and a constrained channel, are shown in Table 12 along with the range of headcut depths for the modeling effort. The headcut depths are based on the beginning bed elevations in the models.



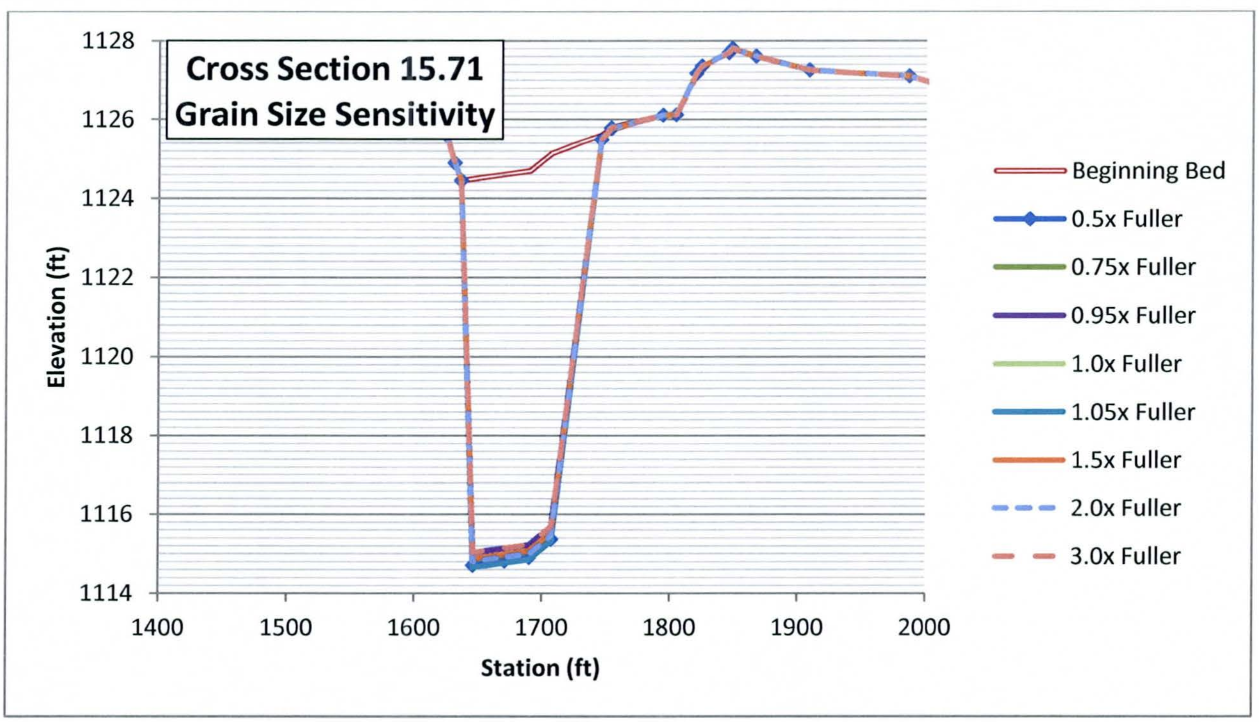


Figure 31. Cross Sections 15.67 (at Pit Brink) and 15.71 (one Cross Section Upstream from Brink) showing Variations in Ending Bed Elevations for Various Bed Sediment Distribution Size Ranges.

Table 11. Minimum Thalweg Elevations for Bed Sediment Gradation Runs.

Beginning Bed Elevation	Observed Post 2010 Thalweg Elevation	River Mile / Cross Section #	Multiplier for Original (WEST/Fuller) Bed Sediment Gradation – $SMOOTH turned off													Min Bed Elevation	Max Bed Elevation (Min Erosion)	Delta Max to Min	Average Delta Max to Min	Delta Min to Orig Bed Elev	Averaged Min to Orig Bed Elev	% Change Max-Min to Orig HC (Uncertainty)
			0.5x	0.75x	0.95x	0.99x	1.0x - Base	1.01x	1.05x	1.25x	1.5x	2.0x	2.25x	2.5x	3.0x							
1152.39	1154	17.02	1150.94	1151.34	1152.01	1152.02	1152.05	1152.08	1152.26	1152.27	1152.39	1152.39	1152.39	1152.39	1152.39	1150.94	1152.39	-1.44877	/\	-1.44877	/\	
1151.02	1152	16.91	1150.66	1150.83	1150.71	1151.02	1151.02	1151.02	1151.02	1151.01	1151.02	1151.02	1151.02	1151.02	1151.02	1150.66	1151.02	-0.35613	|	-0.35613	|	
1148.87	1149.35	16.82	1148.72	1148.87	1148.81	1148.78	1148.78	1148.78	1148.78	1148.76	1148.8	1148.84	1148.85	1148.85	1148.85	1148.72	1148.87	-0.14535	|	-0.14754	|	
1146.45	1146	16.72	1145.96	1146.01	1145.81	1144.78	1144.69	1144.81	1144.78	1144.76	1145.04	1145.69	1145.7	1145.70	1145.73	1144.69	1146.01	-1.31829	|	-1.76297	|	
1145.32	1144	16.63	1144.48	1144.43	1144.08	1143.73	1143.71	1143.82	1144.00	1143.74	1143.84	1143.97	1145.32	1145.32	1145.32	1143.71	1145.32	-1.60854	|	-1.60853	|	
1143.98	1142	16.55	1143.18	1142.62	1142.77	1143.02	1142.78	1142.77	1142.82	1142.99	1143.26	1143.37	1143.19	1143.19	1143.28	1142.62	1143.38	-0.75257	|	-1.35755	|	
1142.31	1142	16.48	1141.02	1140.99	1141.65	1140.53	1140.51	1140.49	1140.77	1140.88	1141.02	1141.68	1142.30	1142.30	1142.23	1140.49	1142.30	-1.81	-0.94935	-1.82	-1.20628	78.7[1]
1141.99	1140	16.42	1139.57	1140.31	1139.62	1140.14	1140.02	1139.80	1140.16	1140.53	1140.70	1140.98	1140.96	1140.97	1141.04	1139.57	1141.04	-1.47487	|	-2.42487	|	
1139.9	1138	16.33	1138.73	1138.10	1139	1138.77	1138.84	1138.88	1138.75	1138.76	1138.76	1138.99	1139.10	1139.10	1139.15	1138.10	1139.15	-1.05111	|	-1.80111	|	
1136.37	1134.2	16.24	1136.31	1136.30	1136.29	1136.30	1136.27	1136.27	1136.26	1136.21	1136.22	1136.27	1136.28	1136.28	1136.28	1136.21	1136.31	-0.09437	|	-0.15882	|	
1134.1	1132.11	16.15	1133.99	1133.82	1134.1	1134.1	1134.1	1133.72	1134.1	1134.1	1134.1	1134.1	1134.1	1134.1	1134.1	1133.72	1134.10	-0.3828	\/	-0.38278	\/	
1133.4	1129.62	16.07	1130.10	1130.37	1129.56	1129.38	1129.16	1129.54	1129.55	1129.62	1129.69	1130.28	1130.66	1130.68	1130.78	1129.16	1130.78	-1.62586	/\	-4.2419	/\	
1130.05	1126.85	15.98	1127.72	1128.00	1128.42	1128.64	1128.40	1128.47	1128.58	1128.56	1128.56	1128.24	1128.07	1128.24	1128.09	1127.72	1128.64	-0.91586	|	-2.32756	|	
1127.92	1125.23	15.94	1125.81	1125.61	1125.46	1125.83	1125.57	1125.58	1125.80	1125.77	1126.21	1126.12	1125.86	1126.00	1125.83	1125.46	1126.21	-0.74832	|	-2.45685	|	
1127.94	1124	15.9	1125.63	1124.69	1125.26	1125.84	1125.75	1125.82	1125.91	1125.57	1125.59	1125.92	1125.72	1125.67	1125.50	1124.69	1125.92	-1.23188	-1.56483	-3.2524	-6.44429	24.3
1126.52	1122	15.86	1123.29	1122.92	1122.69	1123.47	1123.42	1123.27	1123.25	1123.56	1123.6	1123.96	1123.75	1123.60	1123.42	1122.69	1123.96	-1.26896	|	-3.82989	|	
1125.94	1120	15.81	1119.67	1120.45	1120.50	1121.11	1121.02	1121.04	1120.80	1120.8	1121.18	1121.70	1121.48	1121.37	1121.19	1119.67	1121.70	-2.02237	|	-6.2652	|	
1125.22	1118	15.76	1117.11	1117.01	1116.4	1117.97	1117.8	1117.66	1117.57	1118.53	1118.51	1118.52	1118.40	1118.28	1118.49	1116.40	1118.53	-2.13109	|	-8.82014	|	
1124.44	1116	15.71	1113.37	1112.38	1113.69	1113.20	1113.06	1113.43	1113.63	1114.05	1114.00	1114.09	1114.21	1114.11	1114.06	1112.38	1114.21	-1.83658	|	-12.0621	|	
1123.16	1114	15.67	1110.00	1108.42	1109.22	1108.95	1109.10	1109.35	1109.28	1109.45	1110.35	1110.65	1110.65	1110.71	1110.72	1108.42	1110.72	-2.30255	\/	-14.7425	\/	
1092.02	1108	15.62	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	-0.00311				
1092.04	1107.19	15.58	1092.00	1092.00	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092.00	1092.00	-0.00068				
Headcut Length (ft)	5068		2112	2112	2112	2112	2112	2112	2112	2112	2112	2112	2112	2112	2112	2112	2112					
(green)	Observed Headcut Beyond Modeled Headcut																					
(blue)	Area Showing Headcut in Model																					

[1] 22.3% of difference is due to change in bed elevation

[2] 75.7% of difference is due to change in bed elevation

Table 12. Headcut Length, Depth and Profiles for Constrained Channel with no Bed Smoothing.

	Bed Gradation Multiplier																		Minimum	Maximum	Delta	HC	
	0.5	0.75	0.95	0.99	Base	1.01	1.5	2.5	2	3	0.5	0.75	0.95	0.99	1.01	1.05	1.25	2.25	Change	Change	(ft)	Length	
17.02	-1.45	-1.05	-0.38	-0.37	-0.34	-0.31	0.00	0.00	0.00	0.00	-1.45	-1.05	-0.38	-0.37	-0.31	-0.13	-0.12	0.00	0.00	-1.45	-1.45		
16.91	-0.36	-0.19	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	0.00	-0.36	-0.19	-0.31	0.00	0.00	0.00	0.00	0.00	0.00	-0.36	-0.36		
16.82	-0.15	0.00	-0.06	-0.09	-0.09	-0.09	-0.07	-0.02	-0.03	-0.02	-0.15	0.00	-0.06	-0.09	-0.09	-0.09	-0.11	-0.02	0.00	-0.15	-0.15		
16.72	-0.49	-0.44	-0.64	-1.67	-1.76	-1.64	-1.41	-0.75	-0.76	-0.72	-0.49	-0.44	-0.64	-1.67	-1.64	-1.67	-1.69	-0.75	-0.44	-1.76	-1.32		
16.63	-0.84	-0.89	-1.24	-1.59	-1.61	-1.50	-1.48	0.00	-1.35	0.00	-0.84	-0.89	-1.24	-1.59	-1.50	-1.32	-1.58	0.00	0.00	-1.61	-1.61		
16.55	-0.80	-1.36	-1.21	-0.96	-1.20	-1.21	-0.72	-0.79	-0.60	-0.70	-0.80	-1.36	-1.21	-0.96	-1.21	-1.16	-0.99	-0.79	-0.60	-1.36	-0.75		
16.48	-1.29	-1.32	-0.66	-1.78	-1.80	-1.82	-1.29	-0.01	-0.63	-0.08	-1.29	-1.32	-0.66	-1.78	-1.82	-1.54	-1.43	-0.01	-0.01	-1.82	-1.81		
16.42	-2.42	-1.68	-2.37	-1.85	-1.97	-2.19	-1.29	-1.02	-1.01	-0.95	-2.42	-1.68	-2.37	-1.85	-2.19	-1.83	-1.46	-1.03	-0.95	-2.42	-1.47		
16.33	-1.17	-1.80	-0.90	-1.13	-1.06	-1.02	-1.14	-0.80	-0.91	-0.75	-1.17	-1.80	-0.90	-1.13	-1.02	-1.15	-1.14	-0.80	-0.75	-1.80	-1.05		
16.24	-0.06	-0.07	-0.08	-0.07	-0.10	-0.10	-0.15	-0.09	-0.10	-0.09	-0.06	-0.07	-0.08	-0.07	-0.10	-0.11	-0.16	-0.09	-0.06	-0.16	-0.09		
16.15	-0.11	-0.28	0.00	0.00	0.00	-0.38	0.00	0.00	0.00	0.00	-0.11	-0.28	0.00	0.00	-0.38	0.00	0.00	0.00	0.00	-0.38	-0.38		
16.07	-3.30	-3.03	-3.84	-4.02	-4.24	-3.86	-3.71	-2.72	-3.12	-2.62	-3.30	-3.03	-3.84	-4.02	-3.86	-3.85	-3.78	-2.74	-2.62	-4.24	-1.63	/\	
15.98	-2.33	-2.05	-1.63	-1.41	-1.65	-1.58	-1.49	-1.81	-1.81	-1.96	-2.33	-2.05	-1.63	-1.41	-1.58	-1.47	-1.49	-1.98	-1.41	-2.33	-0.92	|	
15.94	-2.11	-2.31	-2.46	-2.09	-2.35	-2.34	-1.71	-1.92	-1.80	-2.09	-2.11	-2.31	-2.46	-2.09	-2.34	-2.12	-2.15	-2.06	-1.71	-2.46	-0.75	|	
15.9	-2.31	-3.25	-2.68	-2.10	-2.19	-2.12	-2.35	-2.27	-2.02	-2.44	-2.31	-3.25	-2.68	-2.10	-2.12	-2.03	-2.37	-2.22	-2.02	-3.25	-1.23	2112 ft	
15.86	-3.23	-3.60	-3.83	-3.05	-3.10	-3.25	-2.92	-2.92	-2.56	-3.10	-3.23	-3.60	-3.83	-3.05	-3.25	-3.27	-2.96	-2.77	-2.56	-3.83	-1.27	|	
15.81	-6.27	-5.49	-5.44	-4.83	-4.92	-4.90	-4.76	-4.57	-4.24	-4.75	-6.27	-5.49	-5.44	-4.83	-4.90	-5.14	-5.14	-4.46	-4.24	-6.27	-2.02	|	
15.76	-8.11	-8.21	-8.82	-7.25	-7.42	-7.56	-6.71	-6.94	-6.70	-6.73	-8.11	-8.21	-8.82	-7.25	-7.56	-7.65	-6.69	-6.82	-6.69	-8.82	-2.13	|	
15.71	-11.07	-12.06	-10.75	-11.24	-11.38	-11.01	-10.44	-10.33	-10.35	-10.38	-11.07	-12.06	-10.75	-11.24	-11.01	-10.81	-10.39	-10.23	-10.23	-12.06	-1.84	|	
15.67	-13.16	-14.74	-13.94	-14.21	-14.06	-13.81	-12.81	-12.45	-12.51	-12.44	-13.16	-14.74	-13.95	-14.21	-13.81	-13.88	-13.71	-12.51	-12.44	-14.74	-2.30	\/	

4.5.2 Headcut Lengths

The headcut lengths are all predicted to be in the 2100 ft range regardless of the grain size used in the modeling effort. This compares with the observed headcut length of about 5,068 ft in the observed data (See Table 10 and Table 12).

4.5.3 Bed Gradation Sensitivity Results

The sensitivity to changes in the bed gradation for the model is was investigated and found to not be extremely large. The averaged maximum scour depth for the full model can be predicted as follows:

Bed Smoothing off (NS):

$$y = -0.181x^2 + 1.0108x - 2.3043 \qquad R^2 = 0.9967 \qquad (19)$$

Bed Smoothing On:

$$y = -0.1691x^2 + 0.9287x - 2.2245 \qquad R^2 = 0.9933 \qquad (20)$$

And the rate of change for averaged maximum scour depth for the model:

$$\frac{dy}{dx} = -0.362x + 1.0108 \text{ (no smoothing)} \qquad \frac{dy}{dx} = -0.3382x + 0.9287 \text{ (smoothing on)} \qquad (21)$$

If these values are averaged the rate of change for the full model becomes:

$$\frac{dy}{dx} = -0.350x + 1.0021 \qquad (22)$$

When only the negative values are included the equations become:

$$y = -0.212x^2 + 1.1536x - 2.9045 \qquad R^2 = 0.9929 \text{ (NS)} \qquad (23)$$

$$y = -0.1743x^2 + 0.9434x - 2.6095 \qquad R^2 = 0.9896 \text{ (SM)} \qquad (24)$$

when these equations are differentiated they give:

$$\frac{dy}{dx} = -0.424x+1.1536 \text{ (NS)} \qquad \frac{dy}{dx} = -0.3486+0.9434 \text{ (SM)} \qquad (25)$$

If these equations are averaged the average slope for only negative values becomes:

$$\frac{dy}{dx} = -0.3863x + 1.0485 \qquad (26)$$

The equations predicting the **averaged maximum scour depth for the headcut reach** are:

Bed Smoothing off (NS):

$$y = -0.2463x^2 + 1.2244x - 6.6068 \qquad R^2 = 0.8057 \qquad (27)$$

Bed Smoothing on (Sm)

$$y = -0.2268x^2 + 1.066x - 6.3718 \qquad R^2 = 0.681 \qquad (28)$$

The rate of change per unit multiplier in the bed gradation for the averaged maximum scour depth in the headcut reach is approximately equal to:

$$\frac{dy}{dx} = -0.4926x + 1.2244 \text{ (NS)} \qquad \frac{dy}{dx} = -0.4536x + 1.066 \text{ (Sm)} \tag{29}$$

If these are averaged together the final equation for the rate of change of the averaged maximum scour depth within the headcut reach becomes:

$$\frac{dy}{dx} = -0.4731x + 1.1452 \tag{30}$$

The headcut length was predicted to be 2112 ft for all cases.

4.6 SENSITIVITY TO INFLOWING SEDIMENT LOAD

The HEC-6T model of the Hassayampa River was evaluated to determine the sensitivity of the model to the inflowing load in this reach of the river. Initially sediment loads of 0.5, 2, 3, and 4 times the inflowing load in the WEST/Fuller model were run and the results compared visually. This range of input values gave almost no discernible results except for some minor changes at the inflow boundary. The sensitivity range was then expanded from no inflowing load (0 tons/day for all size classes) to 100 times the WEST/Fuller load. The results for the thalweg data is shown in Figure 32 for the inflow area and Figure 33 for the area near the Pioneer Pit.

It can be noted in Figure 32 that the inflowing load quickly reaches equilibrium and downstream changes are very small for very large changes in the inflowing load to the model. Only the 100 time the WEST/Fuller load test resulted in changes beyond the first three cross sections. Changes in the reach of the Pioneer Pit headcut are very slight as shown in Figure 33.

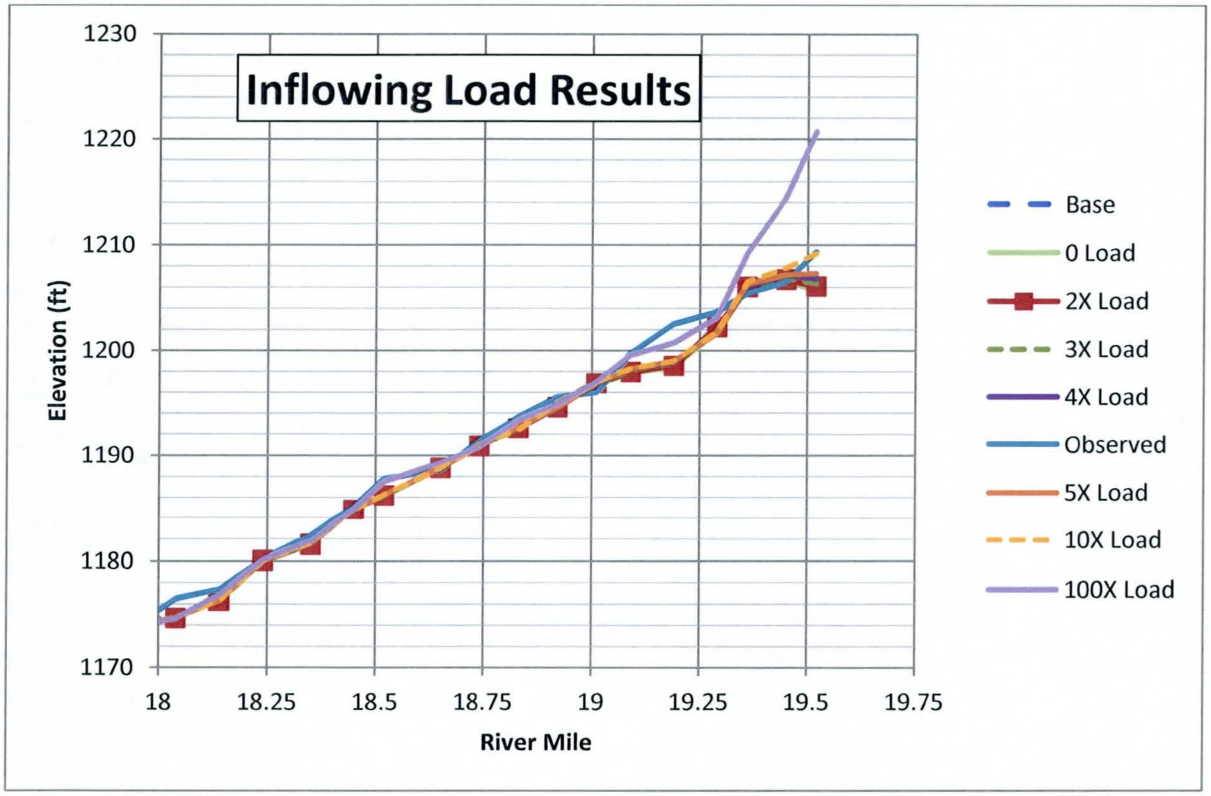


Figure 32. Thalweg Data for the Tested Inflowing Load Values.

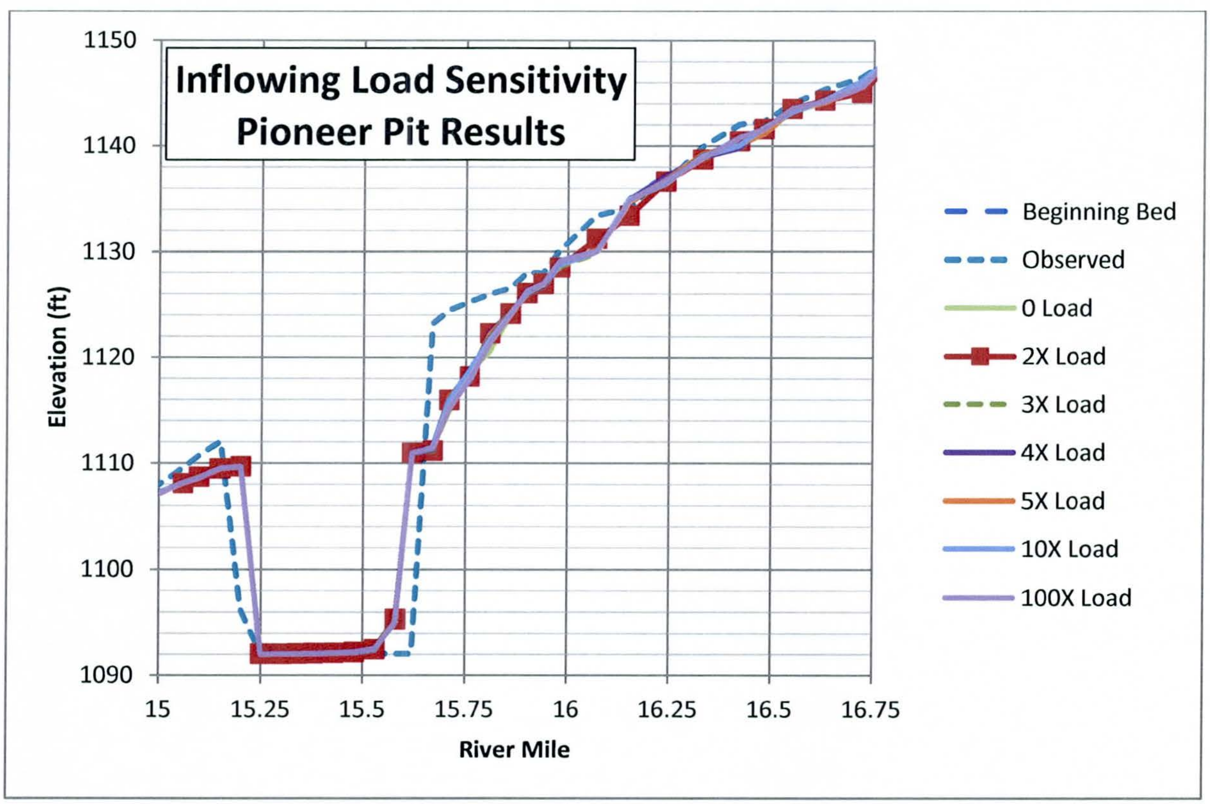


Figure 33. Inflowing Load Sensitivity Results for Area near Pioneer Pit.

The changes in the average values for the full model and for the Pioneer headcut are shown in Figure 34 and Figure 35. The changes in bed elevations are very small for the range of sediment loadings tested. The changes are erratic at this scale but the range of the changes is less than 0.09 ft for the full model and less than 0.04 ft for the headcut reach. This indicates that this particular model is very stable when the inflowing load is varied dramatically. The slope of the fitted lines – while the R^2 values are not great for the model and pitiful for the headcut - show almost no change in bed elevations for large changes in inflowing load. The slope of the lines varies from 0.0003 to 0.0005 ft per unit multiplier in the inflowing load ratio.

The impact of inflowing loads ranging from 0.0 to 100 x the WEST/Fuller load at the upstream model cross section is shown in Figure 36. It can be seen that the impacts at the inflow boundary for the very high loads are significant and that the model is being significantly overloaded by sediment at the higher values. As mentioned above, this deposition does not carry far down the channel due to the width of the river valley (See Figure 32). The 0.0 load condition erodes less than 4 ft to reach equilibrium for the modeled flows. Normally a variation in the inflowing load of two orders of magnitude would cause much more significant changes for a longer reach of the model and this would likely be true for flows with higher peaks and longer durations. For this effort the lack of impact further down the channel is due to the very broad floodplain and deep sediment reservoir associated with the model at the upstream end of the modeled reach. This broad floodplain allows deposition of excess sediment or the scouring of needed sediment such that the model quickly reaches transport equilibrium. These data indicate that for this reach of the Hassayampa River the inflowing sediment load is not an important factor in the results other than for the first three to six cross sections of the model (for these lower flows). This indicates very good stability in the model and no significant impact due to changes in sediment loading unless the upstream boundary is very near the area of interest. The data for the two figures are included in Table 13.

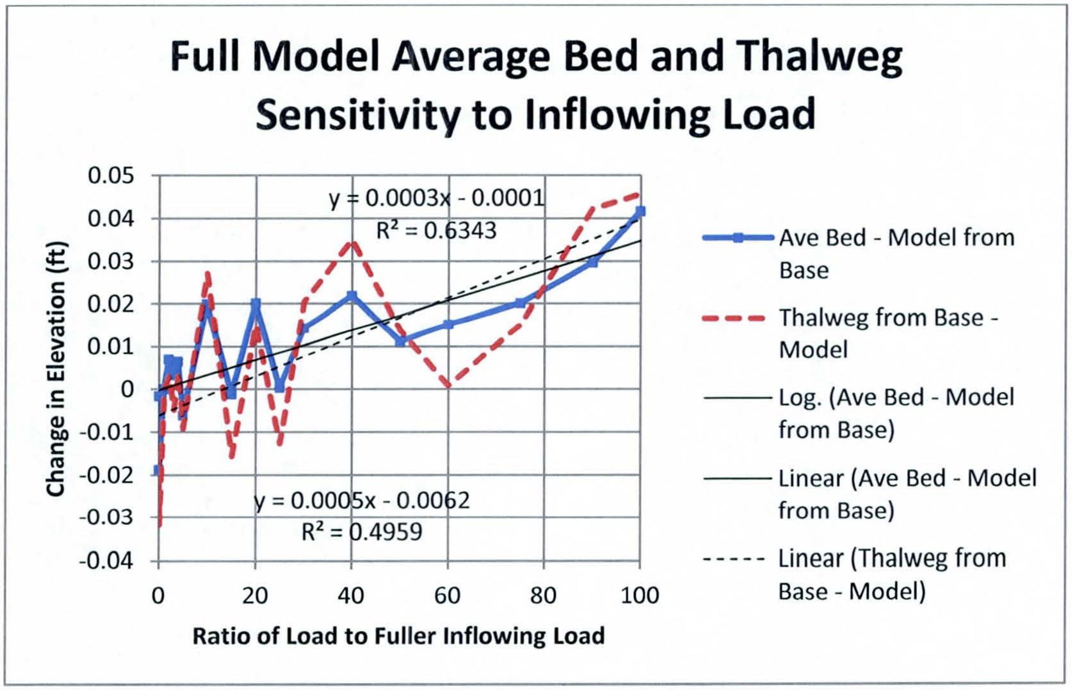


Figure 34. Change in Average Bed and Thalweg Elevations for Full Model for Changes in the Inflowing Load.

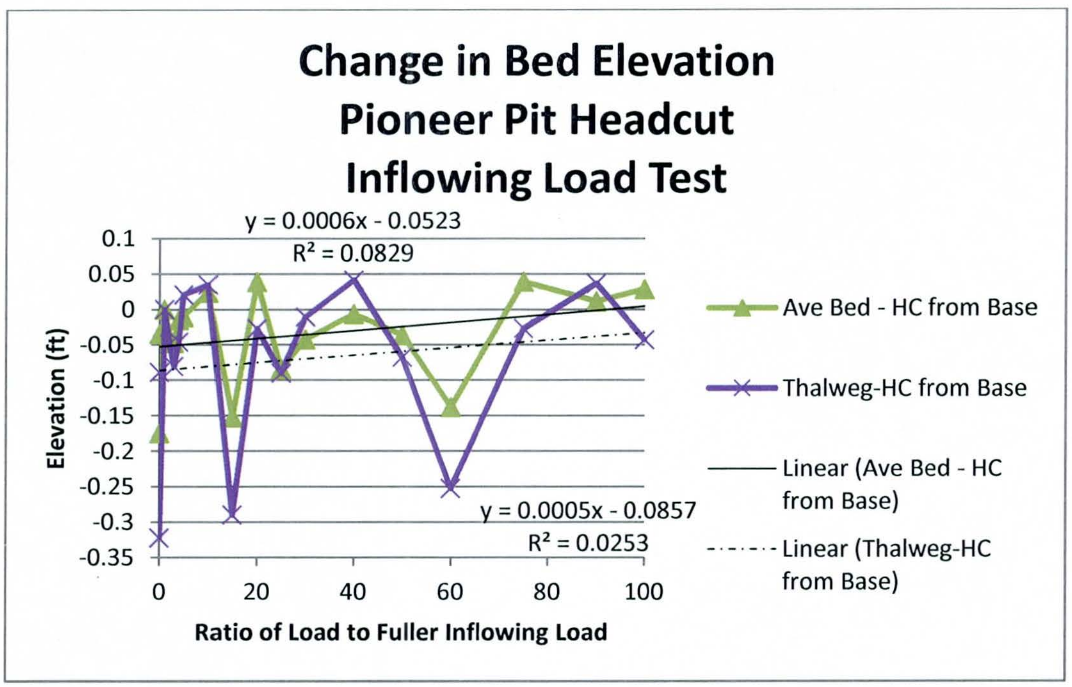


Figure 35. Changes in the Pioneer Pit Headcut Average Bed and Thalweg Elevations Resulting from Changes in the Inflowing Load.

While runs were being performed for the inflowing load test it was noted that several cross sections were showing large amounts of scour. There appeared to be no reason for scour on the order of that being noted. A check was made to determine why large maximum scour depths were being found in the model. The large scour depths were not found in the plot files (.t98) so additional investigation was performed.

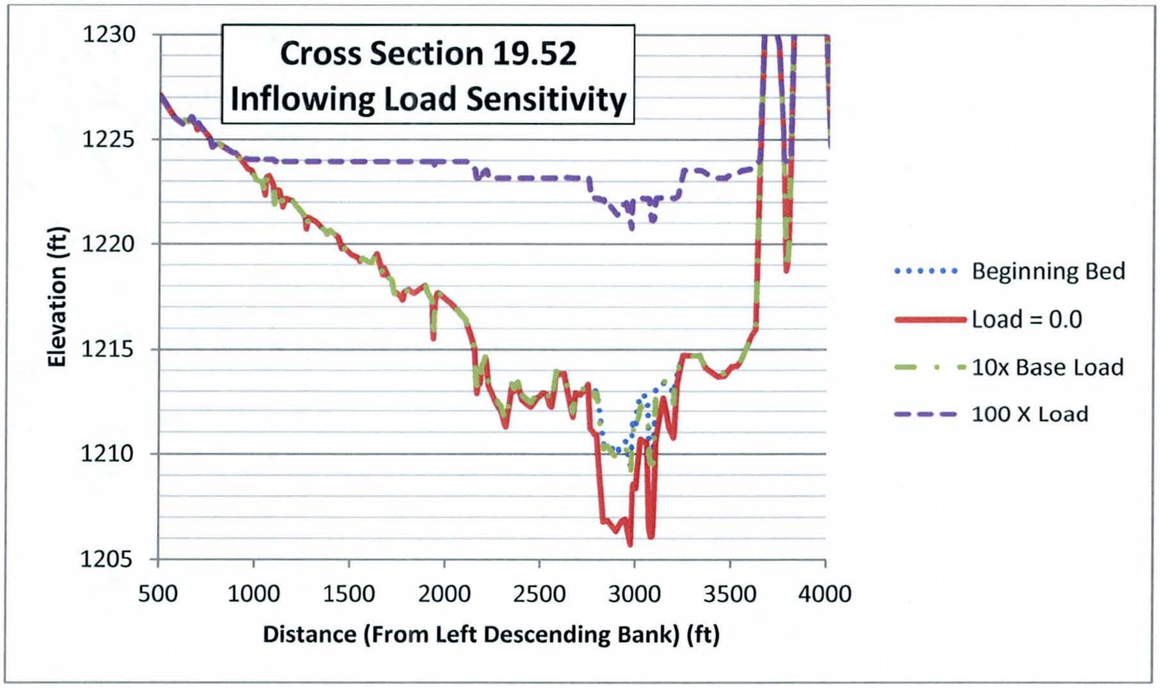


Figure 36. Inflowing Load Impacts to Most Upstream Cross Section (RM 19.52) for Hassayampa River Model.

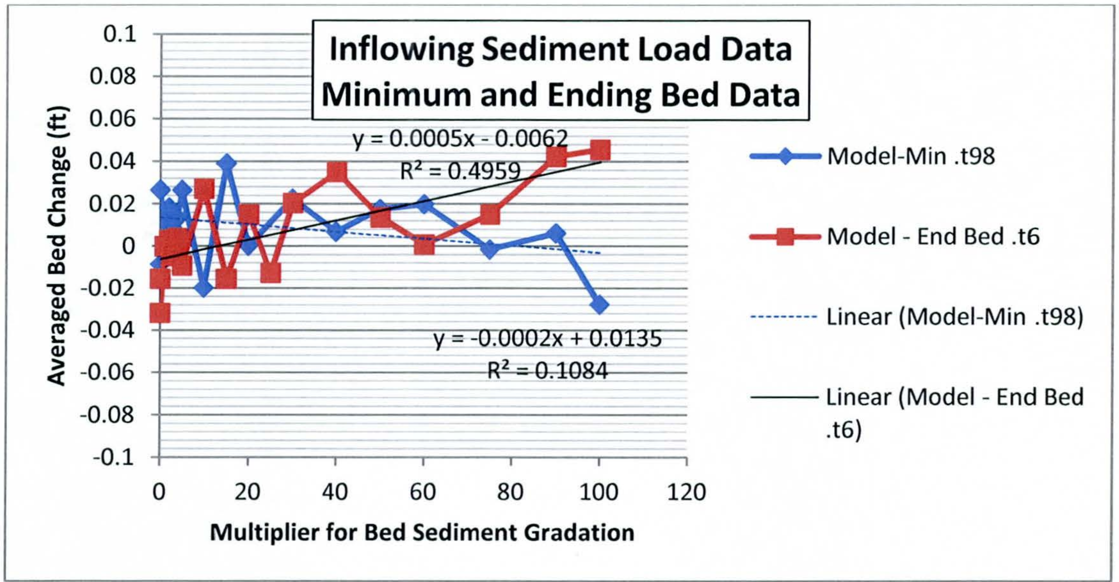


Figure 37. Comparison Minimum Bed Elevation Data from .t98 and Ending Bed Elevation Data from .t6 output files for Inflowing Sediment Load Runs.

The data for the averaged changes in minimum and ending thalweg elevations for the full model are shown in Figure 37 to compare the data from the .t6 (output) and .t98 (plot) files. It can be seen that there are variations between the two sets of data when data should be very similar if not identical. The variations are again less than 0.1 ft for all runs but when the thalweg data was plotted significant differences were present. The difference between data in the .t6 and the .t98 output files with the $SMOOTH card turned on are shown in Figure 38. These differences and the discovery of significant differences at individual cross sections led to an investigation of bed sediment reservoir depth as well as discussions with the model developer to understand what was causing the differences described previously.

Table 13. Averaged Bed Change Data for Inflowing Load Tests. Smoothing was on for all runs.

	Minimum Bed .t98		Ending Thalweg	
Multiplier	Model	HC	Model	HC
0	-0.008825	0.120254	-0.01564	-0.08882
1	0	0	0	0
2	0.0180088	0.309306	0.003008	-0.04824
3	0.00809	0.212568	-0.00489	-0.08059
4	0.0131188	0.167976	0.00391	-0.04588
5	0.0263686	0.098097	-0.00917	0.020588
10	-0.020012	-0.04829	0.027218	0.034706
15	0.0388452	0.479855	-0.01564	-0.29
20	0.0001242	0.263994	0.015038	-0.02706
30	0.0223519	0.336505	0.020451	-0.01059
40	0.0066647	0.088774	0.035038	0.041176
50	0.0174697	0.145227	0.013684	-0.06765
60	0.0197928	0.50163	0.000827	-0.25294
75	-0.001721	-0.07471	0.015038	-0.02706
90	0.0059541	0.183211	0.042256	0.036471
100	-0.027994	-0.06281	0.045564	-0.04294

4.6.1 Inflowing Load Sensitivity Results

The sensitivity analysis indicates that the model results for the Hassayampa River and for the Pioneer headcut are very insensitive to changes in the inflowing load. This is due to the deep bed sediment reservoir and the very broad floodplain present in the model at the upstream boundary of the model. No equations for the change in average or minimum bed elevation the inflowing load were determined to be applicable since all of the R^2 values are less than 0.65. The inflowing sediment load does not create significant changes in the model results for this application.

4.7 Sensitivity to Bed Sediment Reservoir Depth

A comparison of the results from the .T6 (output) files for the maximum scour depth (i.e. minimum bed elevation during the simulation from the .t98 file) indicated that the sediment bed reservoir depth used in the HEC-6T model may be important to the results. In order to address this issue a few runs were made where the bed sediment reservoir depth was varied. This was done by varying the original model used for the flow tests. In the base model the bed sediment reservoir depth was set to 25 ft with the exception of the following four cross sections: 12.65 – 30 ft, 13.58 – 28 ft, 15.67 – 30 ft, and 15.71 – 26 ft. Additional runs were made with all depth set to 15 ft, 20 ft, 25 ft, and 30 ft. A few runs were also made where individual values were modified to address warnings in the results regarding the bed sediment reservoir being too shallow. Two runs were included even though a massive number of errors regarding excessive residuals being found in the bed sediment reservoir calculations (>500 errors in some models). The errors occurred at three to five cross sections in the models as shown in Figure 38.

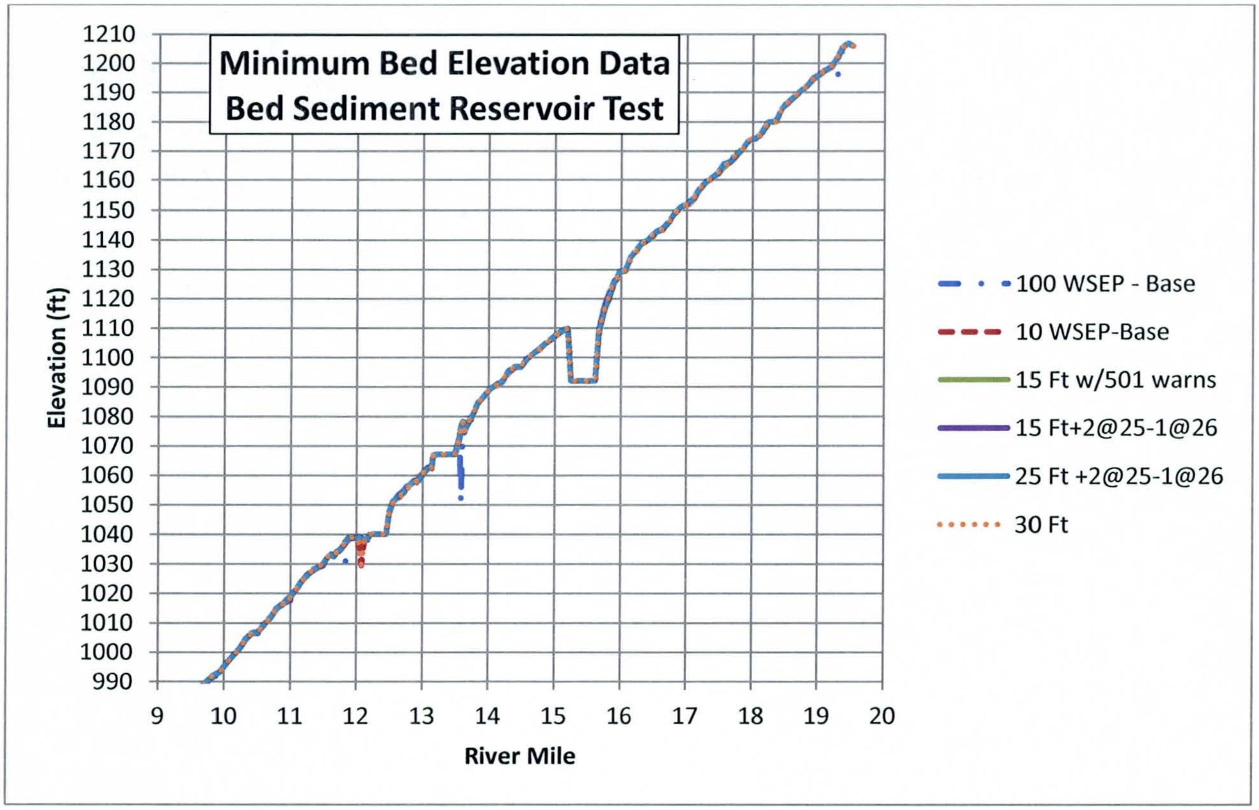


Figure 38. Minimum Bed Elevation Results for Runs with Differing Bed Sediment Reservoir Depths. WSEP = Water Surface Elevation Profiles between smoothing calculations. With exception of 100 WSEP data all models have 10 WSEP between smoothing calculations. The notes after the bed sediment reservoir depth indicate how many cross sections were deeper than the test depth and the depths they were set to. For example 25 ft+2@30=1@26/28 indicates the bed sediment reservoir was set at 25 ft with two cross sections set to 30 and one cross section set to 26 ft and one set to 28 ft in depth.

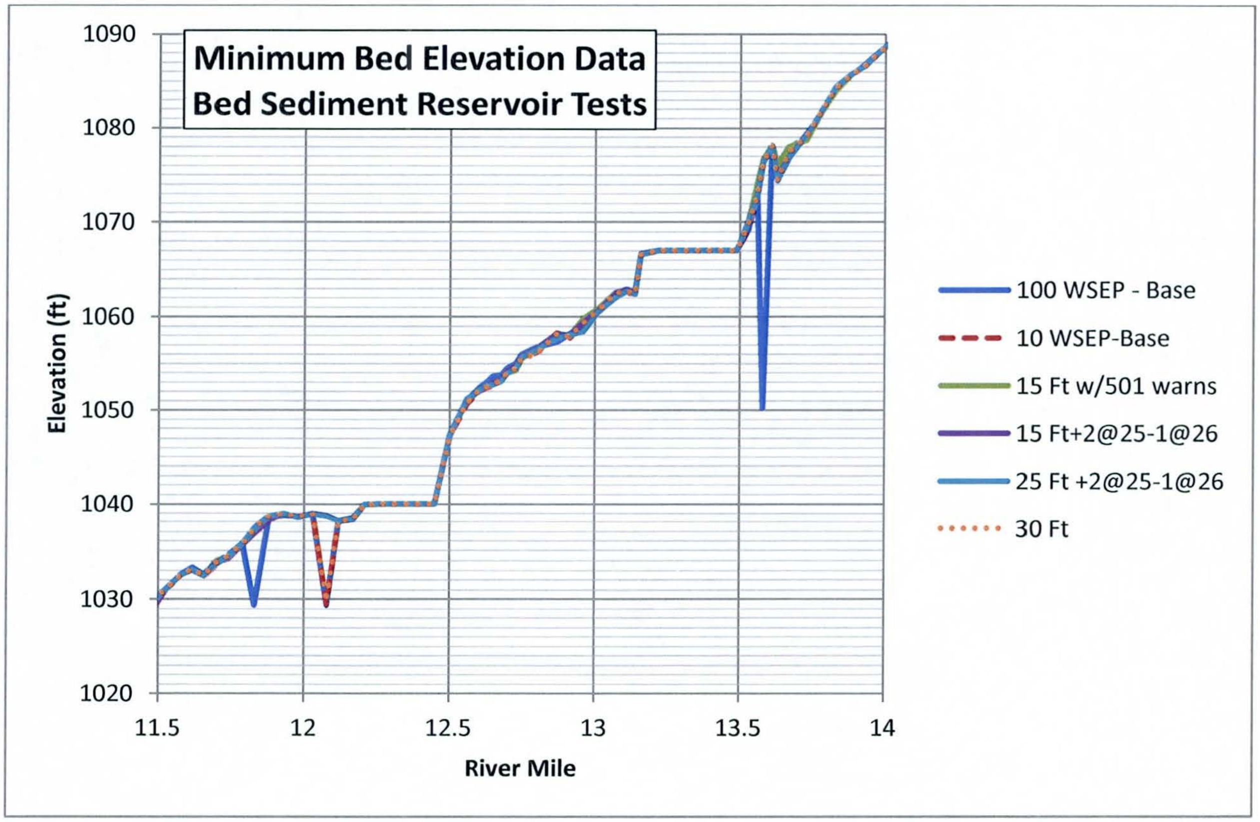


Figure 39. Minimum Bed Depth Results for the Bed Sediment Reservoir sensitivity evaluation for the Hanson and CEMEX pit reach. See Figure 38 for discussion of labels.

From Figure 38 and Figure 39 (identical to Figure 4) it can be seen that a few cross sections exhibit 8-10 ft of scour at isolated cross sections and the locations are not consistent across the various bed sediment reservoir depths. The change at cross section 13.58 was on the order of 26 ft. The data for this figure were obtained from the minimum bed elevation data in the .t6 files.

During the analysis the data from the .t98 (plot) file was reviewed. These data did not exhibit the same instabilities that can be seen above in Figure 38 and Figure 39. These data did show some variability based on the bed sediment reservoir depth but the maximum variance at a cross section was 2.12 ft rather than 26.45 ft from the .t6 data. The conclusion was reached (in conjunction with the model developers) that the data from the .t98 files should be used rather than the data from the .t6 files. The model was run in the latest version of the model and no differences were found between the data in the .t6 files and that found in the .t98 files so the problem has apparently been previously located and corrected.

A comparison of the .t98 data located in the Appendix shows that only one other cross section showed a difference of more than 2.0 ft between the various runs so most values are within a reasonable difference based on the selection of the bed sediment reservoir depth.

Another important observation from this set of data was that the maximum residual depth during the calculations was significantly lower for runs with large numbers of warnings regarding the bed sediment reservoir depth. It appears that the value given at the end of the HEC-6T runs should be checked for reasonableness but not used as a calibration tool. The values for this test varied from 0.43 to 1.0 with the results from both ends being unacceptable due to various cross sections showing excessive warnings regarding the depth of the bed sediment reservoir. The values obtained for models that were acceptable were in the 0.74 to 0.86 range but several of the unacceptable runs produced values of 0.86 for the minimum residual depth as well as one of the acceptable runs.

These results and the model were sent to the model developers and the recommendation was made to turn off the $SMOOTH cards in the version of the HEC-6T model being used. This was done and the results rerun with the exception of the inflowing load runs. The models with the $SMOOTH card turned off (i.e. no bed smoothing) were more stable and gave better results in most areas. It was also noted that the newest version of the HEC-6T model did not produce the anomalies found in the version of the model used in this study (version 5.13.22.05 May 20, 2006).

Extensive analysis of the impact of the bed sediment reservoir depths was not undertaken since this analysis was outside the scope of the original project. These results do, however; indicate that the values used for the bed sediment reservoir depth can also be important to the model at particular cross sections. The adjustment of problematic cross sections is normally straight forward – especially if the warnings are reviewed in the model. The maximum scour depths in the .t6 file should be compared with the ending depth to insure that one or more cross sections are not skewing results due to the cross section definition or an anomaly in the model. If cross sections are found similar to those shown in Figure 39 they should be checked with minimum bed data from the .t98 file or .t6 file – especially in older versions of the HEC-6T model.

5.0 Pit Dimension Sensitivity Analysis

The impact of the size of mining pits and their configuration was investigated to view the impacts of varying sizes of pits on the headcut results obtained from the HEC-6T model. The length of the pit in the river channel, the width of the pit in relation to the river channel and the depth of the pit below the river thalweg were all investigated to determine how the changes in size and shape would impact the length and depth of the headcut associated with each pit. Each of the parameters was modified at least three times to both increase and decrease the length, width and depth of the pit. The project scope called for an analysis to determine the impact of the changes on the headcut depth and length for each of the tests.

5.1 Pit Width

The width of the Pioneer pit varied throughout the length of the pit. Since the pit was not rectangular it was decided that the general shape of the pit would not be changed but the changes in the width dimension would be made by adjusting the width by the same factor for each cross section in the pit. The change in the pit width varied from half the original width of the pit to double the original pit width. This was done primarily by widening the pit to the west (right descending bank) and narrowing the pit on the east. Modifications were made to the east side of the pit (left descending bank) for only three cases. The first was the 0.5 width case where the width of the pit was reduced to half its original width from the east while the west side was left in its original position. The other two cases were at cross section 15.62 for the 1.5 and 2.0 times the original pit width case where the increase in pit width was taken 50% on each side of the channel. This is illustrated graphically in Figure 40 and was done to keep the pit bank line smooth as the pit was expanded.

The original pit cross section at RM 15.62 included a section of the pit that was ineffective and behind a narrow peninsula which can be seen in Figure 40. This can also be seen in Figure 41 for the "Base Xsect" plot. The portion of the original pit to the east of station 2100 was eliminated after some problems were noted in the results for the width runs. The area between station 1900 and 2100 (see Figure 41) was set approximately to the pre-pit channel elevation for the 1.0 and 0.5 runs. The area was partially utilized for the 1.5x run and fully removed for the 2.0x run. The various pit cross sections at RM 15.62 can be seen in Figure 41. Since there is a relatively high bluff along the east bank for the remaining length of the pit the balance of the adjustments were made to the west bank (right descending bank) for the alternatives where the pit was expanded. This adjustment removed all of the observed model instabilities for this case.

Once the model instabilities were corrected the HEC-6T model was run for each of the four conditions (0.5, 1.0, 1.5 and 2.0 x the original pit width) and the results were plotted for comparison. The results for the headcut depth and length are shown in Table 14. The averaged values are shown in Figure 42. It can be seen that the averaged data shows a slight trend towards increasing headcut depth with increasing pit width but the increase is not large (approximately 0.5 ft total). The actual data is as follows: 0.5x Width =-5.454 ft, 1.0x = -5.628 ft, 1.5x = 5.723 ft, and 2.0x = 5.91 ft.

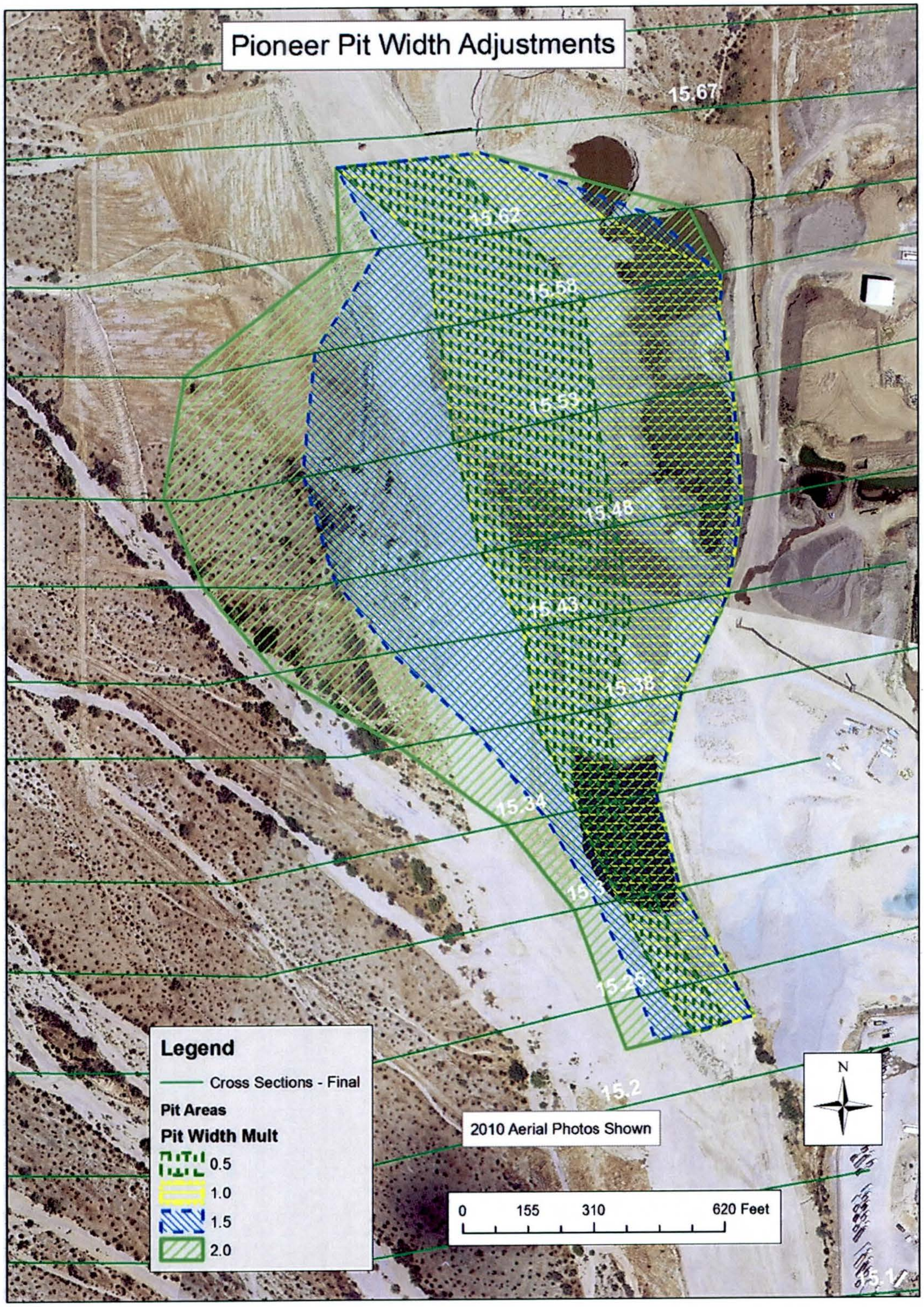


Figure 40. Pit Width Layouts for Evaluation of Impact on Headcut Potential.

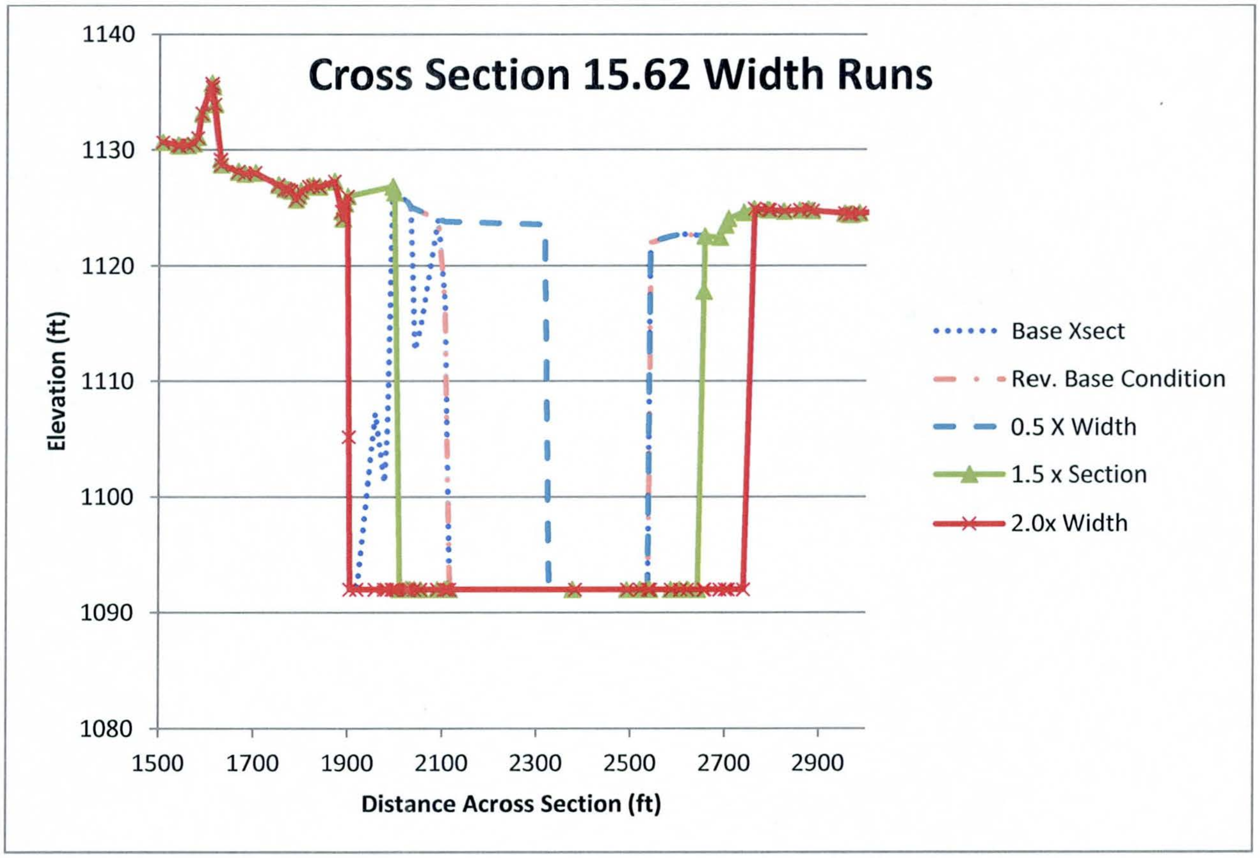


Figure 41. Cross Section Plots for Width Variations at Cross Section 15.62.

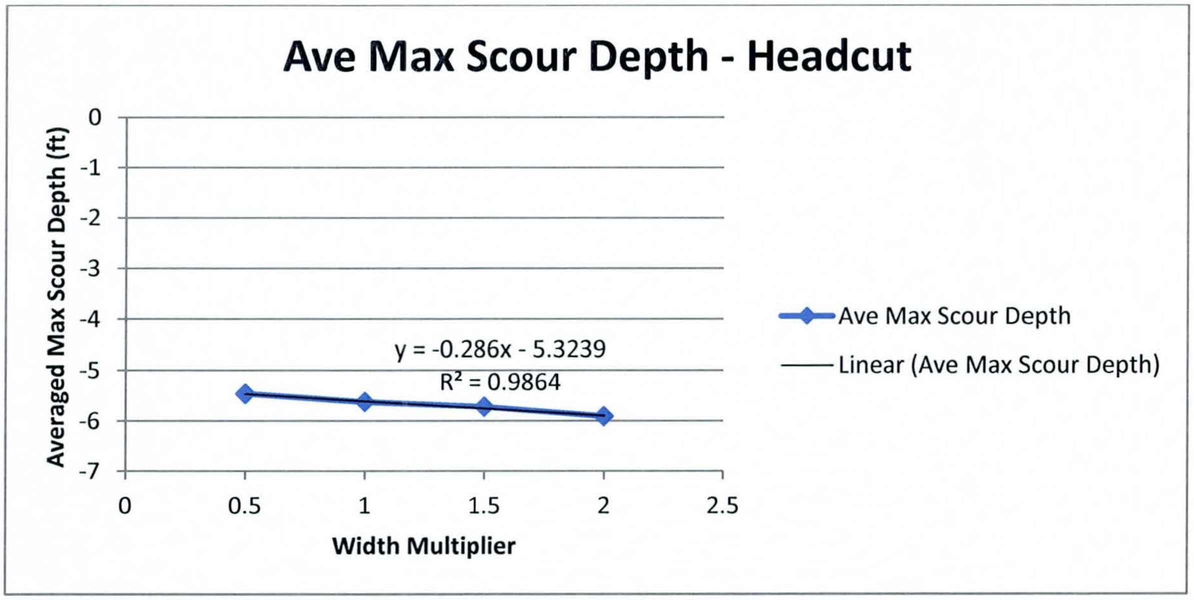


Figure 42. Averaged Maximum Scour Depth vs. Width Multiplier.

Table 14. Bed Change Data for Pit Width Variation Tests. Negative values show Scour and Positive Values show Deposition.

Ending Scour/Deposition Depth					Maximum Scour/Deposition Depth				
Cross Section	0.5x	Base	1.5x	2.0x	Cross Section	0.5x	Base Max	1.5x	2.0x
16.72	-1.52	-1.31	-1.38	-1.46	16.72	-1.86	-1.44	-1.71	-1.68
16.63	-0.81	-0.71	-0.74	-0.78	16.63	-1.77	-1.47	-1.51	-1.73
16.55	-0.43	-0.84	-0.36	-0.94	16.55	-1.34	-1.14	-1.24	-1.15
16.48	-0.64	-1.45	-0.68	-1.43	16.48	-0.97	-1.80	-0.86	-1.67
16.42	-1.58	-1.39	-1.62	-1.45	16.42	-1.58	-2.10	-1.62	-2.17
16.33	-1.53	-0.96	-1.53	-1.03	16.33	-2.02	-1.03	-2.06	-1.03
16.24	0.21	0.63	0.15	0.72	16.24	-0.10	-0.09	-0.11	-0.09
16.15	0.83	0.72	0.85	0.73	16.15	1.7E-05	1.7E-05	1.7E-05	1.7E-05
16.07	-3.51	-3.62	-3.56	-3.56	16.07	-3.99	-4.16	-4.00	-4.17
15.98	-1.44	-1.5	-1.55	-1.68	15.98	-1.44	-1.50	-1.55	-1.68
15.94	-1.6	-1.51	-1.81	-1.72	15.94	-2.20	-2.05	-2.27	-2.29
15.9	-1.89	-1.78	-2.21	-2.15	15.9	-2.02	-2.07	-2.20	-2.22
15.86	-2.75	-2.68	-3.06	-3.08	15.86	-3.03	-2.82	-3.17	-3.48
15.81	-4.79	-4.7	-5.02	-5.32	15.81	-4.79	-4.70	-5.02	-5.32
15.76	-6.63	-6.92	-7.2	-7.26	15.76	-7.13	-7.76	-7.41	-7.87
15.71	-8.73	-9.03	-9.77	-9.54	15.71	-10.99	-11.47	-11.18	-11.46
15.67	-12.3	-12.62	-12.78	-13.86	15.67	-13.60	-14.14	-14.70	-14.71
15.62	18.54	18.52	18.59	15.27	15.62	21.09	20.58	19.20	15.27
15.58	16.35	5.74	1.51	0.79	15.58	16.35	5.74	1.51	0.79
15.53	2.49	0.6	0.28	0.14	15.53	2.485	0.60	0.28	0.14
15.48	0.94	0.25	0.08	0.03	15.48	0.94	0.25	0.08	0.034
15.43	0.66	0.15	0	0.02	15.43	0.66	0.15	0	0.017
15.38	0.47	0.08	0.03	0.01	15.38	0.47	0.08	0.026	0.010
15.34	0.38	0.05	0.02	0.01	15.34	0.38	0.05	0.017	0.006
15.3	0.09	0.03	0.01	0	15.3	0.09	0.03	0.008	0.003
15.25	0.04	0.02	0	0	15.25	0.04	0.02	0.0004	0.0001
15.2	-4.11	-4.1	-4.06	-4.05	15.2	-4.11	-4.09	-4.06	-4.05
15.15	-2.95	-2.94	-2.97	-2.98	15.15	-2.97	-2.94	-2.97	-2.98
15.1	-2.08	-2.18	-2.18	-2.19	15.1	-2.08	-2.18	-2.18	-2.19
15.06	-1.41	-1.57	-1.5	-1.49	15.06	-1.41	-1.57	-1.50	-1.49
14.96	-0.41	-0.51	-0.44	-0.44	14.96	-0.41	-0.51	-0.44	-0.44
14.86	0.26	0.24	0.23	0.21	14.86	2.1E-05	1.9E-05	1.8E-05	1.7E-05

16.15-16.72 Upper Observed Headcut – Above Modeled Headcut
15.67-16.07 Lower Observed Headcut – Modeled Headcut Length for Most Runs
15.25-15.62 Observed Pioneer Pit
18.86-15.20 Modeled Tailcut

The headcut depth for both the ending bed and minimum bed is shown in Figure 43. Both the ending bed and minimum bed elevations tend to lower (i.e. scour depth increases) as the pit is widened for the cross section immediately upstream from the pit (15.67). When the headcut scour depth reaches a depth of approximately 0.5 ft lower than the outlet elevation (minimum tailcut elevation) the maximum headcut depth stabilizes as can be seen in Figure 44. This indicates that the final tailcut elevation very likely controls the headcut elevation at the pit entrance when the pit is filled with water.

The results show that the headcut length does not vary due to changes in pit width. The headcut length was 2112 ft for all runs reaching from cross section 15.67 to 16.07. This data can be found in Table 14.

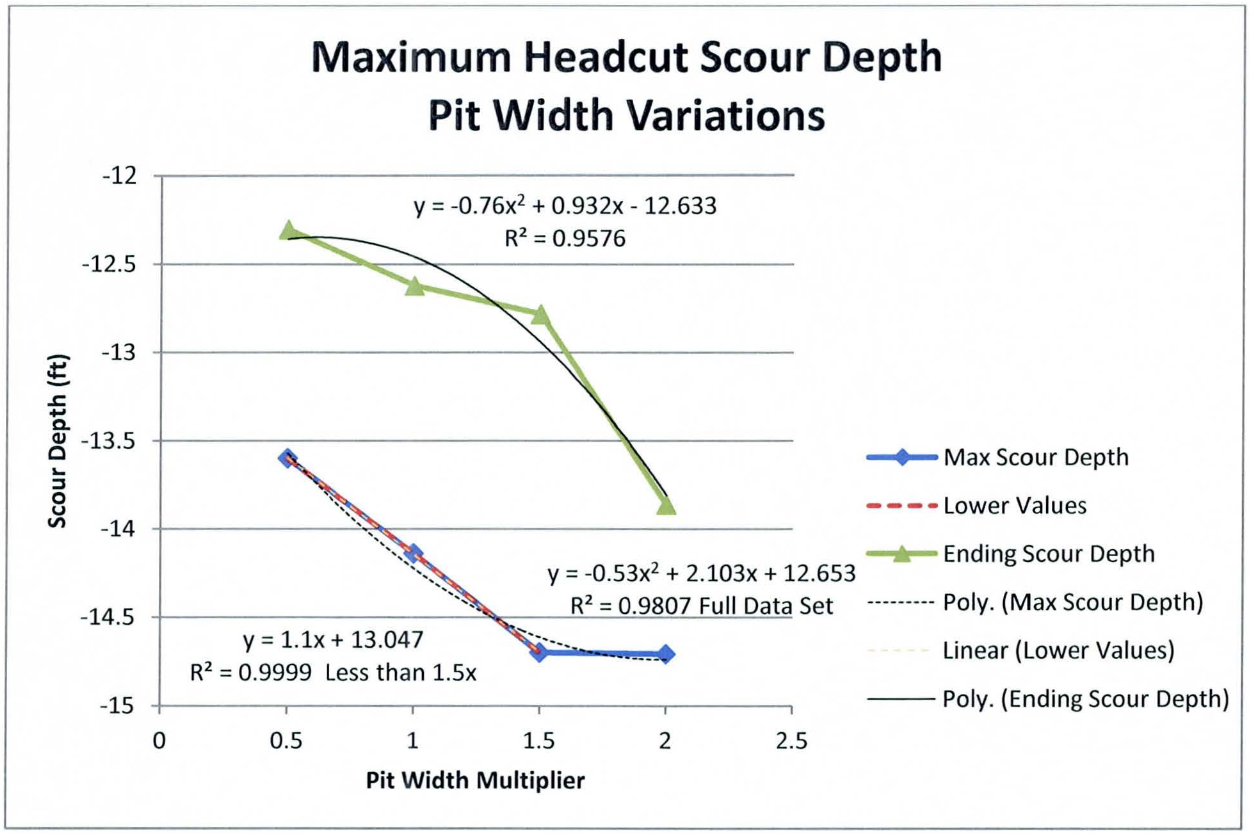


Figure 43. Headcut Depth for Width Variation plots.

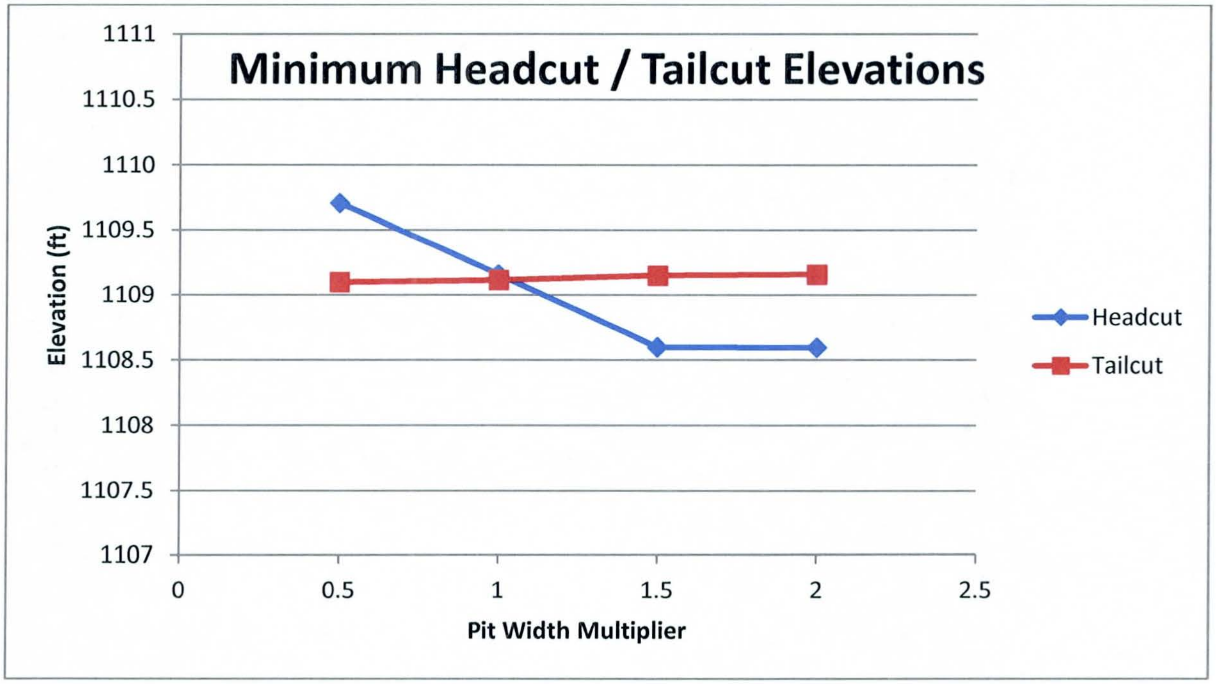


Figure 44. Minimum Headcut and Tailcut Elevations for Pit Width Modeling.

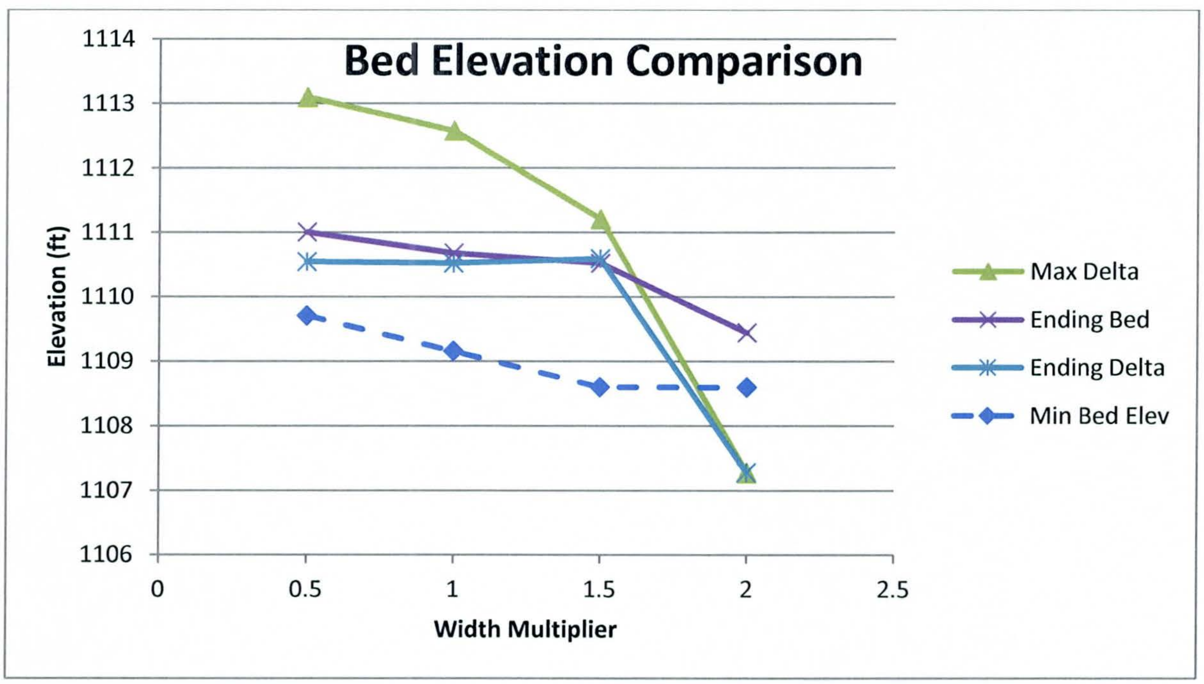


Figure 45. Relation between Ending Bed, Minimum Bed and Maximum Delta Elevations for Pit Width Runs.

The increase in scour depth with increasing pit width appears to be due to the impact of deposition in the upstream portion of the pit. By viewing Figure 45 it can be seen that the minimum bed elevation roughly parallels the ending bed elevation but is approximately 1 to 2 ft lower. The ending headcut elevation is controlled by the depositional delta building in the pit. The elevation of the delta is higher in the narrower pit since there is less volume for the deposition to fill. This can be seen graphically in

Figure 46 which shows the minimum headcut and tailcut elevations for the runs as well as the maximum pit deposition (delta) elevations for the various runs. Looking at it another way the volume eroded from the headcut as well as that flowing into the pit from above the headcut is spread over a wider area for the wider pits and it takes more sediment to fill the pit to the level of the headcut. In the widest pit modeled the delta never reaches the elevation of the headcut and never impacts the headcut elevation. Both the ending and minimum headcut elevation approaches the tailcut elevation of approximately 1109 ft. This again indicates that the tailcut elevation controls the headcut elevation for this pit. This may not be true for pits that take a long period of time to fill since the downstream control on headcut elevation will not impact headcut scour until the pit fills with water.

Equations were developed to predict the rate of change for the headcut depth due to changes in pit width. The equations for the change in maximum head cut for the minimum bed (maximum depth) and the ending bed are as follows:

Averaged Maximum Scour Depth for the Headcut Reach

$$y = -0.286x - 5.3239 \qquad R^2 = 0.9864 \qquad (31)$$

$$\frac{dy}{dx} = -0.286 \qquad (32)$$

Maximum Scour Depth

Full Data Set $$y = -0.53x^2 + 2.103x + 12.653 \qquad R^2 = 0.9807 \qquad (33)$$

$$\frac{dy}{dx} = 1.06x+2.103 \qquad (34)$$

Only Data 1.5x & Below $$y = 1.1x + 13.047 \qquad R^2 = 0.9999 \qquad (35)$$

$$\frac{dy}{dx} = 1.1 \qquad (36)$$

Ending Scour Depth

$$y = -0.76x^2 + 0.932x - 12.633 \qquad R^2 = 0.9576 \qquad (37)$$

$$\frac{dy}{dx} = -1.52x+0.932 \qquad (38)$$

The change in maximum headcut elevation (minimum bed elevation) is 8.1% (based on the 0.5x value) between the narrowest pit and the widest pit. The change in ending bed elevation is slightly higher at approximately 12.7% again using the 0.5x value as the basis for the calculation.

Figure 46 shows the maximum (pit) and minimum (headcut and tailcut) profile elevations for the area surrounding the Pioneer pit. This shows differences in the bed elevation in the pit due to changes in the pit width. The deposit is deeper and carries further into the pit for the narrower pits. This is a result of the same erosion volume form the headcut requiring differing lengths within the pit to contain the eroded volume.

The tailcut is also shown for reference and shows no significant impact due to pit width as discussed earlier. The maximum difference is approximately 0.12 ft with most differences being more like 0.04 ft (see Figure 43 and Table 14) at the various cross sections impacted by the tailcut.

5.1.1 Conclusion

The width of the pit does have an influence on the depth of the headcut calculated by HEC-6T although not an extremely large impact. The impact ranges from approximately 8 to 12% depending on which elevation (maximum depth or ending depth) is used and based on a range of 50% to 200% of the original pit width. The headcut depth tends to decrease with the narrowing of the pit due to deposits in the upstream portion of the pit that limits the scour depth. The predicted headcut length was 2112 ft.

The maximum headcut depth appears to be limited by approximately the elevation of the maximum tailcut depth. The final headcut elevation is controlled by the interaction between the headcut, the delta formation and the pit outlet (tailcut). The maximum headcut was approximately 0.5 ft lower than the elevation of the tailcut depth but the headcut appears to stabilize near the value of the tailcut (±0.6 ft) for this set of tests.

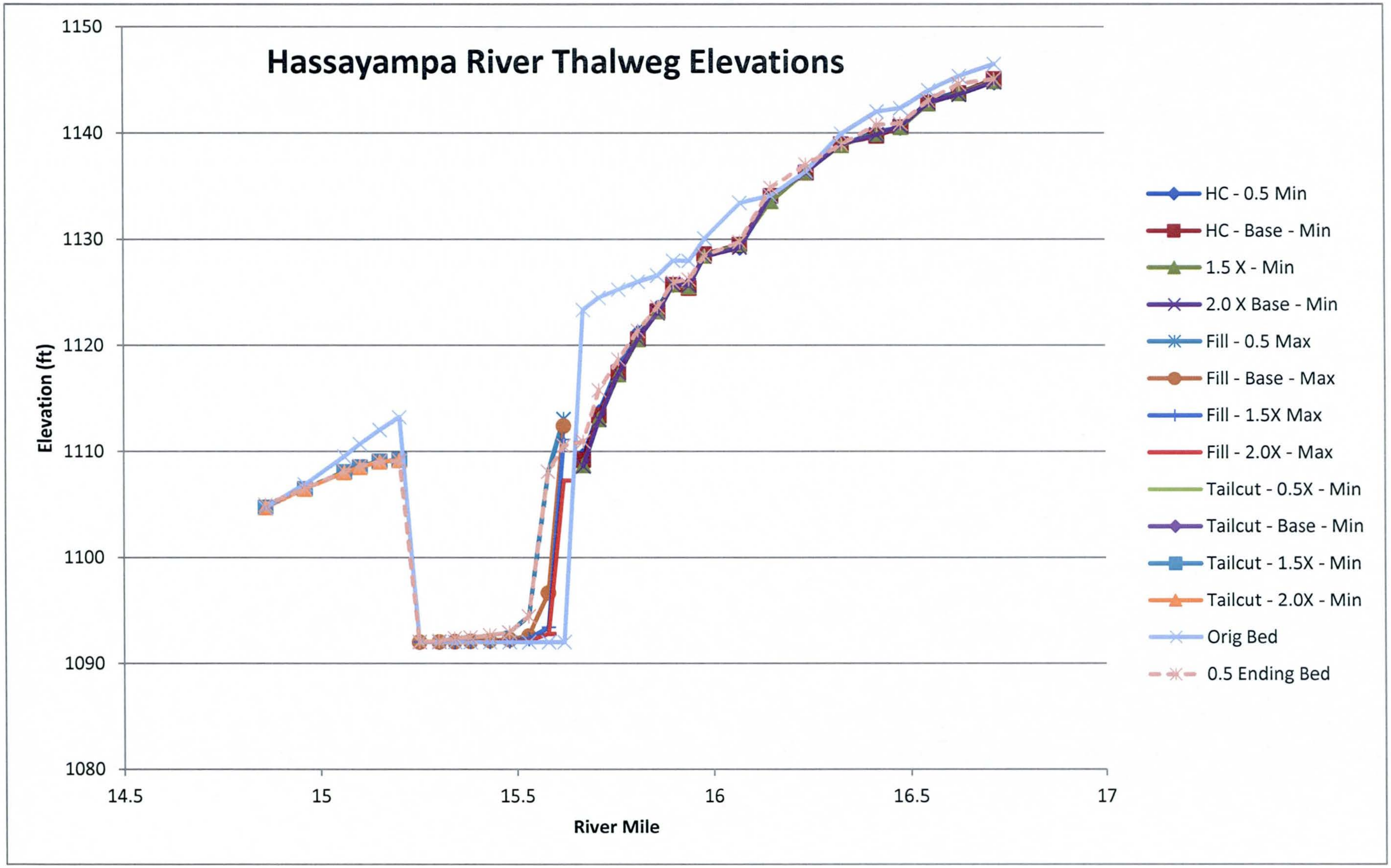


Figure 46. Thalweg Elevations showing Minimum and Maximum Bed Elevations for Width Variations in Pioneer Pit Reach.

5.2 Pit Depth

The pit depth was originally modeled as being 30 ft in depth. The cut was assumed to be flat and 30 ft deep when measured from the upstream thalweg. Additional runs were performed with pit depths of 60 ft, 45 ft, 20 ft and 10 ft. A single run was made in the earlier study with a depth of 20 ft and no significant changes were noted. The 20 ft depth model was also rerun in this study to provide an additional data point. The pit depth and base elevation for the various pit runs is shown in Table 15.

Table 15. Pioneer Pit Depths Run to Determine Impacts of Pit Depth on Headcut Depth and Length in HEC-6T.

Pit Depth	Pit Bed Elevation	Description
60 ft	1062 ft	2 x Depth
45 ft	1077 ft	1.5 x Depth
30 ft	1092 ft	1.0 x Depth - Original Model
20 ft	1102 ft	0.67 x Depth
10 ft	1112 ft	0.33 x Depth

The results of the modeling are shown in Figure 47. In addition to showing the headcut the predicted pit infill (delta) was also plotted. The figure shows the results as well as the beginning bed elevation for the various runs. Figure 48 shows a more detailed view of the headcut / pit delta area and it can be noted that the predicted deposition in the pit all occurs within the first 2-3 cross sections with the exception of the 10 ft deep pit. The figures show that for the 10 ft deep pit the flow does not have the ability to scour below the 10 ft original depth of the pit which results in a shallower headcut than the rest of the pit depths. The 20, 30, 45, and 60 ft deep pits result in very similar headcut depths. The headcut depths and elevations are shown in Table 16 and Table 17.

The averaged maximum scour depth for the headcut reach is shown in Figure 49 and shows an increasing average to approximately a 30 ft deep pit with a possible slight increase once the pit reaches approximately 60 ft in depth. An additional data point would be useful to see if this is a trend for deeper pits or if the flat trend continues beyond the 60 ft depth.

The actual headcut depth results are plotted in Figure 50 and it can be seen that except for the shallow (10 ft) pit the headcuts area all very similar for the minimum bed elevation. The ending bed headcut depth tends to increase with increasing pit depth to about the 45 ft depth after which both the ending and minimum bed elevations do not appear to be impacted by increasing pit depth. It should be noted that the modeling effort assumes the pits to be full when the model starts. If the pits are dry the initial headcut depth could be significantly deeper than that predicted in this effort for the area immediately upstream of the pit.

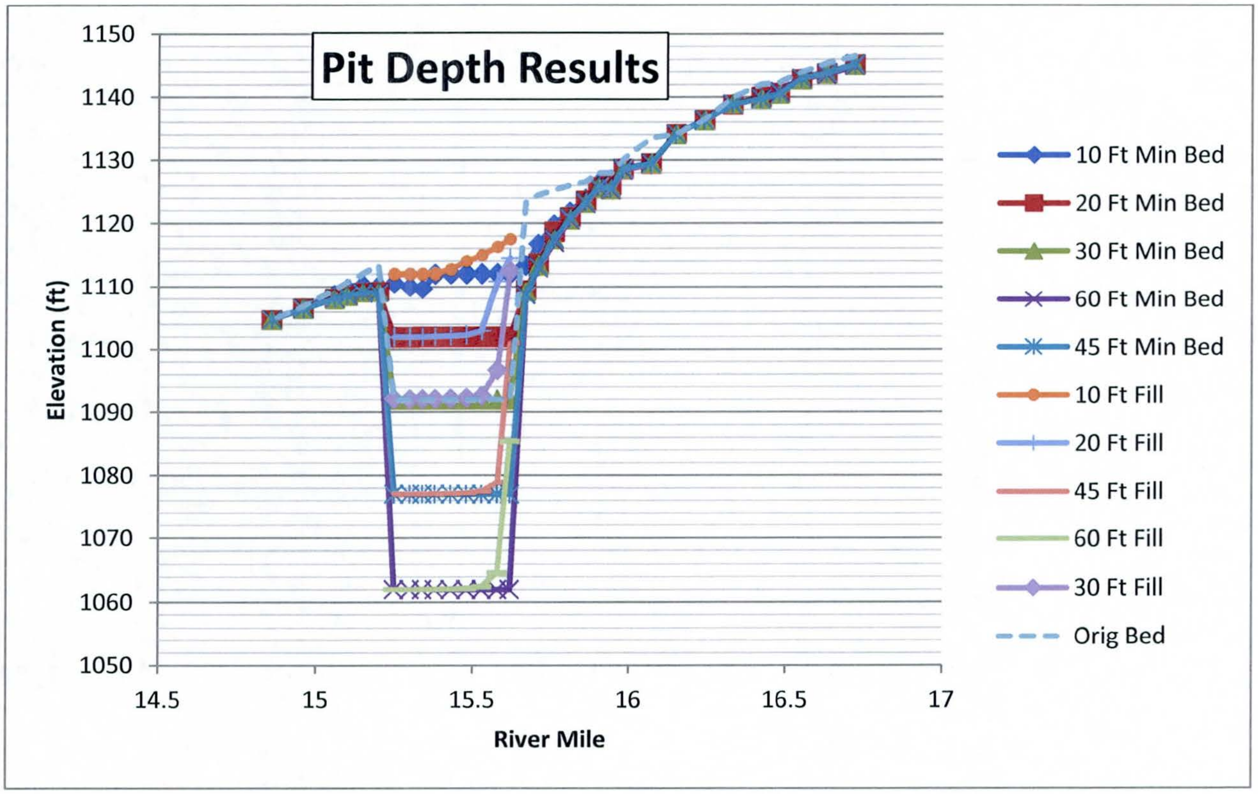


Figure 47. Minimum Bed (Maximum Scour Depths) for the Pit Depths Modeled Including Maximum Deposits in Pit.

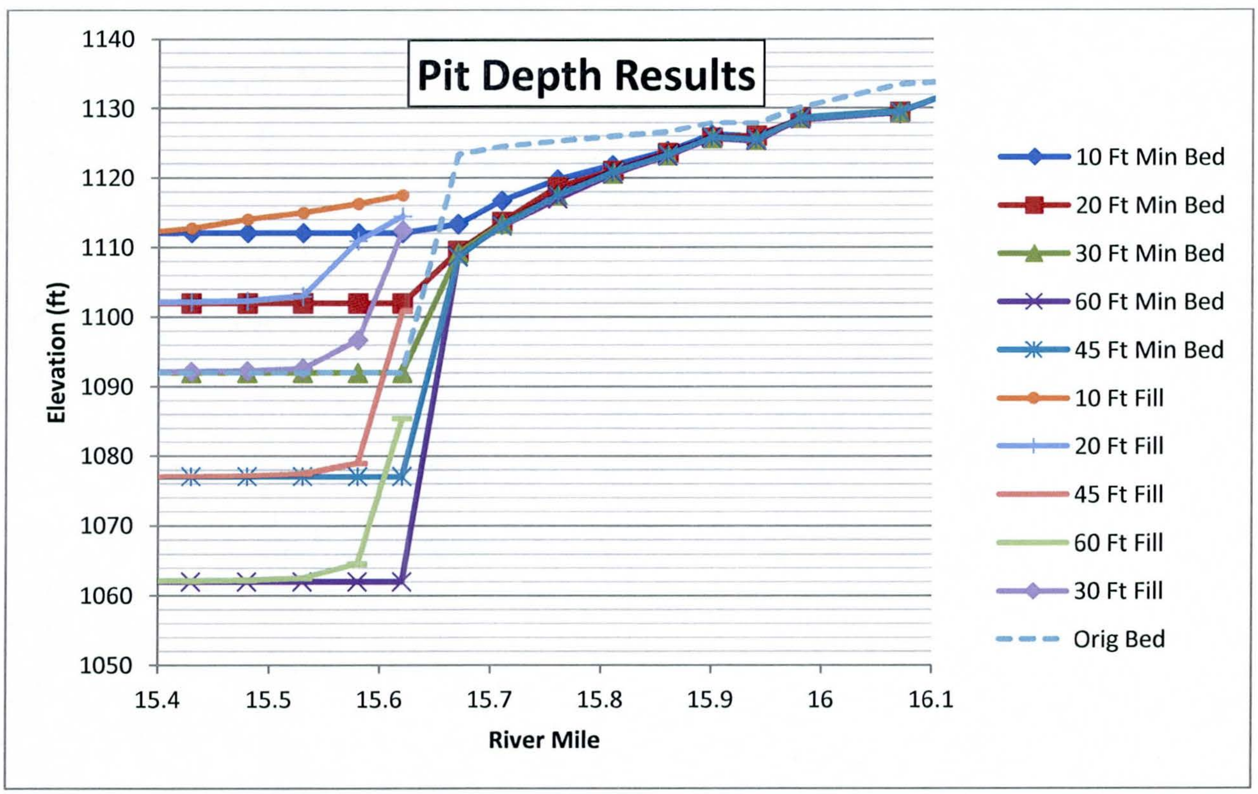


Figure 48. Headcut and Pit Filling Data for Pioneer Pit with Differing Modeled Pit Depths.

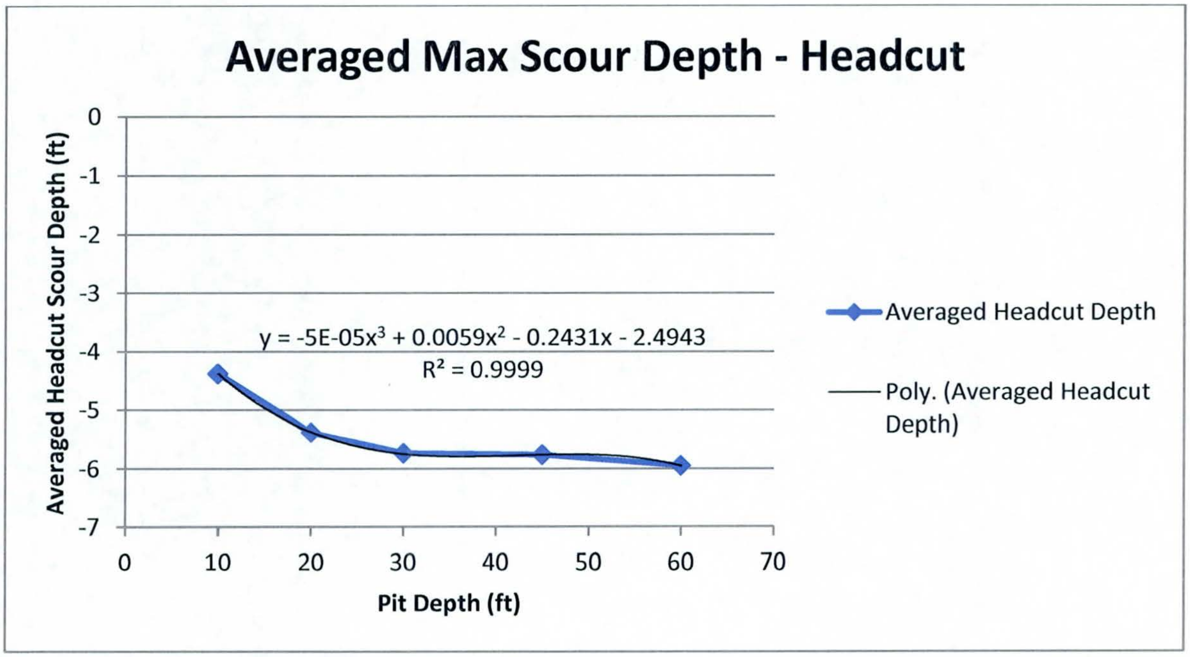


Figure 49. Averaged Maximum Scour Depth for Headcut Reach.

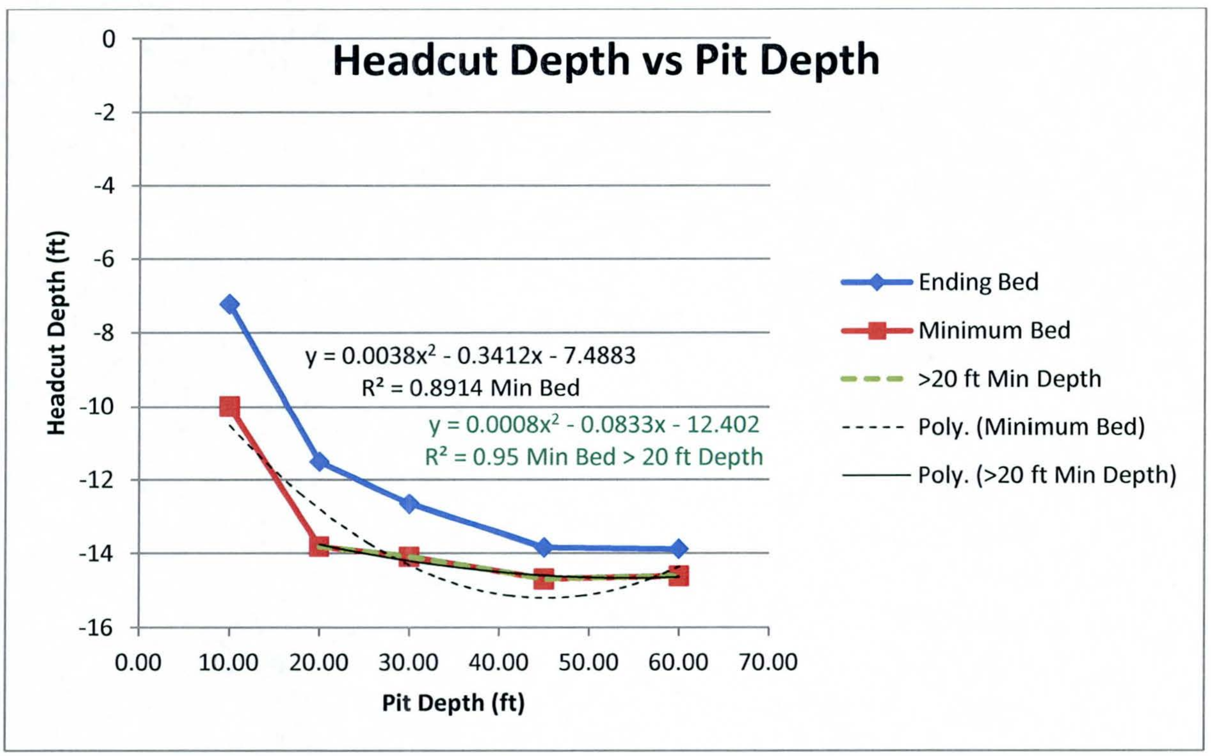


Figure 50. Relationship between Pit Depth and Headcut Depth for Maximum Scour Depth and Ending Scour Depth.

The equation to predict the averaged maximum scour depth in the headcut reach is:

$$y = -5E\text{-}05x^3 + 0.0059x^2 - 0.2431x - 2.4943 \qquad R^2 = 0.9999 \qquad (39)$$

and the slope of the equation (rate of change of the averaged scour depth) is:

$$\frac{dy}{dx} = -15E\text{-}05x^2 + 0.0118x - 0.2431 \quad (40)$$

The equation of the maximum scour depth from Figure 50 is as follows:

For the full data set (10 to 60 ft pit depth):

$$y = 0.0038x^2 - 0.3412x - 7.4883 \qquad R^2 = 0.8914 \qquad \text{Min Bed} \quad (41)$$

$$\frac{dy}{dx} = 0.0076x - .3412 \quad (42)$$

For the data for 20 ft in depth and deeper (20 to 60 ft in depth):

$$y = 0.0008x^2 - 0.0833x - 12.402 \qquad R^2 = 0.95 \qquad \text{Min Bed > 20 ft Depth} \quad (43)$$

$$\frac{dy}{dx} = 0.0016x - 0.0833 \quad (44)$$

It is likely that an additional run with a 15 ft pit depth would help better define the curve but it is apparent that there is a significantly difference in response when the pit is very shallow. The length of the headcut was constant at 2112 ft for all of the runs evaluating the impact of pit depth.

Table 16. Bed Change due to Changes in Pioneer Pit Depth. All Data are Reported in Feet.

Ending Bed						Minimum Bed					
Cross Section	Pit Depth					Cross	Pit Depth				
	10 Ft	20 Ft	Base - 30 Ft	45 Ft	60 Ft	Section	10 Ft	20 Ft	Base - 30 Ft	45 Ft	60 Ft
16.72	-1.13	-1.15	-1.19	-1.2	-1.37	16.72	-1.41	-1.36	-1.41	-1.24	-1.49
16.63	-0.73	-0.73	-0.71	-0.74	-0.77	16.63	-1.39	-1.57	-1.59	-1.49	-1.81
16.55	-1.07	-1.09	-1.1	-0.73	-0.81	16.55	-1.09	-1.18	-1.20	-1.01	-1.02
16.48	-1.27	-1.29	-1.46	-1.5	-1.39	16.48	-1.63	-1.70	-1.79	-1.77	-1.44
16.42	-1.49	-1.48	-1.51	-1.37	-1.5	16.42	-2.00	-1.98	-2.30	-2.27	-2.21
16.33	-1.11	-1.13	-0.95	-0.94	-1.14	16.33	-1.11	-1.13	-0.97	-1.05	-1.14
16.24	0.74	0.81	0.47	0.38	0.69	16.24	-0.10	-0.10	-0.10	-0.09	-0.08
16.15	0.77	0.77	0.35	0.37	0.55	16.15	0.00	0.00	0.00	0.00	0.00
16.07	-3.48	-3.35	-3.13	-3.17	-3.26	16.07	-4.08	-3.94	-3.90	-3.96	-3.98
15.98	-1.41	-1.47	-1.44	-1.4	-1.65	15.98	-1.41	-1.47	-1.44	-1.40	-1.65
15.94	-1.24	-1.69	-1.89	-1.74	-1.84	15.94	-2.05	-1.84	-2.50	-2.39	-2.62
15.9	-1.34	-1.91	-2.24	-2.11	-2.27	15.9	-1.76	-2.20	-2.24	-2.11	-2.26
15.86	-1.71	-2.52	-2.92	-2.89	-2.97	15.86	-2.69	-2.92	-3.30	-3.19	-3.42
15.81	-2.82	-4.9	-4.7	-5.12	-5.26	15.81	-4.18	-4.97	-5.36	-5.12	-5.37
15.76	-5.43	-6.17	-7.13	-7.08	-7.38	15.76	-5.50	-6.52	-7.78	-7.71	-8.26
15.71	-6.37	-9.83	-9.14	-9.38	-9.97	15.71	-7.76	-10.78	-11.05	-11.32	-11.40
15.67	-7.23	-11.52	-12.66	-13.85	-13.89	15.67	-10.0	-13.81	-14.09	-14.69	-14.61
15.62	4.53	9.93	18.52	23.95	23.4	15.62	5.50	12.44	20.41	23.95	23.40
15.58	4.11	8.67	4.68	1.93	2.6	15.58	4.28	8.86	4.68	1.93	2.60
15.53	2.98	0.99	0.58	0.47	0.49	15.53	2.98	0.99	0.58	0.47	0.49
15.48	1.86	0.31	0.25	0.2	0.21	15.48	2.01	0.31	0.25	0.20	0.21
15.43	0.71	0.18	0.15	0.12	0.13	15.43	0.71	0.18	0.15	0.12	0.13
15.38	-0.06	0.1	0.08	0.07	0.08	15.38	0.02	0.10	0.08	0.07	0.08
15.34	-1.93	0.02	0.05	0.05	0.05	15.34	0.00	0.02	0.05	0.05	0.05
15.3	-2.03	-0.06	0.03	0.03	0.03	15.3	0.00	0.00	0.03	0.03	0.03
15.25	-1.51	-0.04	0.02	0.02	0.02	15.25	0.00	0.00	0.02	0.02	0.02
15.2	-3.12	-3.99	-4.08	-4.19	-4.1	15.2	-3.12	-3.99	-4.08	-4.19	-4.10
15.15	-1.78	-2.94	-2.94	-2.91	-3.06	15.15	-1.80	-2.94	-2.94	-2.91	-3.06
15.1	-0.98	-2.16	-2.17	-2.21	-2.2	15.1	-0.98	-2.16	-2.17	-2.21	-2.20
15.06	-0.72	-1.44	-1.49	-1.47	-1.44	15.06	-0.83	-1.44	-1.49	-1.47	-1.44
14.96	-0.34	-0.41	-0.43	-0.43	-0.43	14.96	-0.35	-0.41	-0.43	-0.43	-0.43
14.86	0.38	0.17	0.21	0.22	0.24	14.86	0.00	0.00	0.00	0.00	0.00

Table 17. Modeled Elevations for Pioneer Pit Depth Analysis. All data is in Feet above MSL.

Cross Section	Begin Bed Elev.	Ending Bed					Minimum Bed (Pit Elevations are Maximum Bed)				
		Pit Depth					Pit Depth				
		10 Ft	20 Ft	30 Ft	45 Ft	60 Ft	10 Ft	20 Ft	30 Ft	45 Ft	60 Ft
16.72	1146.45	1145.32	1145.30	1145.26	1145.25	1145.08	1145.04	1145.09	1145.04	1145.21	1144.96
16.63	1145.32	1144.59	1144.59	1144.61	1144.58	1144.55	1143.93	1143.75	1143.73	1143.83	1143.51
16.55	1143.98	1142.91	1142.89	1142.88	1143.25	1143.17	1142.89	1142.80	1142.78	1142.97	1142.96
16.48	1142.31	1141.04	1141.02	1140.85	1140.81	1140.92	1140.68	1140.61	1140.52	1140.54	1140.87
16.42	1141.99	1140.50	1140.51	1140.48	1140.62	1140.49	1139.99	1140.01	1139.69	1139.72	1139.78
16.33	1139.90	1138.79	1138.77	1138.95	1138.96	1138.76	1138.79	1138.77	1138.93	1138.85	1138.76
16.24	1136.37	1137.11	1137.18	1136.84	1136.75	1137.06	1136.27	1136.27	1136.27	1136.28	1136.29
16.15	1134.10	1134.87	1134.87	1134.45	1134.47	1134.65	1134.10	1134.10	1134.10	1134.10	1134.10
16.07	1133.40	1129.92	1130.05	1130.27	1130.23	1130.14	1129.32	1129.46	1129.50	1129.44	1129.42
15.98	1130.05	1128.64	1128.58	1128.61	1128.65	1128.40	1128.64	1128.58	1128.61	1128.65	1128.40
15.94	1127.92	1126.68	1126.23	1126.03	1126.18	1126.08	1125.87	1126.08	1125.42	1125.53	1125.30
15.90	1127.94	1126.60	1126.03	1125.70	1125.83	1125.67	1126.18	1125.74	1125.70	1125.83	1125.68
15.86	1126.52	1124.81	1124.00	1123.60	1123.63	1123.55	1123.83	1123.60	1123.22	1123.33	1123.10
15.81	1125.94	1123.12	1121.04	1121.24	1120.82	1120.68	1121.76	1120.97	1120.58	1120.82	1120.57
15.76	1125.22	1119.79	1119.05	1118.09	1118.14	1117.84	1119.72	1118.70	1117.44	1117.51	1116.96
15.71	1124.44	1118.07	1114.61	1115.30	1115.06	1114.47	1116.68	1113.66	1113.39	1113.12	1113.04
15.67	1123.30	1116.07	1111.78	1110.64	1109.45	1109.41	1113.30	1109.49	1109.21	1108.61	1108.69
15.62	1092.00	1116.53	1111.93	1110.52	1100.95	1085.40	1117.50	1114.44	1112.41	1100.95	1085.40
15.58	1092.00	1116.11	1110.67	1096.68	1078.93	1064.60	1116.28	1110.86	1096.68	1078.93	1064.60
15.53	1092.00	1114.98	1102.99	1092.58	1077.47	1062.49	1114.98	1102.99	1092.58	1077.47	1062.49
15.48	1092.00	1113.86	1102.31	1092.25	1077.20	1062.21	1114.01	1102.31	1092.25	1077.20	1062.21
15.43	1092.00	1112.71	1102.18	1092.15	1077.12	1062.13	1112.71	1102.18	1092.15	1077.12	1062.13
15.38	1092.00	1111.94	1102.10	1092.08	1077.07	1062.08	1112.02	1102.10	1092.08	1077.07	1062.08
15.34	1092.00	1110.07	1102.02	1092.05	1077.05	1062.05	1112.00	1102.02	1092.05	1077.05	1062.05
15.30	1092.00	1109.97	1101.94	1092.03	1077.03	1062.03	1112.00	1102.00	1092.03	1077.03	1062.03
15.25	1092.00	1110.49	1101.96	1092.02	1077.02	1062.02	1112.00	1102.00	1092.02	1077.02	1062.02
15.20	1113.21	1110.09	1109.22	1109.13	1109.02	1109.11	1110.09	1109.22	1109.13	1109.02	1109.11
15.15	1112.01	1110.23	1109.07	1109.07	1109.10	1108.95	1110.21	1109.07	1109.07	1109.10	1108.95
15.10	1110.69	1109.71	1108.53	1108.52	1108.48	1108.49	1109.71	1108.53	1108.52	1108.48	1108.49
15.06	1109.51	1108.79	1108.07	1108.02	1108.04	1108.07	1108.68	1108.07	1108.02	1108.04	1108.07
14.96	1106.87	1106.53	1106.46	1106.44	1106.44	1106.44	1106.52	1106.46	1106.44	1106.44	1106.44
14.86	1104.69	1105.07	1104.86	1104.90	1104.91	1104.93	1104.69	1104.69	1104.69	1104.69	1104.69
16.15 to 16.72 - Upper Headcut – Observed but not Noted in Model											
15.67 to 16.07 – Modeled Headcut											
15.25 to 15.62 – Pioneer Pit											
14.86 to 15.20 - Pit Tailcut Data											

Figure 51 includes not only the headcut elevation but the top of the pit delta and the elevation of the exit from the pit (i.e. the minimum tailcut elevation). This data shows that up to a 30 ft pit depth the delta has been sufficient to impact the inflow in the headcut area and resulted in a reduced ending headcut elevation. Beyond a depth of 30 ft for this model the pit delta has no impact on the inflowing water and thus the ending bed is approximately equal to the minimum bed elevation.

Perhaps the most interesting feature shown by the plot is that the minimum bed is again almost equal to the elevation of the ending tailcut. This is shown more clearly in Figure 52 where it can be noted that the minimum headcut elevation (i.e. maximum headcut depth) is very closely related to the ending tailcut elevation with the exception of the 10 ft pit depth. The deeper pits (40 ft and 60 ft depths) do show some slight reduction in the minimum bed elevation (i.e. increase in scour depth) for the headcut below the out flowing (tailcut) elevation likely due to the delta being significantly below the headcut elevation. This difference is about 0.4 ft maximum which is similar to the 0.5 ft depth found in the pit width modeling. This would indicate that for pits that fill quickly the maximum headcut depth perhaps can be estimated as being approximately the same as the elevation of the downstream exit after tailcutting has occurred.

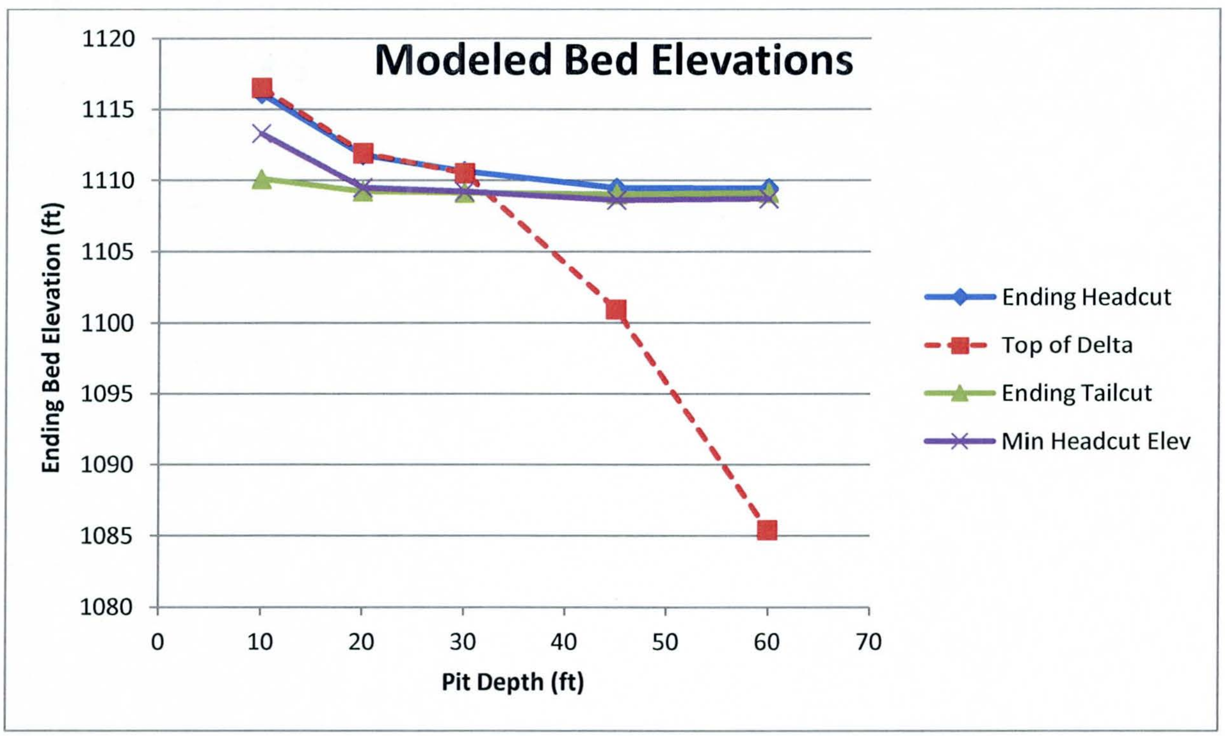


Figure 51. Modeled Bed Elevations for Pioneer Pit showing Relationship between Headcut, Tailcut, and Pit Delta Deposit Elevations and Pit Depth.

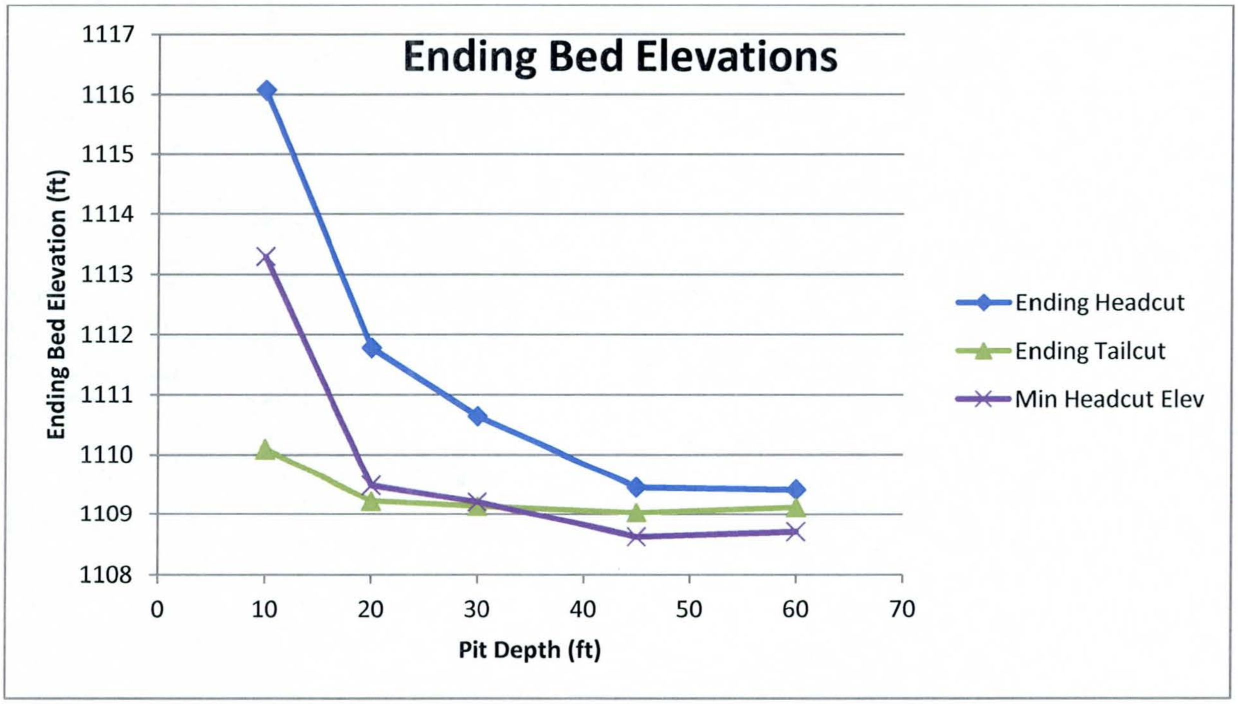


Figure 52. Ending Bed Elevations Showing Relationship between Headcut Elevation and Tailcut Elevation without Pit Delta Elevation for Clarity.

5.2.1 Conclusion

The data shows that the averaged maximum headcut scour (depth) increases with increasing pit depth to a depth of approximately 30 ft in depth. There may be a slight trend towards in an increasing headcut depth when the pit approaches a 60 ft depth but this needs further runs to ascertain if this is the case. The slope of the increase can be predicted by the equation:

$$\frac{dy}{dx} = -15E\text{-}05x^2 + 0.0118x - 0.2431 \qquad (40)$$

The data also indicates that for pits that are filled with water the maximum headcut elevation may be very near the outflow elevation for the pit. For pits that are not filled quickly this may not be the case depending on how quickly the pits fill with water. The maximum headcut being approximately equal to the outflow elevation is likely also true for pits where the inflowing load is not sufficient to fill the pit during the event being modeled.

5.3 Pit Length

The pit length was modeled by varying the length of the lower section of the pit to achieve the desired length. This is in contrast to the method used in the width modeling where the adjustment factor was multiplied by the pit dimension. After reviewing the pit configuration and length data is was determined that it would be more efficient to simply extend the lower portion of the pit rather than to extend each section proportionally. This significantly reduced the potential for errors in pit modification. For the 0.5x case with a shorter pit length the pit was simply truncated to the desired length (approx 1,000 ft).

The longer pits were created by extending the length of the width at the third cross section from the downstream end (183 ft in width) to a long enough section to arrive at the desired pit length. A wider section was also tested to view the impact of the 183 ft section on the results. The extension area for this test was widened to 337 ft (the width of the fourth cross section from the end of the original pit.

The various pit layouts for the pit length runs are shown in Figure 53. The 2.0 x pit length with the wider throat is shown in Figure 54. The elevation of the bottom of the pit was set at an elevation of 1092 ft as was used in all previous model runs with the pits in place. The pit width and beginning profile information is contained in Table 18. The width data and pit bank stations are included for reference.

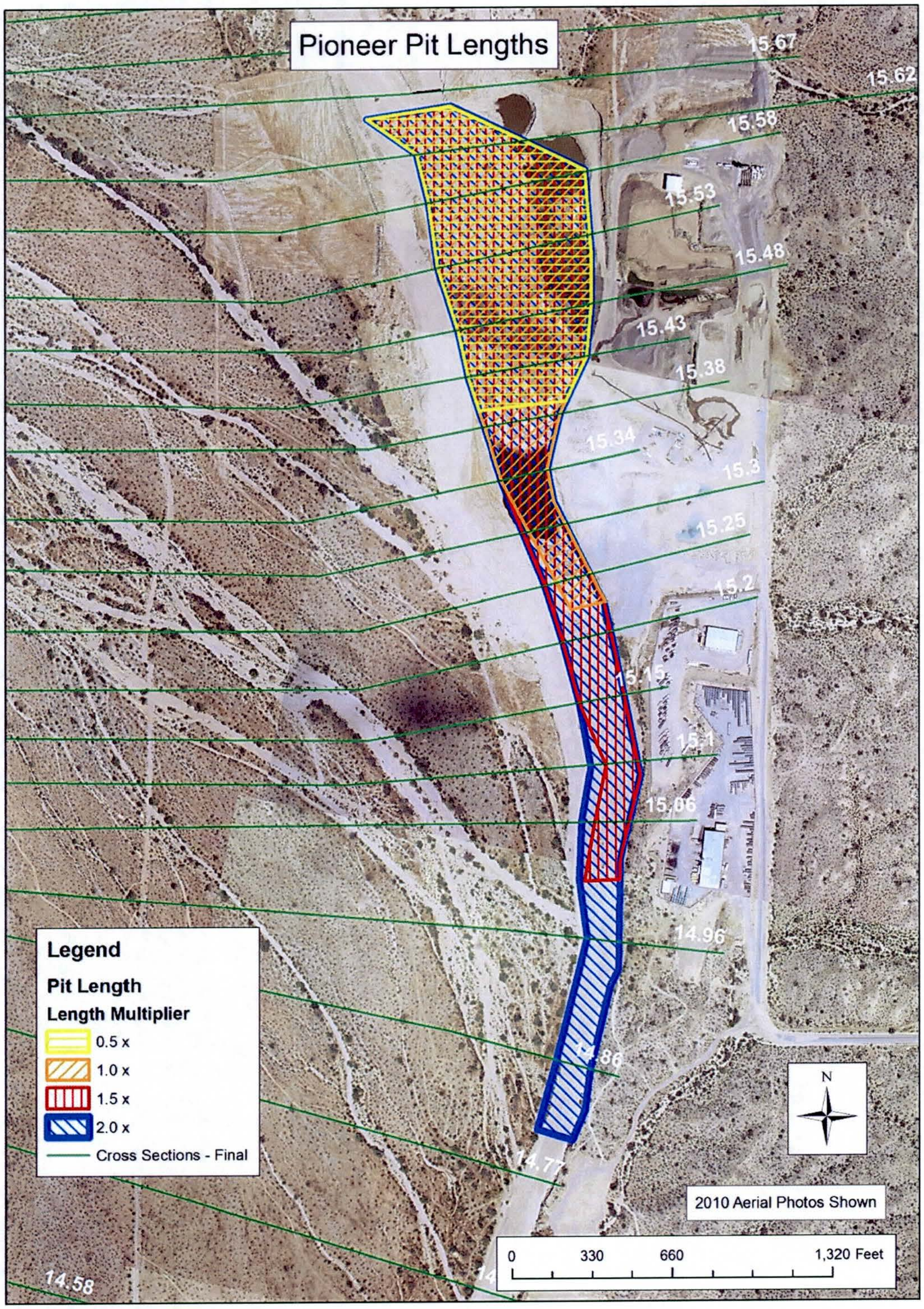


Figure 53. Pit Lengths used in runs to Determine Impact of Pit Length on Headcut Scour Depths.

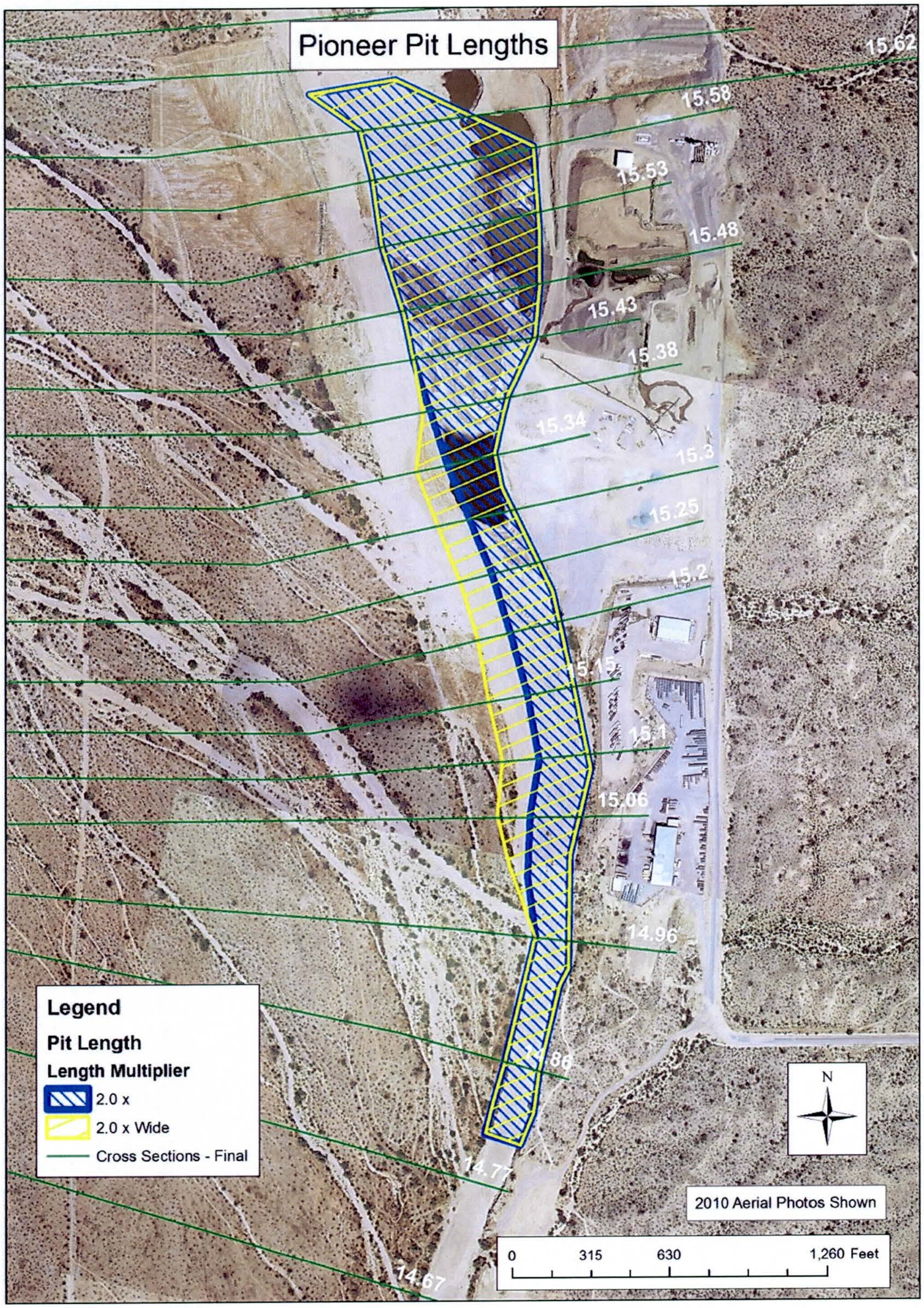


Figure 54. Doubled Pit Length Layouts with Original Layout and Wide Throat Layout.

Table 18. Pit Length Evaluation Dimensions and Stations.

		0.5X Length		1.0X Length - Original Pit Dimensions				1.5X Length				2X Length			
Cross Section	Dist. (ft)	Thalweg Elev. (ft)	Pit Width	Thalweg Elev. (ft)	East Left Sta	West Right Sta	Pit Width	Thal. Elev. (ft)	East / LOB Station	West / RDB Station	Pit Width	Thalweg Elev. (ft)	East / LOB Sta.	West / ROB Sta.	Pit Width
15.62	0	1092	421.98	1092	2116.03	2538.01	421.98	1092	2116.03	2538.01	421.98	1092	2116.03	2538.01	421.98
15.58	211.2	1092	653.61	1092	833.35	1486.96	653.61	1092	833.35	1486.96	653.61	1092	833.35	1486.96	653.61
15.53	475.2	1092	694.47	1092	481.91	1176.38	694.47	1092	481.91	1176.38	694.47	1092	481.91	1176.38	694.47
15.48	739.2	1092	633.81	1092	756.46	1390.27	633.81	1092	756.46	1390.27	633.81	1092	756.46	1390.27	633.81
15.43	1003.2	1092	538.95	1092	375.71	914.66	538.95	1092	375.71	914.66	538.95	1092	375.71	914.66	538.95
15.38	1267.2	1117.75		1092	680.1	1017.14	337.04	1092	680.1	1017.14	337.04	1092	680.1	1017.14	337.04
15.34	1478.4	1116.87		1092	395.94	579.31	183.37	1092	395.94	579.31	183.37	1092	395.94	579.31	183.37
15.3	1689.6	1115.42		1092	904.09	1037.07	132.98	1092	904.09	1087.46	183.37	1092	904.09	1087.46	183.37
15.25	1953.6	1114.92		1092	727.5	877.98	150.48	1092	727.5	910.87	183.37	1092	727.5	910.87	183.37
15.2	2217.6	1113.21		1113.21				1092	622.23	805.6	183.37	1092	622.23	805.6	183.37
15.15	2481.6	1112.01		1112.01				1092	164.44	347.81	183.37	1092	164.44	347.81	183.37
15.1	2745.6	1110.69		1110.69				1092	309.96	442.94	132.98	1092	309.96	493.33	183.37
15.06	2956.8	1109.51		1109.51				1092	285.02	435.56	150.54	1092	285.02	468.39	183.37
14.96	3484.8	1106.87		1106.87				1106.87				1092	433.24	566.22	132.98
14.86	4012.8	1104.69		1104.69				1104.69				1092	116.91	267.45	150.54
14.77	4488	1103.87		1103.87				1103.87				1103.87			
14.67	5016	1101.85		1101.85				1101.85				1101.85			

[1]The pit 2.0x pit length was also run with a widened throat (337.04 vs 183.87 ft) to determine if the narrow lengthened from cross section 15.06 to cross section 15.34 was impacting results. No significant impacts were found.

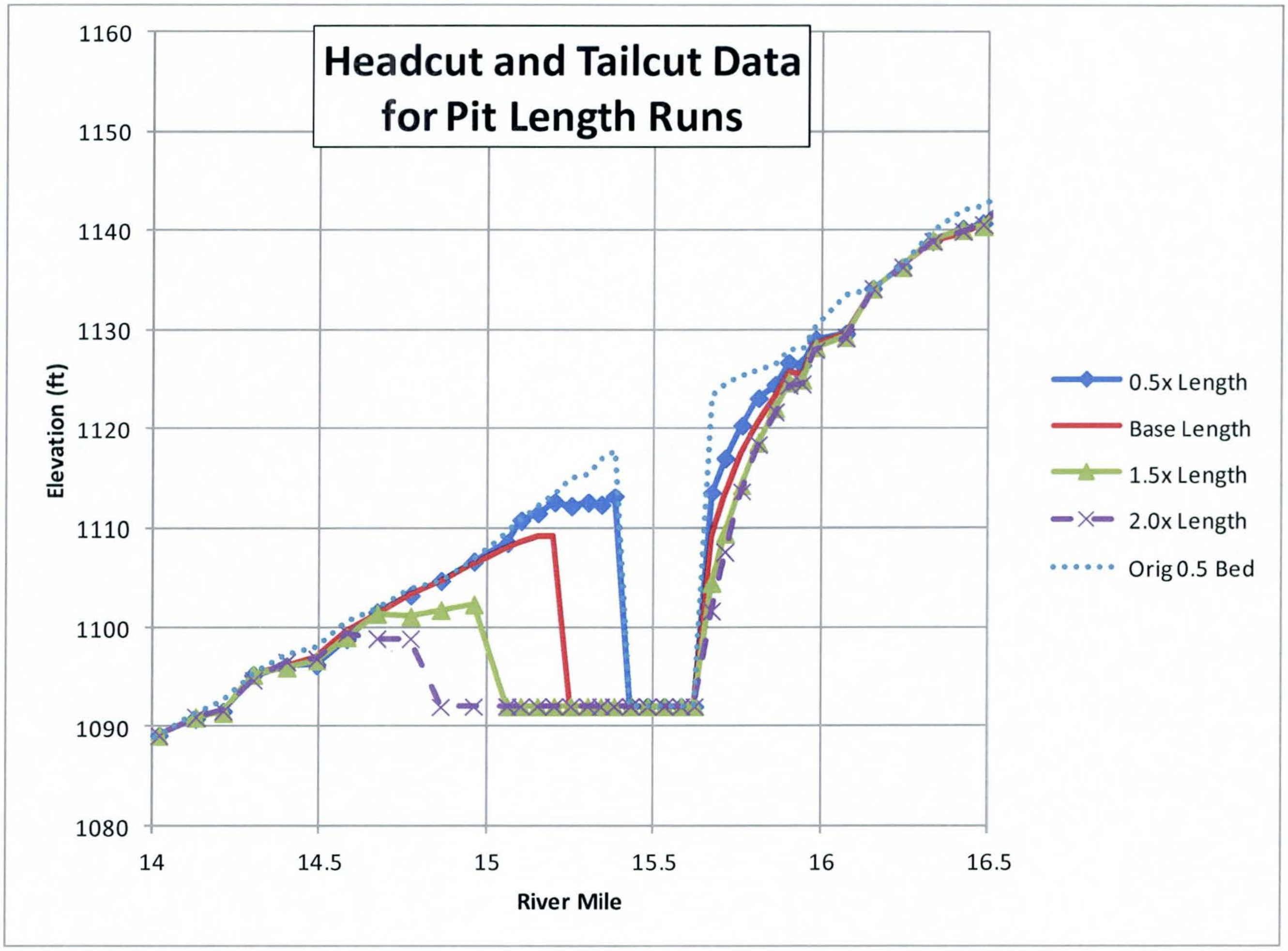


Figure 55. Minimum Bed Elevation Data for various Pioneer Pit Lengths showing Change in Maximum Headcut and Tailcut Scour for Various Pit Lengths.

Five models were run including the 0.5x, 1.0x (base), 1.5x and 2.0x pit lengths as well at the 2.0x length with the wider throat section. The minimum bed profiles of the various pits are shown in Figure 55. The original profiles for the longer pits (i.e. at the beginning of a simulation) match the initial bed profile for the 0.5 x pit length from the downstream end of the respective tailcut to the downstream end of the respective pit length.

The tailcut and headcut information is also included in Figure 55. It can be seen that the pit length has a significant impact on the depth of the headcut but no impact on the headcut length for this model. This is also apparent in Figure 55 where it can be observed that the headcut length does not vary with changes in pit length for this simulation. The summary data is provided in Table 20 for ease in reviewing the data.

Table 19. Ending and Maximum Scour Depths for Pit Length Runs.

Ending Bed						Minimum Bed					
Xsect	0.5x	1.0x	1.5x	2.0x	2.0x Wide	Xsect	0.5x	1.0x	1.5x	2.0x	2.0x Wide
16.24	0.65	0.47	0.44	0.45	0.08	16.24	-0.09	-0.10	-0.10	-0.10	-0.09
16.15	0.76	0.35	0.35	0.03	0.71	16.15	0.00	0.00	0.00	0.00	0.00
16.07	-3.26	-3.13	-3.33	-3.25	-4.04	16.07	-3.85	-3.90	-4.12	-4.24	-4.38
15.98	-1.09	-1.44	-1.87	-2.14	-2.06	15.98	-1.09	-1.44	-1.87	-2.14	-2.06
15.94	-1.03	-1.89	-2.30	-2.85	-3.16	15.94	-1.57	-2.50	-3.00	-3.43	-3.27
15.90	-1.18	-2.24	-2.85	-3.56	-4.03	15.90	-1.34	-2.24	-3.29	-3.56	-4.03
15.86	-1.53	-2.92	-3.66	-4.32	-5.11	15.86	-2.14	-3.30	-4.48	-4.86	-5.29
15.81	-2.48	-4.70	-7.39	-7.11	-7.51	15.81	-2.89	-5.36	-7.39	-7.60	-8.07
15.76	-4.87	-7.13	-10.06	-11.37	-11.69	15.76	-4.93	-7.78	-11.06	-11.65	-11.69
15.71	-6.25	-9.14	-12.69	-14.62	-14.61	15.71	-7.48	-11.05	-15.01	-16.86	-16.90
15.67	-9.90	-12.66	-17.15	-18.15	-18.10	15.67	-9.87	-14.09	-18.81	-21.65	-21.55
15.62	16.40	18.52	13.95	13.04	12.99	15.62	16.40	20.41	18.09	15.33	15.27
15.58	1.61	4.68	11.67	10.69	10.85	15.58	1.61	4.68	11.67	12.04	12.19
15.53	0.40	0.58	0.91	4.01	4.19	15.53	0.40	0.58	0.91	4.01	4.19
15.48	0.16	0.25	0.37	0.45	0.46	15.48	0.16	0.25	0.37	0.45	0.46
15.43	0.07	0.15	0.21	0.26	0.26	15.43	0.07	0.15	0.21	0.26	0.26
15.38	-4.71	0.08	0.12	0.14	0.13	15.38	-4.71	0.08	0.12	0.14	0.13
15.34	-4.59	0.05	0.07	0.07	0.00	15.34	-4.65	0.05	0.07	0.07	0.00
15.30	-2.97	0.03	0.00	0.00	0.03	15.30	-2.97	0.03	0.00	0.00	0.03
15.25	-2.60	0.02	0.06	0.07	0.05	15.25	-2.86	0.02	0.06	0.07	0.05
15.20	-0.73	-4.08	0.05	0.07	0.00	15.20	-0.73	-4.08	0.05	0.07	0.00
15.15	-0.50	-2.94	0.04	0.06	0.00	15.15	-0.66	-2.94	0.04	0.06	0.00
15.10	0.02	-2.17	0.01	0.05	0.00	15.10	-0.03	-2.17	0.01	0.05	0.00
15.06	-0.54	-1.49	0.00	0.04	0.00	15.06	-1.04	-1.49	0.00	0.04	0.00
14.96	0.02	-0.43	-4.53	-0.02	-0.03	14.96	-0.24	-0.43	-4.53	-0.02	0.03
14.86	0.32	0.21	-2.92	-0.05	-0.06	14.86	0.00	0.00	-2.92	-0.05	0.06
14.77	-0.32	-0.64	-2.74	-5.00	-4.99	14.77				-4.99	-4.99
14.67	-0.30	-0.51	-0.48	-2.97	-2.97	14.67				-2.97	-2.97
Headcut Cross Sections Predicted by Model											
Maximum Headcut Value/Beginning of Headcut											
Pit Area – Depositional Values											
Maximum Tailcut Values											

Table 20. Summary of Headcut and Tailcut Data for Length Tests.

Pit Length (ft)	Length Multiplier	Minimum Bed Headcut (ft)		Minimum Bed Tailcut (ft)		Headcut Length (ft)
		Elevation	Depth	Elevation	Depth	
1003	0.5	1113.43	9.87	1113.04	4.71	2112
1954	1.0	1109.21	14.09	1109.13	4.08	2112
2957	1.5	1104.50	18.81	1102.34	4.53	2112
4013	2.0	1101.66	21.65	1098.87	4.99	2112
4013	2-Wide Throat	1101.75	21.55	1098.88	4.98	2112

The averaged change in scour depth and averaged bed change for the headcut reach are shown in Figure 56 and indicate that when properly scaled the bed change and scour depth data track very similarly. The data show that the scour depth increases with increasing pit length.

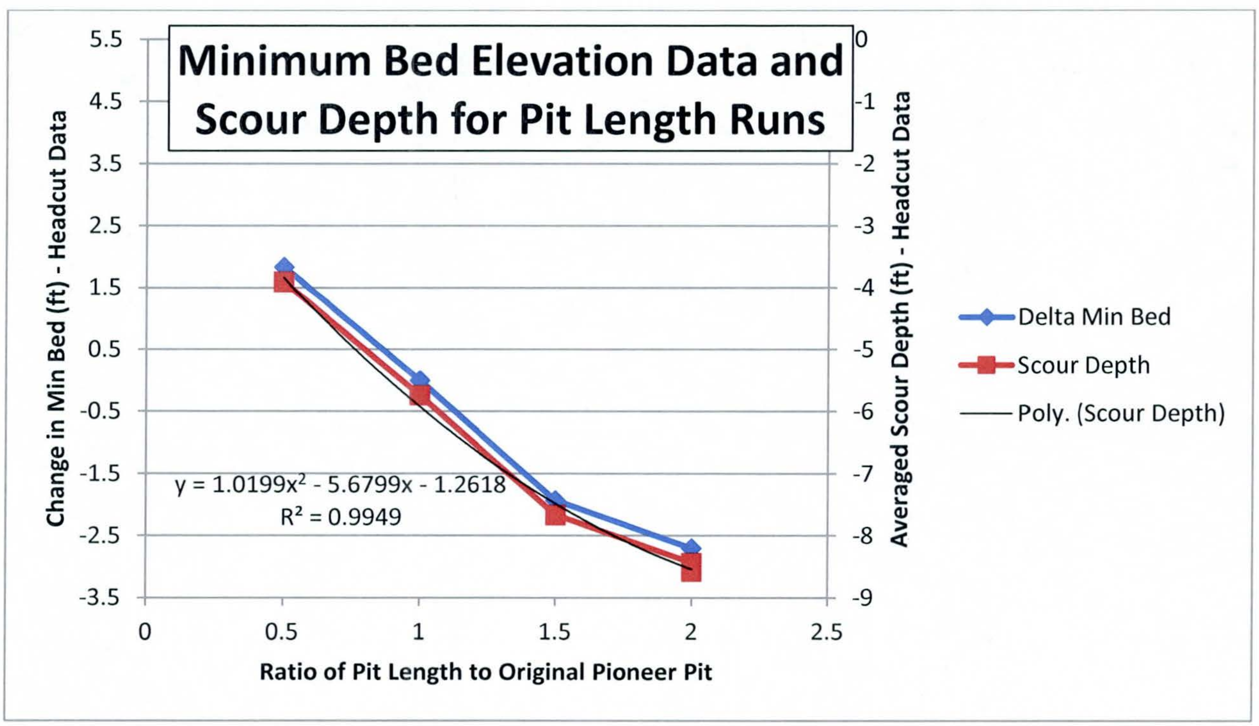


Figure 56. Averaged Minimum Bed Change and Averaged Maximum Scour Depth for Headcut Reach.

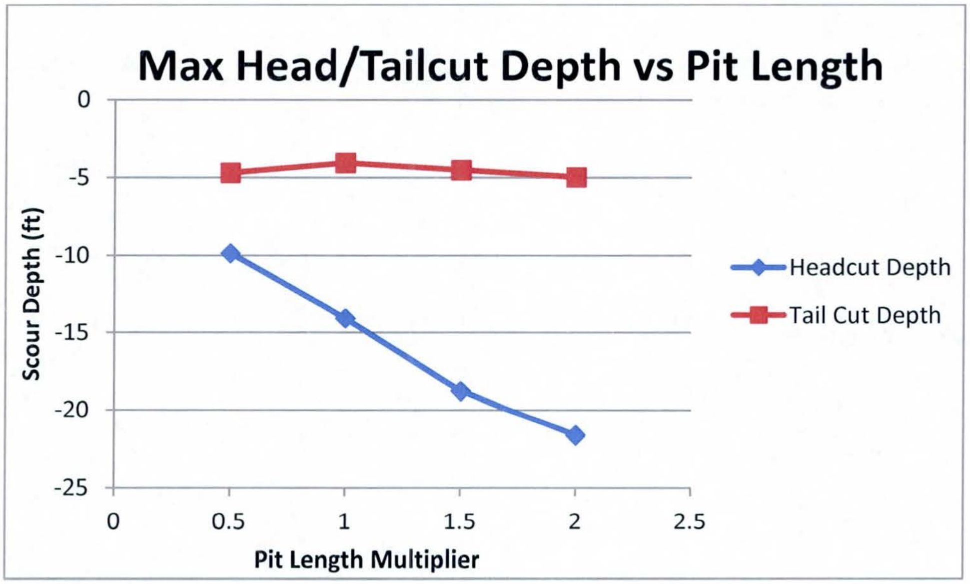


Figure 57. Pioneer Pit Headcut Depth and Tailcut Depth vs, Pit Length

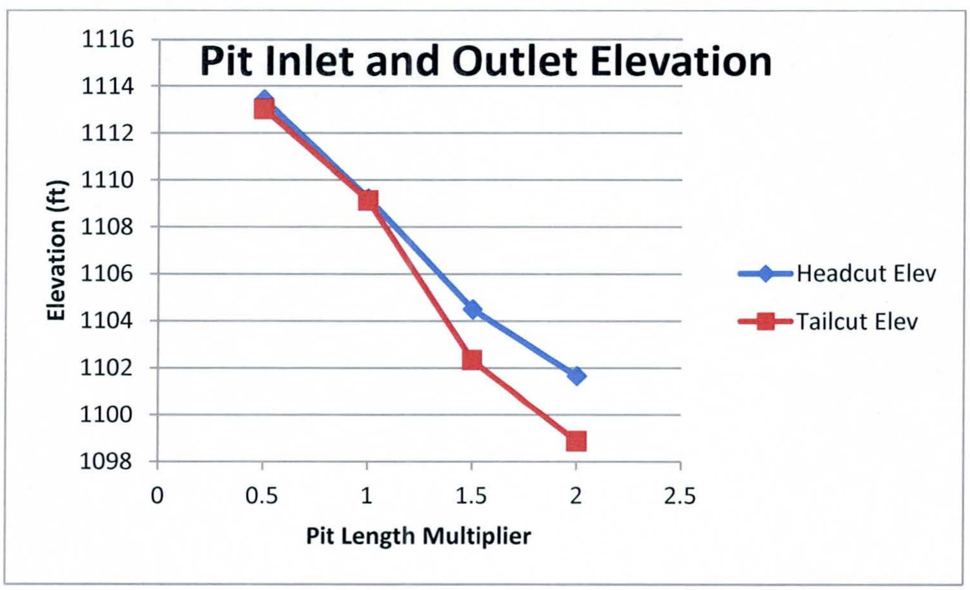


Figure 58. Pioneer Pit Ending Inlet (Headcut) and Outlet (Tailcut) Elevations vs. Pit Length.

The change in elevation for the maximum bed change at the pit inlet and outlet is shown in Figure 57. It can be seen that the tailcut is almost constant and not dependent on pit length but the maximum headcut depth does vary dramatically with pit length. It can be noted that for the 0.5 pit length (1000 ft) a maximum headcut depth of approximately 10 ft was predicted by the model. When the pit length was increased to 2.0 x the original length the scour depth increased to about 22 ft.

The elevation data was also plotted for the Pioneer Pit headcut and tailcut and is shown in Figure 58. It can be noted that the ending headcut and tailcut elevations track almost identically until something over

1.0 times the original pit length (2,000 ft). Beginning with the 1.5 x original pit length (3,000 ft) the tailcut elevation drops away from the headcut elevation. This likely indicates deposition within the pit is high enough to interfere with continued headcut formation. At 2.0 x the original pit length this difference is approximately 2.5 ft. It is possible that this may also be due to the shallower flow in the lower portion of the pit since the elevation of the pit bottom is held constant but the pit is still deep enough that head losses should be minimal for these flow rates. This finding could be explored further to verify what does provide the control for the upstream headcut under these conditions. If the lower portion of the pit were to become shallow enough the flows would represent open river conditions rather than lake hydraulic conditions.

Results. The equations for the averaged maximum scour depth and the rate of change of the scour depth with relation to the pit length are as follows:

For the Pioneer Pit headcut reach (from Figure 56):

$$y = 1.0199x^2 - 5.6799x - 1.2618 \qquad R^2 = 0.9936 \qquad (45)$$

$$\frac{dy}{dx} = 2.2198x - 5.6799 \qquad (46)$$

where x is the pit length multiplier and y is the averaged maximum scour depth in feet.

The data indicates that the pit length is the most important factor impacting the headcut depth of those analyzed in this study. The tailcut appears to be relatively constant but was not analyzed in detail in this study. The headcut was again stable for all pit lengths at 2112 ft.

6.0 Conclusions

This study indicated that the HEC-6T model is stable (i.e. produces the same results for the same inputs) for the modeling of headcuts and gives a good estimate of headcut depths. The lengths predicted by the model are not as accurate for this application and may be too short in most applications. Particular results are as follow:

Manning's N Value Sensitivity

1) The averaged maximum scour depth in the model increases slightly (0.7 ft) from a Manning's n value of 0.02 to 0.05.
2) The rate of change for the averaged maximum scour depth for the full model in relation to a change in Manning's n value is:

$$\frac{dy}{dx} = 21.74 \tag{5}$$

or a change in Manning's of 0.01 will result in a change in averaged maximum scour depth of 0.217 ft.
3) For the headcut reach the data did not produce consistent enough results as to allow any accurate analysis but there does not appear to be any discernible trend towards changes in the averaged minimum bed elevations for changes in Manning's n values.
4) The uncertainty (range of the actual scour data) for the headcut reach was about 1.2 ft.
5) The maximum headcut (scour) depth is not dependent on Manning's n value
6) The predicted headcut length is not dependent on Manning's n value and the calculated headcut length was 2112 ft.

Flow Sensitivity

1. The sensitivity of the averaged minimum bed elevation to peak flow is very low with a variation of approximately 0.7 ft over the range of 3,000 to 15,000 cfs.
2. The equation for the rate of change of the averaged maximum scour depth with respect to the flow rate is:

$$\frac{dy}{dx} = \text{-5E-05} \tag{10}$$

This indicates that a change in flow rate of 10,000 cfs results in an averaged change in the minimum bed elevation of 0.5 ft for the full model.
3. The variation in averaged headcut (scour) depth is 0.5 to 0.75 ft.
4. The maximum headcut depth is somewhat sensitive to flow rate with a variation of 1.5 ft in *depth at higher flow rates for the case with a non-constrained channel.*
5. The calculated headcut lengths vary from 1425 ft to 3485 ft with the headcut length generally increasing with increasing peak flow rates. The most common value was 3009 ft followed very closely by 1425 ft. There was a trend towards an increasing headcut length with increasing flow rate but the data was subject to significant scatter and not particularly consistent.

6. For the headcut reach of the model the rate of bed change $\frac{dy}{dx}$ = -3E-05 (Sm-NC) to -7E-05 (NS-NC) but the R^2 for the lines are very low (<0.56). These rate of change values are, however; on the same order as that predicted for the full model.

Bed Gradation

1. When only the negative values are considered the rate of change in averaged scour depth is:

$$\frac{dy}{dx} = -0.3683x + 1.0486 \quad (26)$$

2. The change in the averaged maximum scour depth for the headcut reach for a unit change in bed gradation is:

$$\frac{dy}{dx} = -0.4731x + 1.1452 \quad (30)$$

3. The headcut data is not smooth but variations are less than ±1.2 ft at the maximum headcut depth at cross section 15.67. The headcut depth is approximately 14.75 ft deep at this location and the variations account for about 15% of the elevation differences calculated by the model for the maximum headcut depth and 24% of the averaged maximum scour depth changes.
4. The headcut length is not sensitive to the bed gradation with all values modeled predicting a headcut length of 2112 ft.

Inflowing Sediment Load

1. The model was insensitive to the inflowing sediment load with the exception of the first 3 – 6 cross sections where the load was adjusting to match the transport capacity of the river in this reach.
2. The broad floodplain and deep sediment reservoirs likely allowed the model to adjust its load to reach the equilibrium load quickly.
3. There was no significant difference in the scour depths due to changes in the inflowing load.

Bed Sediment Reservoir Depth

1. The bed sediment reservoir residual values should be checked for reasonableness but should not be used as a calibration tool. Runs with large numbers of errors (>500) sometimes gave lower residuals than those with no warnings.

Pit Width

1. Averaged Maximum Scour Depth for the Headcut Reach

$$y = -0.286x - 5.3239 \qquad R^2 = 0.9864 \quad (31)$$

$$\frac{dy}{dx} = -0.286 \quad (32)$$

2. The maximum headcut depth increased by approximately one foot due to increasing pit width from 0.5 times the original pit width (approx 1,000 ft) to 2 times the pit width (4,000 ft).
3. The headcut depth matched the ending tailcut elevation to within approximately 0.5 ft.
4. The predicted headcut length was constant at 2112 ft.

Pit Depth

1. The averaged maximum scour depth for the headcut reach increased with increasing depth but was near zero for a depth of 30 ft or more. The equation to predict the averaged maximum scour depth in the headcut reach is:

$$y = -5E\text{-}05x^3 + 0.0059x^2 - 0.2431x - 2.4943 \qquad R^2 = 0.9999 \qquad (39)$$

and the slope of the equation (rate of change of the averaged scour depth) is:

$$\frac{dy}{dx} = -15E\text{-}05x^2 + 0.0118x - 0.2431 \qquad (40)$$

2. The model results showed little change in headcut depth for pits greater than 20 ft in depth. The difference in maximum headcut depth was on the order of 1.0 ft for pit from 20 to 60 ft in depth. The major difference was a much shallower headcut depth for a pit depth of 10 ft. The equation for the data with pit depths greater than 20 ft is:

$$y = 0.0008x^2 - 0.0833x - 12.402 \qquad R^2 = 0.95 \qquad \text{Pit Depth} > 20\text{ ft} \qquad (43)$$

and the slope of the equation is:

$$\frac{dy}{dx} = 0.0016x - 0.0833 \qquad (44)$$

3. The elevation of the maximum headcut depth is again approximately equal to the minimum tailcut elevation with the exception of the 10 ft pit depth where the minimum headcut elevation is above the elevation of the pit outlet. This is due to the shallow pit depth which moderates the headcut depth and likely results in more riverine conditions within the pit – i.e. increased head loss within the pit as compared with deeper pits.
4. The predicted headcut length is 2112 ft.

Pit Length

1. The pit length was the most important of all the variables considered in this study.
2. The averaged maximum scour depth for the headcut reach is given by:

$$y = 1.0199x^2 - 5.6799x - 1.2618 \qquad R^2 = 0.9936 \qquad (41)$$

and the slope (rate of change) of the data is given by:

$$\frac{dy}{dx} = 2.2198x - 5.6799 \quad (42)$$

3. The minimum headcut elevation (maximum scour) is equal to the ending tailcut elevation with the exception of the two longer pits which show a headcut elevation that is approximately 2-3 ft above that of the tailcut elevation. This is due to deposition in the pit that interferes with the formation of the headcut. If the pit were deeper the delta may not interfere with headcut formation.

4. The headcut length is predicted at 2112 ft.

The findings of this report are summarized in Table 21.

Table 21. Summary of the Impact of Changes to Input Variables.

Variable	Modeled Impacts			
	Ave Bed Elevation	Headcut Depth	Headcut Length	Comments
Manning's n	Slight 21.74/Unit Increase (0.001 change = 0.02174 ft Ave)	Slight 0.5 to 0.75 ft Ave 2.5 ft max over full range	No	
Flow Rate	Some -5e-05/Unit	Some -5e-05 to -7.5e-05/Unit 3 ft Max	Yes but erratic predictions	
Bed Gradation	Some -0.334x+0.926 ft /Unit	Some -0.4536x+1.0348 /Unit 1.0 ft Total for Ave 2.3 ft Max	No	
Inflowing Sediment Load	No	No	No	
Pit Width	-	Some (1.5 ft diff)	No	
Pit Depth	-	Slight above 20 ft Depths 1.0 ft max diff > 20 ft	No	Significant headcut depth changes for pits shallower than 20 ft deep
Pit Length	-	Significant 10 to 22 ft	No	

7.0 REFERENCES

River Research & Design (R_2D) 2011. Comparison of Sediment Transport Models for the Lower Hassayampa River. Prepared for the Flood Control District of Maricopa County.

WEST Consultants, Inc. (WEST/Fuller) 2006. Lower Hassayampa River Watercourse Master Plan, Final Hydraulics Report, Hassayampa River. Prepared for JE Fuller Hydrology & Geomorphology, Inc for The Flood Control District of Maricopa County.

Registered Professional Engineer (Civil)
CERTIFICATE NO.
36225
GARY E.
FREEMAN
Date Signed 2/1/13
ARIZONA, U.S.A.

Expires 6/30/2013

APPENDIX I

Bed Sediment Reservoir Depth Sensitivity

Table 22. Minimum Bed Elevations for Bed Sediment Reservoir Depth Sensitivity Analysis (from .t6 output files).

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10				
BSR Depth		25	25	15	15	20	20	30	30	30				
Exception	12.08								35	25				
	12.65	30	30											
	13.53				25	25								
	13.58	28	28											
	15.67	30	30		25	25								
	15.71	26	26		26	26								
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86				
Comment				501 Warnings			501 Warnings				Difference Values > 2.0 Highlighted			
Acceptable?		No	No	Yes?/No?	Yes	Yes	No	No	No	Yes				
Why?		Values	Value	Errors			Values / Errors	Value	Value					
	Cross Section (RM)	PREDICTED MINIMUM BED ELEVATIONS									Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?
	19.52	1205.7	1205.74	1205.81	1205.81	1205.75	1205.75	1205.71	1205.71	1205.7	1205.81	1205.7	0.11	0
	19.45	1206.66	1206.66	1206.66	1206.65	1206.66	1206.66	1206.65	1206.64	1206.64	1206.66	1206.64	0.02	0
	19.36	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	0	0
	19.29	1195.79	1202.05	1201.84	1201.67	1201.96	1202.01	1201.98	1201.93	1201.72	1202.05	1195.79	6.26	YES
	19.19	1198.34	1198.6	1198.55	1198.56	1198.41	1198.54	1198.32	1198.35	1198.27	1198.6	1198.27	0.33	0
	19.09	1197.23	1197.35	1197.34	1197.32	1197.27	1197.35	1197.26	1197.23	1197.25	1197.35	1197.23	0.12	0
	19.01	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	0	0
	18.92	1194.63	1194.8	1194.93	1194.85	1194.73	1194.81	1194.55	1194.66	1194.55	1194.93	1194.55	0.38	0
	18.83	1192.13	1192.08	1192.13	1192.13	1192.11	1192.11	1192.1	1192.09	1192.09	1192.13	1192.08	0.05	0
	18.74	1190.55	1190.54	1190.57	1190.52	1190.55	1190.53	1190.52	1190.53	1190.52	1190.57	1190.52	0.05	0
	18.65	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	0	0
	18.52	1186.17	1186.16	1186.06	1186.1	1186.15	1186.16	1186.17	1186.17	1186.18	1186.18	1186.06	0.12	0
	18.45	1184.69	1184.7	1184.71	1184.71	1184.71	1184.7	1184.69	1184.7	1184.69	1184.71	1184.69	0.02	0
	18.35	1180.08	1180.09	1180.05	1180.16	1180.12	1180.12	1180.05	1180.08	1180.07	1180.16	1180.05	0.11	0
	18.24	1179.88	1179.89	1179.8	1179.9	1179.9	1179.9	1179.89	1179.9	1179.9	1179.9	1179.8	0.1	0
	18.14	1176.28	1176.23	1176.24	1176.29	1176.21	1176.25	1176.2	1176.21	1176.21	1176.29	1176.2	0.09	0
	18.04	1174.09	1174.1	1174.12	1174.1	1174.1	1174.1	1174.1	1174.1	1174.11	1174.12	1174.09	0.03	0
	17.95	1173.86	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.86	0.07	0
	17.85	1170	1170.7	1170.67	1170.65	1170.68	1170.66	1170.68	1170.7	1170.71	1170.71	1170	0.71	0
	17.76	1169.91	1168.6	1169	1168.67	1168.6	1168.59	1168.99	1168.61	1168.63	1169.91	1168.59	1.32	YES
	17.67	1166.1	1165.85	1166.26	1166.39	1165.97	1166.08	1166.23	1165.82	1165.79	1166.39	1165.79	0.6	0
	17.57	1165.43	1165.43	1164.3	1165.43	1165.43	1165.43	1164.31	1165.43	1165.43	1165.43	1164.3	1.13	YES
	17.48	1162.04	1162.07	1162.2	1161.99	1162.07	1162.09	1162.2	1162.06	1162.06	1162.2	1161.99	0.21	0
	17.38	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	0	0
	17.29	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	0	0
	17.2	1156.77	1156.71	1156.83	1156.82	1156.72	1156.7	1156.81	1156.71	1156.72	1156.83	1156.7	0.13	0
	17.11	1153.58	1153.58	1153.62	1153.59	1153.58	1153.55	1153.61	1153.56	1153.62	1153.62	1153.55	0.07	0
	17.02	1152.09	1152.04	1152.12	1152.09	1152.08	1152.06	1152	1152.06	1152.03	1152.12	1152	0.12	0
	16.91	1150.89	1150.88	1150.91	1150.91	1150.89	1150.89	1150.86	1150.89	1150.9	1150.91	1150.86	0.05	0
	16.82	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	0	0
Observed	16.72	1145.67	1145.64	1145.33	1145.47	1145.45	1145.08	1145.5	1145.05	1145.84	1145.84	1145.05	0.79	0
Headcut	16.63	1143.5	1143.61	1143.6	1143.66	1143.43	1143.65	1143.46	1143.58	1143.99	1143.99	1143.43	0.56	0
Length	16.55	1142.87	1142.87	1142.86	1142.82	1142.81	1142.88	1142.87	1142.84	1142.91	1142.91	1142.81	0.1	0
	16.48	1141.18	1141.35	1140.78	1141.34	1141.46	1140.77	1141.33	1140.61	1141.69	1141.69	1140.61	1.08	YES
	16.42	1140.04	1139.75	1139.97	1139.87	1139.81	1139.94	1139.86	1139.69	1139.59	1140.04	1139.59	0.45	0
	16.33	1138.87	1138.84	1138.76	1138.95	1138.95	1138.79	1138.87	1138.87	1138.65	1138.95	1138.65	0.3	0
	16.24	1136.3	1136.29	1136.28	1136.28	1136.28	1136.28	1136.3	1136.27	1136.27	1136.3	1136.27	0.03	0
	16.15	1134.1	1134.1	1134.1	1134.1	1134.1	1134.1	1133.56	1134.1	1134.1	1134.1	1133.56	0.54	0
Calculated	16.07	1129.55	1129.45	1129.38	1129.63	1129.49	1129.65	1129.64	1129.59	1129.24	1129.65	1129.24	0.41	0
Headcut	15.98	1128.83	1129.36	1129.15	1129.26	1129.21	1129.41	1128.98	1129.21	1129.08	1129.41	1128.83	0.58	0
Length	15.94	1126.42	1126.72	1126.73	1126.81	1126.54	1126.79	1126.48	1126.27	1126.38	1126.81	1126.27	0.54	0
	15.9	1126.23	1125.79	1125.96	1125.84	1125.54	1125.87	1125.54	1125.15	1125.35	1126.23	1125.15	1.08	YES
	15.86	1124.1	1123.51	1123.83	1123.6	1122.92	1123.02	1123.24	1122.63	1122.91	1124.1	1122.63	1.47	YES
	15.81	1121.16	1119.99	1120.23	1121.04	1119.38	1120.16	1119.68	1119.05	1119.67	1121.16	1119.05	2.11	YES
	15.76	1117.88	1117.02	1117.58	1117.87	1116.4	1117.58	1116.43	1116.12	1116.59	1117.88	1116.12	1.76	YES
	15.71	1113.32	1113.07	1113.69	1113.12	1112.18	1112.52	1112.35	1112.19	1112.87	1113.69	1112.18	1.51	YES
	15.67	1108.84	1108.12	1108.74	1108.34	1108.14	1108.06	1108.1	1108.19	1108.08	1108.84	1108.06	0.78	0
Pioneer	15.62	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
Pit	15.58	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.53	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.48	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.43	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10				
BSR Depth		25	25	15	15	20	20	30	30	30				
Exception	12.08								35	25				
	12.65	30	30											
	13.53				25	25								
	13.58	28	28											
	15.67	30	30		25	25								
	15.71	26	26		26	26								
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86				
Comment				501 Warnings			501 Warnings				Difference Values > 2.0 Highlighted			
Acceptable?		No	No	Yes?/No?	Yes	Yes	No	No	No	Yes				
Why?		Values	Value	Errors			Values / Errors	Value	Value					
	Cross Section (RM)	PREDICTED MINIMUM BED ELEVATIONS									Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?
	15.38	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.34	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.3	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.25	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	1092	0	0
	15.2	1109.62	1109.69	1109.74	1109.73	1109.71	1109.72	1109.68	1109.68	1109.68	1109.74	1109.62	0.12	0
	15.15	1109.48	1109.45	1109.51	1109.51	1109.46	1109.46	1109.44	1109.44	1109.44	1109.51	1109.44	0.07	0
	15.1	1108.63	1108.65	1108.75	1108.71	1108.66	1108.67	1108.65	1108.63	1108.63	1108.75	1108.63	0.12	0
	15.06	1108.07	1108.13	1108.25	1108.23	1108.14	1108.14	1108.12	1108.13	1108.12	1108.25	1108.07	0.18	0
	14.96	1106.33	1106.51	1106.38	1106.37	1106.49	1106.5	1106.51	1106.51	1106.51	1106.51	1106.33	0.18	0
	14.86	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	0	0
	14.77	1102.72	1102.78	1102.69	1102.69	1102.8	1102.8	1102.62	1102.63	1102.73	1102.8	1102.62	0.18	0
	14.67	1101.16	1101.21	1101.21	1101.22	1101.24	1101.25	1101.25	1101.23	1101.23	1101.25	1101.16	0.09	0
	14.58	1099.31	1099.26	1099.34	1099.43	1099.2	1099.38	1099.39	1099.34	1099.33	1099.43	1099.2	0.23	0
	14.49	1096.62	1096.68	1096.74	1096.73	1096.68	1096.72	1096.87	1096.91	1096.77	1096.91	1096.62	0.29	0
	14.4	1096.75	1096.76	1096.67	1096.62	1096.78	1096.63	1096.67	1096.77	1096.77	1096.78	1096.62	0.16	0
	14.3	1095.2	1094.87	1095.24	1095.24	1095.19	1095.24	1095.24	1095.18	1095.18	1095.24	1094.87	0.37	0
	14.21	1091.53	1091.51	1091.75	1091.66	1091.65	1091.78	1092.27	1091.64	1091.57	1092.27	1091.51	0.76	0
	14.13	1090.72	1090.91	1090.74	1090.8	1090.83	1090.74	1090.52	1090.9	1090.89	1090.91	1090.52	0.39	0
	14.02	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	1089.1	0	0
	13.93	1086.68	1086.61	1086.59	1086.61	1086.59	1086.6	1086.58	1086.6	1086.6	1086.68	1086.58	0.1	0
	13.89	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	0	0
	13.83	1084.12	1084.28	1084	1084.29	1084.29	1084.14	1084.27	1084.12	1083.83	1084.29	1083.83	0.46	0
	13.77	1081	1081.01	1081.02	1081.02	1081.05	1080.86	1081.19	1081.14	1080.87	1081.19	1080.86	0.33	0
	13.73	1078.78	1079.24	1078.67	1079.37	1079.21	1079.45	1079.07	1078.98	1079.5	1079.5	1078.67	0.83	0
	13.67	1077.91	1076.74	1078	1076.74	1076.73	1076.65	1077.45	1077.78	1077.44	1078	1076.65	1.35	YES
	13.63	1074.46	1074.37	1076.03	1074.49	1074.32	1074.26	1074.43	1074.51	1074.39	1076.03	1074.26	1.77	YES
	13.61	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	0	0
	13.58	1050.2	1076.33	1076.65	1076.37	1076.33	1076.41	1076.4	1076.42	1076.3	1076.65	1050.2	26.45	YES
	13.56	1073.76	1072.68	1073.99	1072.69	1072.58	1073.58	1072.72	1072.56	1072.62	1073.99	1072.56	1.43	YES
	13.53	1069.2	1069.53	1070.01	1069.88	1069.99	1070.1	1069.89	1069.95	1069.63	1070.1	1069.2	0.9	0
CEMEX	13.49	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
Pit	13.47	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.44	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.39	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.36	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.32	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.28	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.22	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	1067	0	0
	13.16	1066.62	1066.59	1066.65	1066.65	1066.59	1066.61	1066.6	1066.58	1066.56	1066.65	1066.56	0.09	0
	13.14	1062.41	1062.29	1062.69	1062.61	1062.37	1062.46	1062.36	1062.35	1062.26	1062.69	1062.26	0.43	0
	13.11	1062.8	1062.7	1062.72	1062.89	1062.74	1062.49	1062.74	1062.82	1062.48	1062.89	1062.48	0.41	0
	13.07	1062.23	1062.44	1062.53	1062.5	1062.01	1062.51	1062.48	1062.55	1062.13	1062.55	1062.01	0.54	0
	13.01	1060.67	1060.55	1060.76	1060.58	1060.44	1060.65	1060.57	1060.57	1060.29	1060.76	1060.29	0.47	0
	12.96	1059	1059.18	1059.76	1059.36	1058.39	1059.05	1059.34	1059.3	1057.98	1059.76	1057.98	1.78	YES
	12.91	1058.08	1057.64	1057.87	1058.02	1058.02	1057.89	1057.82	1056.99	1058.04	1058.08	1056.99	1.09	YES
	12.87	1057.31	1058.28	1058.02	1058.14	1057.72	1057.79	1058.15	1057.9	1057.54	1058.28	1057.31	0.97	0
	12.8	1056.72	1056.23	1056.38	1056.64	1056.49	1056.57	1056.02	1056.36	1056.54	1056.72	1056.02	0.7	0
	12.75	1055.97	1055.73	1055.55	1055.82	1055.67	1055.74	1055.58	1055.48	1055.62	1055.97	1055.48	0.49	0
	12.73	1054.99	1054.55	1054.24	1054.78	1054.48	1054.63	1054.4	1054.29	1054.3	1054.99	1054.24	0.75	0
	12.7	1054.49	1054.08	1053.97	1054.24	1053.95	1054.06	1054.13	1054.16	1053.96	1054.49	1053.95	0.54	0
	12.68	1053.75	1053.19	1053.08	1053.21	1053.1	1053.33	1053.1	1053.18	1053.37	1053.75	1053.08	0.67	0
	12.65	1053.56	1052.61	1052.68	1052.97	1052.7	1052.65	1052.82	1053.05	1052.69	1053.56	1052.61	0.95	0
	12.63	1053	1052.44	1052.62	1052.61	1052.67	1052.86	1052.5	1052.73	1052.95	1053	1052.44	0.56	0
	12.6	1052.29	1051.98	1052.01	1051.93	1051.94	1051.95	1052.05	1052.09	1052.14	1052.29	1051.93	0.36	0
	12.56	1051.08	1050.68	1051.08	1051.18	1051.16	1051.16	1050.79	1051.13	1051.17	1051.18	1050.68	0.5	0

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10
BSR Depth		25	25	15	15	20	20	30	30	30
Exception	12.08								35	25
	12.65	30	30							
	13.53				25	25				
	13.58	28	28							
	15.67	30	30		25	25				
	15.71	26	26		26	26				
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86
Comment				501 Warnings			501 Warnings			
Acceptable?		No	No	Yes?/No?	Yes	Yes	No	No	No	Yes
Why?		Values	Value	Errors			Values / Errors	Value	Value	

Difference Values > 2.0 Highlighted

	Cross Section (RM)	PREDICTED MINIMUM BED ELEVATIONS									Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?
	12.5	1047.16	1047.15	1047.27	1047.27	1047.27	1047.27	1047.16	1047.16	1047.16	1047.27	1047.15	0.12	0
Hanson	12.45	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	0	0
Pit	12.38	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	0	0
	12.35	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	0	0
	12.3	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	0	0
	12.26	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	1040	0	0
	12.21	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	0	0
	12.17	1038.22	1038.28	1038.44	1038.44	1038.37	1038.36	1038.24	1038.3	1038.26	1038.44	1038.22	0.22	0
	12.12	1038.05	1038.09	1038.07	1038.07	1038.08	1038.12	1038.1	1038.14	1038.09	1038.14	1038.05	0.09	0
	12.08	1029.37	1029.45	1038.73	1038.74	1038.59	1038.6	1029.75	1029.18	1038.59	1038.74	1029.18	9.56	YES
	12.03	1038.82	1038.89	1038.95	1038.96	1038.88	1038.94	1038.91	1038.94	1038.87	1038.96	1038.82	0.14	0
	11.98	1038.6	1038.5	1038.55	1038.56	1038.45	1038.59	1038.55	1038.59	1038.53	1038.6	1038.45	0.15	0
	11.93	1038.65	1038.87	1038.9	1038.91	1038.92	1038.86	1038.93	1038.94	1038.8	1038.94	1038.65	0.29	0
	11.88	1038.49	1038.48	1038.2	1038.2	1038.64	1038.78	1038.61	1038.65	1038.39	1038.78	1038.2	0.58	0
	11.83	1029.37	1037.16	1036.86	1036.86	1037.32	1029.41	1037.33	1037.26	1037.11	1037.33	1029.37	7.96	YES
	11.79	1035.64	1035.63	1035.64	1035.62	1035.71	1035.77	1035.67	1035.6	1035.61	1035.77	1035.6	0.17	0
	11.74	1034.45	1034.4	1034.29	1034.28	1034.46	1034.7	1034.48	1034.4	1034.4	1034.7	1034.28	0.42	0
	11.7	1033.91	1033.69	1034	1033.88	1033.72	1033.99	1033.86	1033.68	1033.77	1034	1033.68	0.32	0
	11.66	1032.51	1032.38	1032.43	1032.44	1032.45	1032.47	1032.45	1032.48	1032.6	1032.6	1032.38	0.22	0
	11.62	1033.31	1033.04	1033.04	1033.04	1033.06	1033.05	1033.1	1033.15	1033.06	1033.31	1033.04	0.27	0
	11.58	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	0	0
	11.53	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	0	0
	11.49	1029.8	1029.83	1029.31	1029.31	1029.95	1029.84	1029.94	1029.66	1030.14	1030.14	1029.31	0.83	0
	11.44	1028.69	1028.82	1028.82	1028.81	1028.9	1028.81	1029.2	1028.5	1029.23	1029.23	1028.5	0.73	0
	11.35	1027.95	1027.87	1027.99	1027.98	1028.08	1027.93	1028.43	1027.77	1028.56	1028.56	1027.77	0.79	0
	11.25	1025.68	1026.01	1026.21	1026.21	1025.68	1025.84	1025.41	1026.07	1025.35	1026.21	1025.35	0.86	0
	11.17	1024.02	1024.02	1023.97	1023.98	1024.02	1024.02	1024.02	1024.02	1024.02	1024.02	1023.97	0.05	0
	11.09	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	0	0
	11.01	1019.12	1019.14	1019.07	1019.11	1019.29	1019.31	1019.2	1018.5	1019.01	1019.31	1018.5	0.81	0
	11	1018.53	1018.49	1017.55	1017.55	1018.52	1018.52	1018.49	1018.36	1018.55	1018.55	1017.55	1	0
	10.98	1017.94	1018.32	1017.88	1017.96	1018	1018.01	1017.94	1017.9	1018.1	1018.32	1017.88	0.44	0
	10.97	1018.23	1018.43	1017.35	1017.38	1018.34	1018.46	1018.49	1017.21	1017.5	1018.49	1017.21	1.28	YES
	10.88	1016.21	1016.07	1016.4	1016.4	1016.17	1016.32	1016.19	1016.07	1016.53	1016.53	1016.07	0.46	0
	10.79	1014.8	1014.8	1014.61	1014.61	1014.8	1014.8	1014.8	1014.72	1014.13	1014.8	1014.13	0.67	0
	10.73	1012.59	1012.52	1012.54	1012.6	1012.46	1012.4	1012.41	1012.59	1012.71	1012.71	1012.4	0.31	0
	10.68	1011.74	1011.21	1011.07	1011.07	1011.42	1011.42	1011.4	1010.96	1011.06	1011.74	1010.96	0.78	0
	10.6	1008.81	1009.31	1009.19	1009.18	1008.96	1008.91	1008.94	1009.16	1009.19	1009.31	1008.81	0.5	0
	10.51	1006.35	1006.74	1006.75	1006.75	1006.76	1006.75	1006.73	1006.7	1007.01	1007.01	1006.35	0.66	0
	10.43	1006.55	1006.57	1006.48	1006.54	1006.56	1006.54	1006.57	1006.57	1006.71	1006.71	1006.48	0.23	0
	10.33	1004.5	1004.38	1004.38	1004.37	1004.39	1004.48	1004.43	1004.53	1004.38	1004.53	1004.37	0.16	0
	10.24	1001.25	1001.26	1001.26	1001.26	1001.26	1001.26	1001.27	1001.28	1001.27	1001.28	1001.25	0.03	0
	10.14	998.69	998.66	998.66	998.66	998.66	998.66	998.67	998.68	998.67	998.69	998.66	0.03	0
	10.04	996.04	996.19	996.19	996.19	996.19	996.17	996.2	996.16	996.17	996.2	996.04	0.16	0
	9.93	992.63	993.11	993.11	993.11	993.1	993.06	993.11	993.08	993.06	993.11	992.63	0.48	0
	9.84	991.33	991.94	991.94	991.94	991.94	992.01	991.89	991.92	992.02	992.02	991.33	0.69	0
	9.74	989.21	989.62	989.63	989.62	989.63	989.63	989.6	989.63	989.61	989.63	989.21	0.42	0
	9.64	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	0	0

Table 23. HEC-6T Output from .t98 (Plot) File for Bed Sediment Reservoir Sensitivity. Compare with Table 22 above. Differences between .t6 file output and .t98 output shown in last Column.

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10					
BSR Depth		25	25	15	15	20	20	30	30	30					
Exceptions	12.08								35	25					
	12.65	30	30												
	13.53				25	25									
	13.58	28	28												
	15.67	30	30		25	25									
	15.71	26	26		26	26									
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86					
Comment				501 Warns			501 Warns								
Acceptable?		No	No	Yes? / No?	Yes	Yes	No	No	No	Yes					
Why?		Values	Value	Errors			Value / Errors	Value	Value						
	Cross Section (RM)	PREDICTED MINIMUM BED ELEVATIONS									Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?	Diff from t6 Results
	19.52	1205.70	1205.74	1205.81	1205.81	1205.75	1205.75	1205.71	1205.71	1205.70	1205.81	1205.70	0.11		0.00
	19.45	1206.66	1206.66	1206.66	1206.65	1206.66	1206.66	1206.65	1206.64	1206.64	1206.66	1206.64	0.02		0.00
	19.36	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	1205.43	0.00		0.00
	19.29	1202.33	1202.05	1201.84	1201.67	1202.01	1201.96	1201.98	1201.93	1201.72	1202.33	1201.67	0.66		-5.60
	19.19	1198.34	1198.60	1198.55	1198.56	1198.54	1198.41	1198.32	1198.35	1198.27	1198.60	1198.27	0.32		-0.01
	19.09	1197.23	1197.35	1197.34	1197.32	1197.35	1197.27	1197.26	1197.23	1197.25	1197.35	1197.23	0.12		0.00
	19.01	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	1195.97	0.00		0.00
	18.92	1194.63	1194.80	1194.93	1194.85	1194.81	1194.73	1194.55	1194.66	1194.55	1194.93	1194.55	0.38		0.00
	18.83	1192.13	1192.08	1192.13	1192.13	1192.11	1192.11	1192.10	1192.09	1192.09	1192.13	1192.08	0.05		0.00
	18.74	1190.55	1190.54	1190.57	1190.52	1190.53	1190.55	1190.52	1190.53	1190.52	1190.57	1190.52	0.05		0.00
	18.65	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	1188.58	0.00		0.00
	18.52	1186.17	1186.16	1186.06	1186.10	1186.16	1186.15	1186.17	1186.17	1186.18	1186.18	1186.06	0.12		0.00
	18.45	1184.69	1184.70	1184.71	1184.71	1184.70	1184.71	1184.69	1184.70	1184.69	1184.71	1184.69	0.03		0.01
	18.35	1180.08	1180.09	1180.05	1180.16	1180.12	1180.12	1180.05	1180.08	1180.07	1180.16	1180.05	0.11		0.00
	18.24	1179.88	1179.89	1179.80	1179.90	1179.90	1179.90	1179.89	1179.90	1179.90	1179.90	1179.80	0.10		0.00
	18.14	1176.28	1176.23	1176.24	1176.29	1176.25	1176.21	1176.20	1176.21	1176.21	1176.29	1176.20	0.09		0.00
	18.04	1174.09	1174.10	1174.12	1174.10	1174.10	1174.10	1174.10	1174.10	1174.11	1174.12	1174.09	0.03		0.00
	17.95	1173.86	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.93	1173.86	0.07		0.00
	17.85	1170.00	1170.70	1170.67	1170.65	1170.66	1170.68	1170.68	1170.70	1170.71	1170.71	1170.00	0.71		0.00
	17.76	1169.91	1168.60	1169.00	1168.67	1168.59	1168.60	1168.99	1168.61	1168.63	1169.91	1168.59	1.32	YES	0.00
	17.67	1166.10	1165.85	1166.26	1166.39	1166.08	1165.97	1166.23	1165.82	1165.79	1166.39	1165.79	0.59		-0.01
	17.57	1165.43	1165.43	1164.30	1165.43	1165.43	1165.43	1164.31	1165.43	1165.43	1165.43	1164.30	1.13	YES	0.00
	17.48	1162.04	1162.07	1162.20	1161.99	1162.09	1162.07	1162.20	1162.06	1162.06	1162.20	1161.99	0.21		0.00
	17.38	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	1160.46	0.00		0.00
	17.29	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	1159.03	0.00		0.00
	17.2	1156.77	1156.71	1156.83	1156.82	1156.70	1156.72	1156.81	1156.71	1156.72	1156.83	1156.70	0.13		0.00
	17.11	1153.58	1153.58	1153.62	1153.59	1153.55	1153.58	1153.61	1153.56	1153.62	1153.62	1153.55	0.07		0.00
	17.02	1152.09	1152.04	1152.12	1152.09	1152.06	1152.08	1152.00	1152.06	1152.03	1152.12	1152.00	0.12		0.00
	16.91	1150.89	1150.88	1150.91	1150.91	1150.89	1150.89	1150.86	1150.89	1150.90	1150.91	1150.86	0.05		0.00
	16.82	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	1148.81	0.00		0.00
	16.72	1145.67	1145.64	1145.33	1145.47	1145.08	1145.45	1145.50	1145.05	1145.84	1145.84	1145.05	0.80		0.01
	16.63	1143.50	1143.61	1143.60	1143.66	1143.65	1143.43	1143.46	1143.58	1143.99	1143.99	1143.43	0.56		0.00
	16.55	1142.87	1142.87	1142.86	1142.82	1142.88	1142.81	1142.87	1142.84	1142.91	1142.91	1142.81	0.10		0.00
Observed	16.48	1141.18	1141.36	1140.78	1141.34	1140.77	1141.46	1141.33	1140.61	1141.69	1141.69	1140.61	1.08	YES	0.00
Headcut	16.42	1140.04	1139.75	1139.97	1139.87	1139.94	1139.81	1139.86	1139.69	1139.59	1140.04	1139.59	0.45		0.00
	16.33	1138.87	1138.84	1138.76	1138.95	1138.79	1138.95	1138.87	1138.87	1138.65	1138.95	1138.65	0.30		0.00
	16.24	1136.30	1136.29	1136.28	1136.28	1136.28	1136.28	1136.30	1136.27	1136.27	1136.30	1136.27	0.03		0.00
	16.15	1134.10	1134.10	1134.10	1134.10	1134.10	1134.10	1133.56	1134.10	1134.10	1134.10	1133.56	0.54		0.00
	16.07	1129.55	1129.45	1129.38	1129.63	1129.65	1129.49	1129.64	1129.59	1129.24	1129.65	1129.24	0.41		0.00
	15.98	1128.83	1129.36	1129.15	1129.26	1129.41	1129.21	1128.98	1129.21	1129.08	1129.41	1128.83	0.58		0.00
Calculated	15.94	1126.42	1126.72	1126.73	1126.81	1126.79	1126.54	1126.48	1126.27	1126.38	1126.81	1126.27	0.55		0.01
Headcut	15.9	1126.23	1125.79	1125.96	1125.84	1125.87	1125.54	1125.54	1125.15	1125.35	1126.23	1125.15	1.07	YES	-0.01
	15.86	1124.10	1123.51	1123.84	1123.60	1123.02	1122.92	1123.24	1122.63	1122.91	1124.10	1122.63	1.47	YES	0.00
	15.81	1121.16	1119.99	1120.23	1121.04	1120.16	1119.38	1119.68	1119.05	1119.67	1121.16	1119.05	2.11	YES	0.00
	15.76	1117.88	1117.02	1117.58	1117.87	1117.58	1116.40	1116.43	1116.12	1116.59	1117.88	1116.12	1.75	YES	-0.01
	15.71	1113.32	1113.07	1113.69	1113.12	1112.52	1112.18	1112.35	1112.19	1112.87	1113.69	1112.18	1.50	YES	-0.01
	15.67	1108.84	1108.12	1108.74	1108.34	1108.06	1108.14	1108.10	1108.19	1108.08	1108.84	1108.06	0.78		0.00
	15.62	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
	15.58	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
	15.53	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
	15.48	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
	15.43	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00

Difference Values > 1.0 Highlighted

Difference Values > 2.0 Highlight+Box

HEC-6T Sensitivity for Modeling Hassayampa River Headcuts

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10
BSR Depth		25	25	15	15	20	20	30	30	30
Exceptions	12.08								35	25
	12.65	30	30							
	13.53				25	25				
	13.58	28	28							
	15.67	30	30		25	25				
	15.71	26	26		26	26				
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86
Comment				501 Warns			501 Warns			
Acceptable?		No	No	Yes? / No?	Yes	Yes	No	No	No	Yes
Why?		Values	Value	Errors			Value / Errors	Value	Value	

Difference Values > 1.0 Highlighted

Difference Values > 2.0 Highlight+Box

Cross Section (RM)	PREDICTED MINIMUM BED ELEVATIONS									Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?	Diff from t6 Results
15.38	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
15.34	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
15.3	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
15.25	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	1092.00	0.00		0.00
15.2	1109.62	1109.69	1109.74	1109.73	1109.72	1109.71	1109.68	1109.68	1109.68	1109.74	1109.62	0.11		-0.01
15.15	1109.48	1109.45	1109.51	1109.51	1109.46	1109.46	1109.44	1109.44	1109.44	1109.51	1109.44	0.07		0.00
15.1	1108.63	1108.65	1108.75	1108.71	1108.67	1108.66	1108.65	1108.63	1108.63	1108.75	1108.63	0.11		-0.01
15.06	1108.07	1108.13	1108.25	1108.23	1108.14	1108.14	1108.12	1108.13	1108.12	1108.25	1108.07	0.18		0.00
14.96	1106.33	1106.51	1106.38	1106.37	1106.50	1106.49	1106.51	1106.51	1106.51	1106.51	1106.33	0.18		0.00
14.86	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	1104.69	0.00		0.00
14.77	1102.72	1102.78	1102.69	1102.69	1102.80	1102.80	1102.62	1102.63	1102.73	1102.80	1102.62	0.18		0.00
14.67	1101.16	1101.21	1101.21	1101.22	1101.25	1101.24	1101.25	1101.23	1101.23	1101.25	1101.16	0.09		0.00
14.58	1099.31	1099.26	1099.34	1099.43	1099.38	1099.20	1099.39	1099.34	1099.33	1099.43	1099.20	0.23		0.00
14.49	1096.62	1096.68	1096.74	1096.73	1096.72	1096.68	1096.87	1096.91	1096.77	1096.91	1096.62	0.29		0.00
14.4	1096.75	1096.76	1096.67	1096.62	1096.63	1096.78	1096.67	1096.77	1096.77	1096.78	1096.62	0.16		0.00
14.3	1095.20	1094.87	1095.24	1095.24	1095.24	1095.19	1095.24	1095.18	1095.18	1095.24	1094.87	0.37		0.00
14.21	1091.53	1091.51	1091.75	1091.66	1091.78	1091.65	1092.27	1091.64	1091.57	1092.27	1091.51	0.76		0.00
14.13	1090.72	1090.91	1090.74	1090.80	1090.74	1090.83	1090.52	1090.90	1090.89	1090.91	1090.52	0.39		0.00
14.02	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	1089.10	0.00		0.00
13.93	1086.68	1086.61	1086.59	1086.61	1086.60	1086.59	1086.58	1086.60	1086.60	1086.68	1086.58	0.11		0.01
13.89	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	1085.77	0.01		0.01
13.83	1084.12	1084.28	1084.00	1084.29	1084.14	1084.29	1084.27	1084.12	1083.83	1084.29	1083.83	0.46		0.00
13.77	1081.00	1081.01	1081.02	1081.02	1080.86	1081.05	1081.19	1081.14	1080.87	1081.19	1080.86	0.33		0.00
13.73	1078.78	1079.24	1078.67	1079.37	1079.45	1079.21	1079.07	1078.98	1079.50	1079.50	1078.67	0.83		0.00
13.67	1077.91	1076.74	1078.00	1076.74	1076.65	1076.73	1077.45	1077.78	1077.44	1078.00	1076.65	1.35	YES	0.00
13.63	1074.46	1074.37	1076.03	1074.49	1074.26	1074.32	1074.43	1074.51	1074.39	1076.03	1074.26	1.77	YES	0.00
13.61	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	1078.08	0.00		0.00
13.58	1076.88	1076.33	1076.65	1076.37	1076.41	1076.33	1076.40	1076.42	1076.30	1076.88	1076.30	0.57		-25.88
13.56	1073.76	1072.68	1073.99	1072.69	1073.58	1072.58	1072.72	1072.56	1072.62	1073.99	1072.56	1.43	YES	0.00
13.53	1069.20	1069.53	1070.01	1069.88	1070.10	1069.99	1069.89	1069.95	1069.63	1070.10	1069.20	0.90		0.00
13.49	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.47	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.44	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.39	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.36	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.32	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.28	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.22	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	1067.00	0.00		0.00
13.16	1066.62	1066.59	1066.65	1066.65	1066.61	1066.59	1066.60	1066.58	1066.56	1066.65	1066.56	0.09		0.00
13.14	1062.41	1062.29	1062.69	1062.61	1062.46	1062.37	1062.36	1062.35	1062.26	1062.69	1062.26	0.43		0.00
13.11	1062.80	1062.70	1062.72	1062.89	1062.49	1062.74	1062.74	1062.82	1062.48	1062.89	1062.48	0.41		0.00
13.07	1062.23	1062.44	1062.53	1062.50	1062.51	1062.01	1062.48	1062.55	1062.13	1062.55	1062.01	0.54		0.00
13.01	1060.67	1060.55	1060.76	1060.58	1060.65	1060.44	1060.57	1060.57	1060.29	1060.76	1060.29	0.48		0.01
12.96	1059.00	1059.18	1059.76	1059.36	1059.05	1058.39	1059.34	1059.30	1057.98	1059.76	1057.98	1.78	YES	0.00
12.91	1058.08	1057.64	1057.87	1058.02	1057.89	1058.02	1057.82	1056.99	1058.04	1058.08	1056.99	1.09	YES	0.00
12.87	1057.31	1058.28	1058.02	1058.14	1057.79	1057.72	1058.15	1057.90	1057.54	1058.28	1057.31	0.96		-0.01
12.8	1056.72	1056.23	1056.38	1056.64	1056.57	1056.49	1056.02	1056.36	1056.54	1056.72	1056.02	0.70		0.00
12.75	1055.97	1055.73	1055.55	1055.82	1055.74	1055.67	1055.58	1055.48	1055.62	1055.97	1055.48	0.48		-0.01
12.73	1054.99	1054.55	1054.24	1054.78	1054.63	1054.48	1054.40	1054.29	1054.30	1054.99	1054.24	0.76		0.01
12.7	1054.49	1054.08	1053.97	1054.24	1054.06	1053.95	1054.13	1054.16	1053.96	1054.49	1053.95	0.53		-0.01
12.68	1053.75	1053.19	1053.08	1053.21	1053.33	1053.10	1053.10	1053.18	1053.37	1053.75	1053.08	0.68		0.01
12.65	1053.56	1052.61	1052.68	1052.97	1052.65	1052.70	1052.82	1053.05	1052.69	1053.56	1052.61	0.95		0.00
12.63	1053.00	1052.44	1052.62	1052.61	1052.86	1052.67	1052.50	1052.73	1052.95	1053.00	1052.44	0.56		0.00
12.6	1052.29	1051.98	1052.01	1051.93	1051.95	1051.94	1052.05	1052.09	1052.14	1052.29	1051.93	0.36		0.00

$SMOOTH WSP #		100	10	10	10	10	10	10	10	10
BSR Depth		25	25	15	15	20	20	30	30	30
Exceptions	12.08								35	25
	12.65	30	30							
	13.53				25	25				
	13.58	28	28							
	15.67	30	30		25	25				
	15.71	26	26		26	26				
Max Res. Depth		0.86	0.86	0.43	0.74	0.74	0.57	0.86	1	0.86
Comment				501 Warns			501 Warns			
Acceptable?		No	No	Yes? / No?	Yes	Yes	No	No	No	Yes
Why?		Values	Value	Errors			Value / Errors	Value	Value	

Difference Values > 1.0 Highlighted

Difference Values > 2.0 Highlight+Box

PREDICTED MINIMUM BED ELEVATIONS

Cross Section (RM)										Range of Predicted Elevations Max	Min	Difference	> 1.0 Ft?	Diff from t6 Results
12.56	1051.08	1050.68	1051.08	1051.18	1051.16	1051.16	1050.79	1051.13	1051.17	1051.18	1050.68	0.50		0.00
12.5	1047.16	1047.15	1047.27	1047.27	1047.27	1047.27	1047.16	1047.16	1047.16	1047.27	1047.15	0.12		0.00
12.45	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	0.00		0.00
12.38	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	0.00		0.00
12.35	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	0.00		0.00
12.3	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	0.00		0.00
12.26	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	1040.00	0.00		0.00
12.21	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	1039.95	0.00		0.00
12.17	1038.22	1038.28	1038.44	1038.44	1038.36	1038.37	1038.24	1038.30	1038.26	1038.44	1038.22	0.23		0.01
12.12	1038.05	1038.09	1038.07	1038.07	1038.12	1038.08	1038.10	1038.14	1038.09	1038.14	1038.05	0.09		0.00
12.08	1038.52	1038.55	1038.73	1038.74	1038.60	1038.59	1038.58	1038.60	1038.59	1038.74	1038.52	0.22		-9.34
12.03	1038.82	1038.89	1038.95	1038.96	1038.94	1038.88	1038.91	1038.94	1038.87	1038.96	1038.82	0.14		0.00
11.98	1038.60	1038.50	1038.55	1038.56	1038.59	1038.45	1038.55	1038.59	1038.53	1038.60	1038.45	0.15		0.00
11.93	1038.65	1038.87	1038.90	1038.91	1038.86	1038.92	1038.93	1038.94	1038.80	1038.94	1038.65	0.29		0.00
11.88	1038.49	1038.48	1038.20	1038.20	1038.78	1038.64	1038.61	1038.65	1038.39	1038.78	1038.20	0.59		0.01
11.83	1037.27	1037.16	1036.86	1036.86	1037.48	1037.32	1037.33	1037.26	1037.11	1037.48	1036.86	0.62		-7.34
11.79	1035.64	1035.63	1035.64	1035.62	1035.77	1035.71	1035.67	1035.60	1035.61	1035.77	1035.60	0.17		0.00
11.74	1034.45	1034.40	1034.29	1034.28	1034.70	1034.46	1034.48	1034.40	1034.40	1034.70	1034.28	0.41		-0.01
11.7	1033.91	1033.69	1034.00	1033.88	1033.99	1033.72	1033.86	1033.68	1033.77	1034.00	1033.68	0.32		0.00
11.66	1032.51	1032.38	1032.43	1032.44	1032.47	1032.45	1032.45	1032.48	1032.60	1032.60	1032.38	0.22		0.00
11.62	1033.31	1033.04	1033.04	1033.04	1033.05	1033.06	1033.10	1033.15	1033.06	1033.31	1033.04	0.27		0.00
11.58	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	1032.53	0.00		0.00
11.53	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	1031.12	0.00		0.00
11.49	1029.80	1029.83	1029.31	1029.31	1029.84	1029.95	1029.94	1029.66	1030.14	1030.14	1029.31	0.83		0.00
11.44	1028.69	1028.82	1028.82	1028.81	1028.81	1028.90	1029.20	1028.50	1029.23	1029.23	1028.50	0.72		-0.01
11.35	1027.95	1027.87	1027.99	1027.98	1027.93	1028.08	1028.43	1027.77	1028.56	1028.56	1027.77	0.78		-0.01
11.25	1025.68	1026.01	1026.21	1026.21	1025.84	1025.68	1025.41	1026.07	1025.35	1026.21	1025.35	0.86		0.00
11.17	1024.02	1024.02	1023.97	1023.98	1024.02	1024.02	1024.02	1024.02	1024.02	1024.02	1023.97	0.05		0.00
11.09	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	1021.28	0.00		0.00
11.01	1019.12	1019.14	1019.07	1019.11	1019.31	1019.29	1019.20	1018.50	1019.01	1019.31	1018.50	0.81		0.00
11	1018.53	1018.49	1017.55	1017.55	1018.52	1018.52	1018.49	1018.36	1018.55	1018.55	1017.55	1.00	YES	0.00
10.98	1017.94	1018.32	1017.88	1017.96	1018.01	1018.00	1017.94	1017.90	1018.10	1018.32	1017.88	0.44		0.00
10.97	1018.23	1018.43	1017.35	1017.38	1018.46	1018.34	1018.49	1017.21	1017.50	1018.49	1017.21	1.27	YES	-0.01
10.88	1016.21	1016.07	1016.40	1016.40	1016.32	1016.17	1016.19	1016.07	1016.53	1016.53	1016.07	0.46		0.00
10.79	1014.80	1014.80	1014.61	1014.61	1014.80	1014.80	1014.80	1014.72	1014.13	1014.80	1014.13	0.67		0.00
10.73	1012.59	1012.52	1012.54	1012.60	1012.40	1012.46	1012.41	1012.59	1012.71	1012.71	1012.40	0.31		0.00
10.68	1011.74	1011.21	1011.07	1011.07	1011.42	1011.42	1011.40	1010.96	1011.06	1011.74	1010.96	0.78		0.00
10.6	1008.81	1009.31	1009.19	1009.18	1008.91	1008.96	1008.94	1009.16	1009.19	1009.31	1008.81	0.50		0.00
10.51	1006.35	1006.74	1006.75	1006.75	1006.75	1006.76	1006.73	1006.70	1007.01	1007.01	1006.35	0.66		0.00
10.43	1006.55	1006.57	1006.48	1006.54	1006.54	1006.56	1006.57	1006.57	1006.71	1006.71	1006.48	0.23		0.00
10.33	1004.50	1004.38	1004.38	1004.37	1004.48	1004.39	1004.43	1004.53	1004.38	1004.53	1004.37	0.16		0.00
10.24	1001.25	1001.26	1001.26	1001.26	1001.26	1001.26	1001.27	1001.28	1001.27	1001.28	1001.25	0.03		0.00
10.14	998.69	998.66	998.66	998.66	998.66	998.66	998.67	998.68	998.67	998.69	998.66	0.03		0.00
10.04	996.04	996.19	996.19	996.19	996.17	996.19	996.20	996.16	996.17	996.20	996.04	0.16		0.00
9.93	992.63	993.11	993.11	993.11	993.06	993.10	993.11	993.08	993.06	993.11	992.63	0.48		0.00
9.84	991.33	991.94	991.94	991.94	992.01	991.94	991.89	991.92	992.02	992.02	991.33	0.69		0.00
9.74	989.21	989.62	989.63	989.62	989.63	989.63	989.60	989.63	989.61	989.63	989.21	0.43		0.01
9.64	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	987.61	0.00		0.00

APPENDIX II

Coordination with HEC Regarding

Sediment Transport Modeling of Sand and Gravel Mining Pits

Using HEC-RAS

R2D River Research and Design, Inc.

FAX: (888) 670-8890 Phone: (480) 275-5077 E-mail: freeman@r2d-eng.com

Website: www.r2d-eng.com

4359 N. Pine-Featherville Rd
Featherville, ID 83647

December 20, 2012

HEC-RAS Sediment Transport Coordination with HEC

Work done under previous task orders for the Flood Control District of Maricopa County developed data the indicated that the HEC-RAS sediment transport routines were not operating as well as was desired for modeling headcuts in the Hassayampa River. The Hassayampa River is a sand bed stream in western Maricopa County. The modeling performed indicated that the HEC-RAS model performed significantly worse than the HEC-6T and the FLUVIAL-12 model that were also used to model headcuts in a reach primarily above the I-10 crossing of the Hassayampa River. The model included the reach from Buckeye Road to the Olive Avenue alignment. This study was focused on the Pioneer Pit headcut (RM 15.67) since data were available for the direct comparison with modeled results.

Contact was made with Mr. Stanford Gibson the HEC staff member responsible for the development of sediment transport in the HEC-RAS model[3]. Stanford indicated that they had noted a problem with sediment transport in RAS and that they had a new version of the model out that had an updated algorithm for calculating bed mixing and armoring. After a review of the model for the Hassayampa River he indicated that it was unlikely that the problem they had noted with bed mixing was accounting for our inaccuracies since there was very little, if any, material of a size that would create an armor layer on the surface of the bed of the river.

Mr. Gibson provided a beta version of the model (4.2) that had improvements to the bed mixing algorithm and this version was used to model the Hassayampa River. This model provided some differences in the output but no major improvement in model performance for the Pioneer Pit headcut. A September update of version 4.2 was also supplied but no significant differences were noted.

[3] The e-mail correspondence with Mr. Gibson is contained in Appendix A.

APPENDIX A: E-MAIL CHAIN BETWEEN RIVER RESEARCH & DESIGN AND STANFORD GIBSON, HEC

Initial Contact:

Sent: Thursday, January 26, 2012 1:24 PM
To: RAS
Subject: Bug in HEC-RAS Sediment Calculations

We have used HEC-RAS to model the impact of a sand and gravel pit on the Hassayampa River west of Phoenix. The results were not particularly good (bad would be a better description). We also ran the same geometry and inputs in HEC-6T and FLUVIAL-12 and got very good results for the upstream Pioneer pit where our data was the best.

1) My contact info is below.
2) We are running HEC-RAS version 4.1.0
3) The operating system is Windows 7 (also Windows XP was used).
4) None of the transport equations predict even close to the proper amount of scour for this condition. The Engelund Hansen was the best but over predicted significantly. The other equations predicted almost no scour upstream from a 30 ft deep pit. Actual scour depth was approximately 10 ft upstream of the pit. Both HEC-6T and FLUVIAL-12 predicted this depth within a couple of feet. Headcut lengths (the distance the bed lowered by more than a foot) was also way off for all of the equations except the Engelund Hansen which was fairly close. In our review we think there is a problem with the depth used in the Engelund Hansen transport Equation (see footnote 1 on page 41 of the attached report) but we have no idea what is wrong with the other equations. I have attached the model as well as the report. I would be happy to work with you concerning this problem. The Flood Control District of Maricopa County is providing some very limited funding for me to work with you to see if we can resolve this issue. The HEC-RAS model will be a tremendous step forward if we can figure out what is going on in this case. It's possible that I have just missed something simple in the model that needs to be done but it hasn't been obvious up to this point. The geometry, cross section location & spacing, and inputs were fixed since we were comparing three models. If you have suggestions for changes to the models that may help I would be happy to implement them to see if they work.

Feel free to e-mail me or to call me at (480) 275-5077 if you have questions or need additional information.

Gary

--
Gary E. Freeman, PhD, PE, D.WRE, CFM
President

Initial Response:

Hello Gary,

This is an excellent and weighty study. Hopefully I will be able to help.

We have found a couple bugs in 4.1 that could have impacted your results. I'd be happy to provide you a copy of 4.2 (for this comparison). But I am not under the illusion that we have gotten them all. The other two programs literally have a multi decade debugging head start on us. If there is a persistent bug I have to get to the bottom of it and I would be very grateful (to you for your interest and the Water District for the funding) if we could work together to find it. I know this isn't the main problem, but we have fixed a couple bugs wrt ineffective flow areas (which you mention in your report). Also, I think you will find runtimes in 4.2 are improved.

But I something else might be going on. Our default bed mixing model is Exner 5 (the default method in HEC 6). I have found that in most cases, Exner 5 artificially armors, putting a supply limitation on the system that is a numerical artifact. I believe that Exner 7 is the default in 6T (which was designed explicitly for the purpose of getting beyond the scour limitations of Exner 5). I believe fluvial uses a much simpler mixing algorithm, that would also dodge this limitation. If you run with the "active layer" mixing method you will get much more scour. We have found the active layer method produces results much more in line with Exner 7 and it is conceptually much closer to the approach in Fluvial.

Another possible issue is that we do not do super critical flow yet. If the flow goes super critical (which it looks like it does) we default to critical. I don't know what the other two programs do, but that could be an issue, particularly for modeling a head cut, which we do not claim to do well (though I'd like to do it at least as well as the programs that are conceptually like ours).

To start us out, I ran the base model you sent with 4.2 as is and then ran it with 4.2 and the active layer method and compared it to the results you sent. I am not sure I am 100% certain what you are looking for yet, but it looks like 4.2 is producing substantially more head cutting even with Exner 5 (and it looks mostly insensitive to mixing method). I tried it with LC and EX 5 too and there is some strange behavior (that I think we can fix) but it is behaving more believably than the results on page 96 of your report.

Please give me a call when you get a chance to look over this and we can decide where to go from here.

Thanks
stanford

Stanford Gibson, PhD
Research Hydraulic Engineer
Hydrologic Engineering Center

Inquiry 2:

From: Gary E Freeman [mailto:freeman@r2d-eng.com]
Sent: Saturday, February 25, 2012 2:59 PM
To: Gibson, Stanford A IWR-HEC
Subject: Re: 4.2 (UNCLASSIFIED)

Stanford -

I haven't fallen off the face of the earth but some days it feels like it. . . I was tied up with other things the last few weeks. I have had trouble that when I select a transport function in the sediment editor (or the sorting method for that matter) and then save the data. The next time I open it it may give me another transport equation or sorting method. I'm pretty sure I'm not forgetting to save the data as I never select the Exner 5 method but it comes up occasionally. Has anyone else been having this problem. The Engelund Hansen method is working very well in the 4.2 version you provided. A couple of others worked well & then I was getting results like before. It may be that it reverted to the Exner 5 sorting instead of the Exner 7.

Also when I run one time I have 31 output profiles & then I made a change to the sorting (only change) and when I reran it I got 301 profiles. This is the first time I've notice that.

How do you apply the active layer methodology in RAS - i.e. how are the variables set for this case when you have only one layer measured that extends well below the scour depths? Also can you go to a summary in the output that tells you what transport equation and sorting algorithm was used in the run?

I will send you the observed data when I get some more results for comparison.

Thanks!

Gary.

--
Gary E. Freeman, PhD, PE, D.WRE, CFM
President

Response 2:

Hi Gary,

I haven't ever had any trouble with or reports or the transport function or mixing method not saving...or with them changing the output. Can you provide an order of operations that reproduces the bug? It would be an easy and important fix if we can get to the bottom of it.

We have found bugs in Exner 7 since we talked. I don't think you will want to use that for now. I'd stick to Exner 5 and the Active layer method. The active layer method is a simple two-layer method...but given your gradational breakdown, I no longer suspect that the mixing method is driving the train.

Feel free to give me a call if problems with the interface persist or if you have any technical questions.

Stanford Gibson, PhD
Research Hydraulic Engineer
Hydrologic Engineering Center

From: Gary E Freeman [mailto:freeman@r2d-eng.com]
Sent: Monday, March 26, 2012 3:34 PM
To: Gibson, Stanford A IWR-HEC
Subject: Re: 4.2 (UNCLASSIFIED)

Stan - I'm getting back on the HEC-RAS sediment modeling issue again and was wondering if there is a newer version of the RAS beta than the one you provided on January 27, 2012?

I'm going to look at some additional model behavior for the sand pit model and just wanted to make sure I had the best model.

I have attached an Excel spreadsheet with the post flood thalweg data for the Hassayampa River.

Gary

Response May 11, 2012:

Hello Gary,

How are the tests going? Are there any big departures from 6T that I should give attention to?

Stanford Gibson, PhD
Research Hydraulic Engineer
Hydrologic Engineering Center

From: Gary E Freeman [mailto:freeman@r2d-eng.com]
Sent: Tuesday, May 15, 2012 5:46 PM
To: Gibson, Stanford A IWR-HEC
Subject: Re: 4.2 (UNCLASSIFIED)

I'm still seeing some big differences between results - some of the transport equations are working better than others. I've been looking at 6T sensitivity lately but will pull out my results from my comparison and give you an update on what I saw working and what wasn't working.
I'm out of town for the next couple of days and hope I can get it rounded up next week.

Gary.

Response - May 15, 2012

OK, thanks. No hurry. I really appreciate you looking at this.

We are going to have Tony and Ron here in end of July to do some side by side debugging with 6T. Maybe we could use your data sets.

stanford

Sent: Thursday, November 15, 2012 1:47 PM
To: Gibson, Stanford A IWR-HEC
Subject: Re: 4.2 (UNCLASSIFIED)

How are things coming with the next update to HEC-RAS sediment? I have done most of my work on 6T sensitivity for headcuts and we have found that the flow inputs in the model of the Hassayampa that we sent had some flows that weren't right (they were the same in the RAS model). I haven't had a chance to see if that will improve deposition in the pit but will look at that. Is there another version I can try out to see if it's working more like 6T for our application for sand & gravel mining?
The latest version I have is 4.2 from about January 27, 2012.

I finally have some hours I can put into it to see if I can reproduce the error I thought I saw earlier (it actually may have been me forgetting to save the data but I thought I had saved it). It might be nice to have a check to see if you have changed data & ask you if you want to save it if you haven't. That always makes sure you are awake. . . I will update our model to have the right flows and see if it performs better. I will then try it in the latest version of RAS that I can get to see how it does (currently 4.2 from January 27th).

Thanks!

Gary.

--
Gary E. Freeman, PhD, PE, D.WRE, CFM
President

Response – November 15, 2012

Sure,

We have a September set of executables. I'll send them along. If you don't hear from me by tomorrow, drop me a note.

stanford