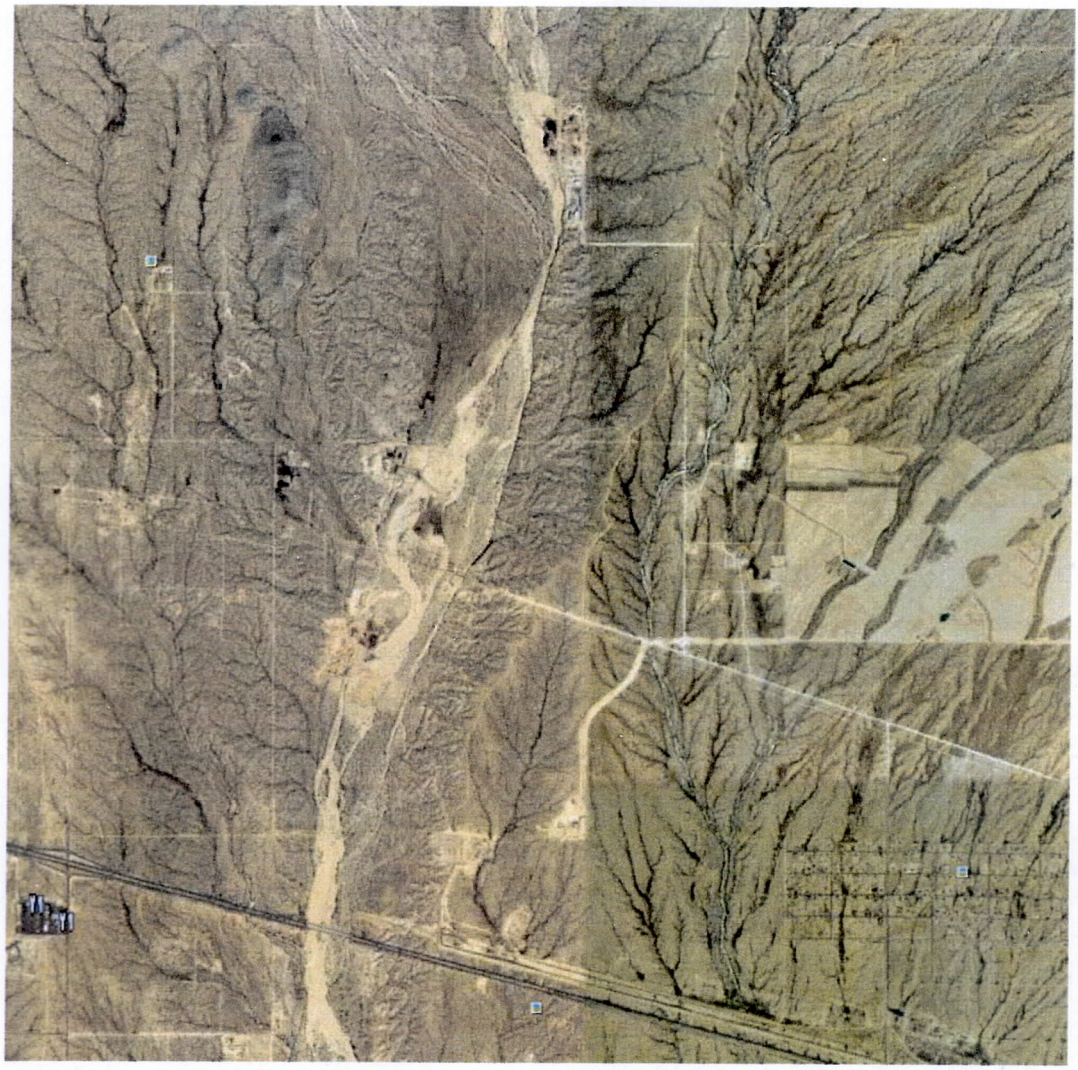
Mining Pit Headcut/tailcut Modeling in Lower Hassayampa River for Major Recent Flooding Events



Prepared for
Engineering Application Development and
River Mechanics Branch
Engineering Division
Flood Control District of Maricopa County

Prepared by
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June 2011

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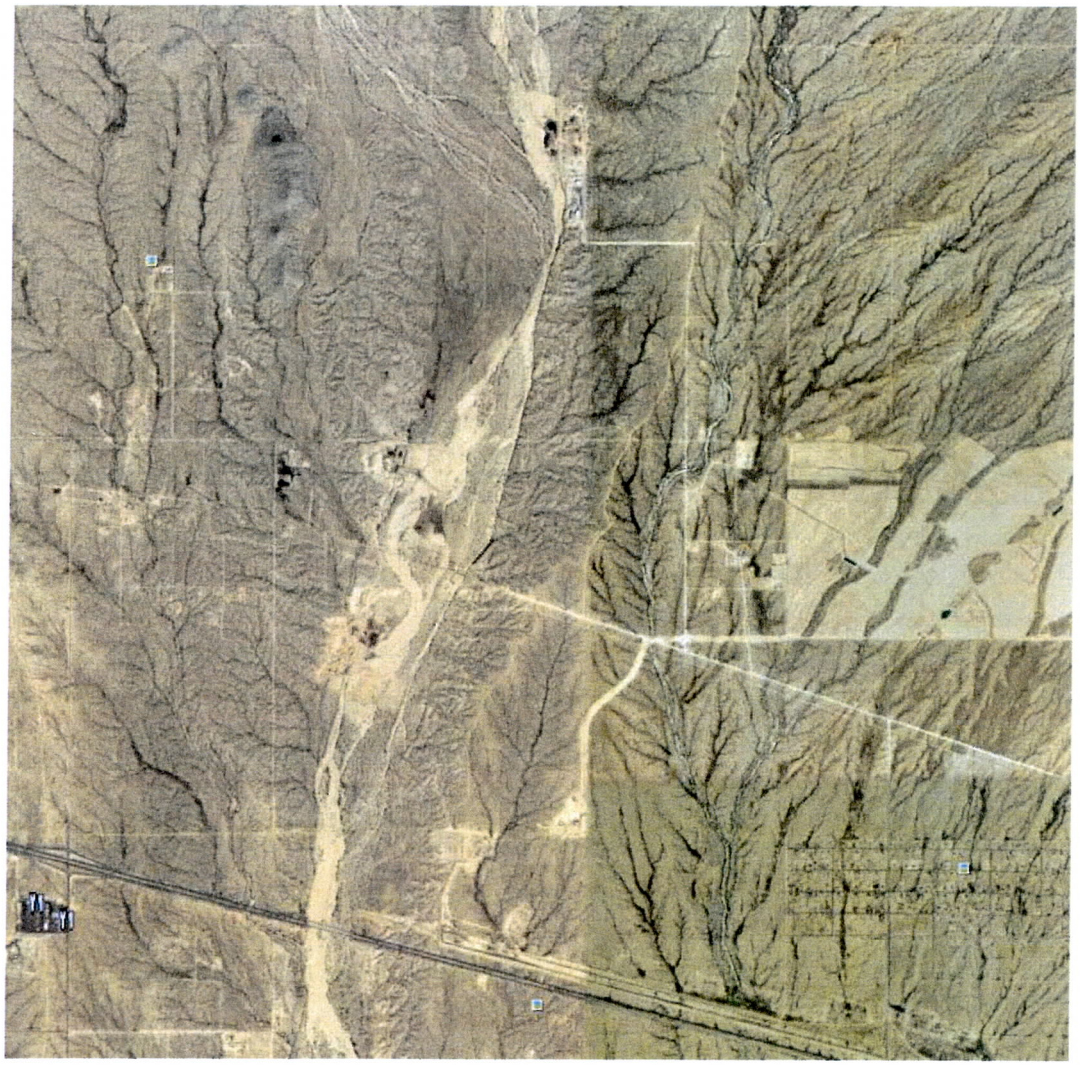

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COMPUTER FILES FOR NON-CALIBRATED GROUP

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HASSA-CUTEH.OUT: FLUVIAL-12 output file for 2010 flood only using Engelund-Hansen formula

HASSA-CUTY.OUT: FLUVIAL-12 output file for 2010 flood only using Yang formula

COMPUTER FILES FOR CALIBRATED GROUP

HASSA-CUTEH.FLU: FLUVIAL-12 input file for 2010 flood only using Engelund-Hansen formula

HASSA-CUTEH.OUT: FLUVIAL-12 output file for 2010 flood using Engelund-Hansen formula

HASSA-EH05.FLU: FLUVIAL-12 input file using 2005 channel data and Engelund-Hansen formula

HASSA-EH05.OUT: Output file produced by HASSA-EH05.FLU

HASSA-EH10.FLU: FLUVIAL-12 input file using the output channel data from HASSA-EH05.OUT plus the mining site data just before 2010 flood

HASSA-EH10.OUT: FLUVIAL-12 output file produced by HASSA-EH10.FLU using the Engelund-Hansen formula and the 2010 flood

HASSA-Y05.FLU: FLUVIAL-12 input file using 2005 channel data and Yang formula

HASSA-Y05.OUT: Output file produced by HASSA-Y05.FLU executed for 2005 flood

HASSA-Y10.FLU: FLUVIAL-12 input file using output channel data from HASSA-Y05.OUT plus mining site data just before 2010 flood

HASSA-Y10.OUT: FLUVIAL-12 output file produced by HASSA-Y10.FLU using Yang formula and 2010 flood.

EXECUTIVE SUMMARY

The sand and gravel mining operations in the lower Hassayampa River have created three pits: Pioneer Pit, Cemex Pit, and Hanson Pit. Significant flooding events on February 11-12, 2005 and January 20-21, 2010 have caused headcuts and tailcuts near the sand and gravel mining pits. The headcut and tailcut modeling study has been made following two approaches. The first approach is to model the January 20-21, 2010 event using 2002 topographic data as the basis and using the pit configuration to modify the topographic data. The pit configuration is estimated for the condition prior to the January 20-21, 2010 event.

For modeling the January 20-21, 2010 event, three pits were incorporated into the initial topographic data. Chang Consultants used these cross sections to develop a FLUVIAL-12 model with Engelund-Hansen transport equation. All other parameters are based on the same parameters from R2D's HEC-6T and HEC-RAS sediment transport models. The mathematical models of FLUVIAL-12 and HEC-RAS are developed to simulate the hydraulics of flow, sediment transport, and river channel changes. Calibration of the FLUVIAL-12 model was made in order to mach the modeled results with measurement.

Simulated Results on Sediment Delivery — Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time. The spatial variation of sediment delivery along the river channel is simulated by FLUVIAL-12. The simulated results show that sediment delivery increases as the flow approaches a mining site. This increase in sediment delivery indicates erosion of the river bed in the process of headcut. The sediment delivery increases as the flow leaves the mining site, indicating erosion in the process of tailcut. The sediment delivery decreases through the three mining sites, indicating deposition since there is more sediment inflow than outflow. Channel changes near the mining sites are simulated by the FLUVIAL-12. Such changes are characterized by headcut upstream of the mining site, sediment deposition in the pit, and tailcut downstream of the pit.

Calibration Study — Topographic survey of the river channel made after the 2010 flood was used to calibrate the modeling results for headcut/tailcut. The purpose of calibration is to match the simulated results for headcut/tailcut with the measurement. To accomplish this objective, the roughness coefficient, the sediment transport formula, and the bank erodibility factor were selected in modeling experiments. In the calibration study, the roughness coefficient that produces the best correlation of simulated and measured results was determined to be 0.026 through modeling experiments. The Engelund-Hansen formula and the Yang formula for sediment transport were used in the FLUVIAL-12 model. The results generated by these sediment transport formulas were compared with the survey. The post-flood channel bed generated by the Engelund-Hansen formula is in general agreement with the post-flood survey. However, the post-flood channel bed generated using the Yang formula correlates poorly with the survey. Model calibration using the Yang formula failed. All other results as presented in the report are based on the Engelund-Hansen formula.

In the FLUVIAL-12 model, the bank erodibility factor (BEF) is the parameter that governs the rate of bank erosion and width change. The width change also affects channel bed aggradation and degradation since these changes are inter-related. In the calibration study, the

BEF value that provides the best correlation of simulated and surveyed results was selected. This value was varied in modeling runs in order to select the value that provides the best correlation of modeling results with the measurement. The BEF value was determined to be 1.0 through this process. This BEF value means that the bank of the headcut/tailcut channel is as erodible as the channel bed for the Hassayampa River.

The simulated results with calibration are presented in two figures. The first figure shows the simulated changes in channel bed profile compared the post-flood survey based on the 2010 flood only. The second figure shows longitudinal bed profile changes simulated using both the 2005 and 2010 floods, also compared with the post-flood survey. The simulated post-flood channel bed profiles for both cases compare favorably with the post-flood survey.

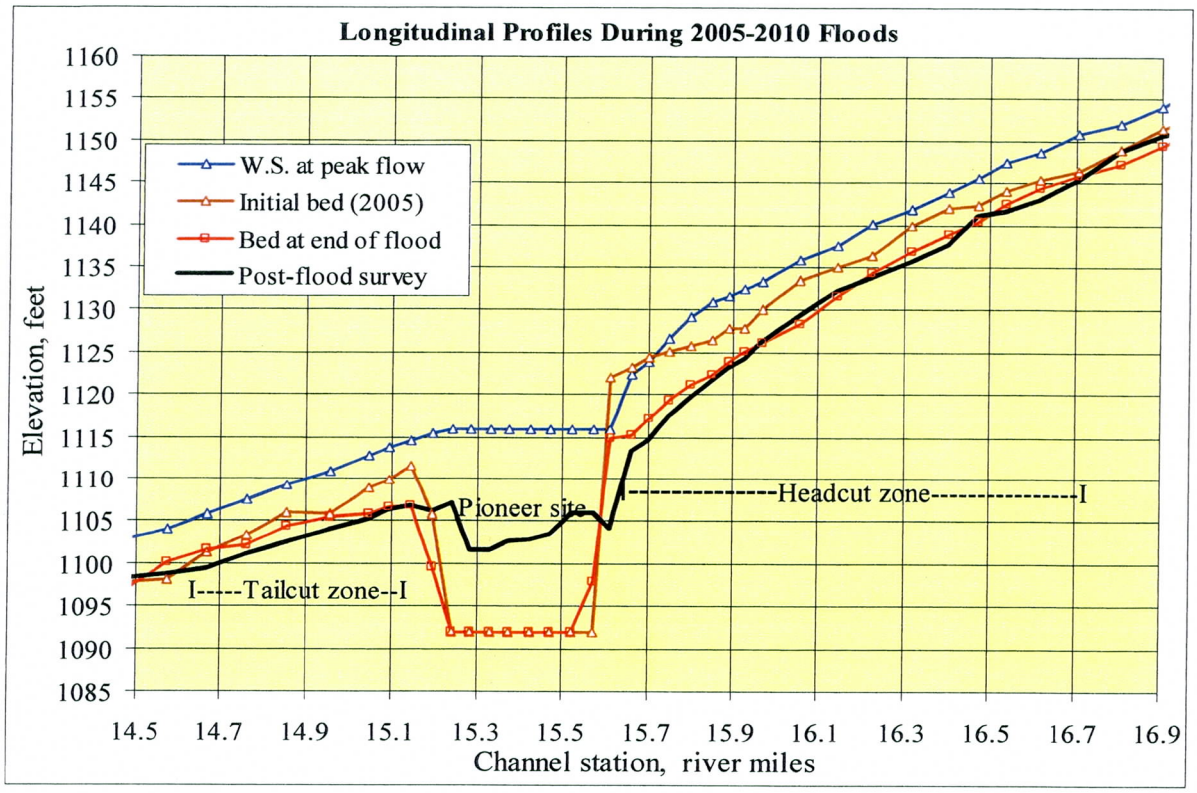
Modeled Results Based on 2010 Flood Only — Channel changes due to headcut/tailcut near the Pioneer pit are shown in the first figure. Headcut developed along the channel reach upstream of the Pioneer site. The headcut zone is from the Pioneer pit at section 15.67 to section 16.72 for a total channel length of about 1 mile. For the channel reach downstream of the Pioneer site, the tailcut zone is from the downstream edge of the Pioneer pit at section 15.15 down to section 14.77 for a total channel length of about 0.5 mile.

River channel changes along reaches near the Cemex site and the Hanson site were caused by both river channel scour and sand mining. The effects of these two factors on channel changes can not be separated; therefore, no attempt is made to determine the scour depth due to headcut/tailcut.

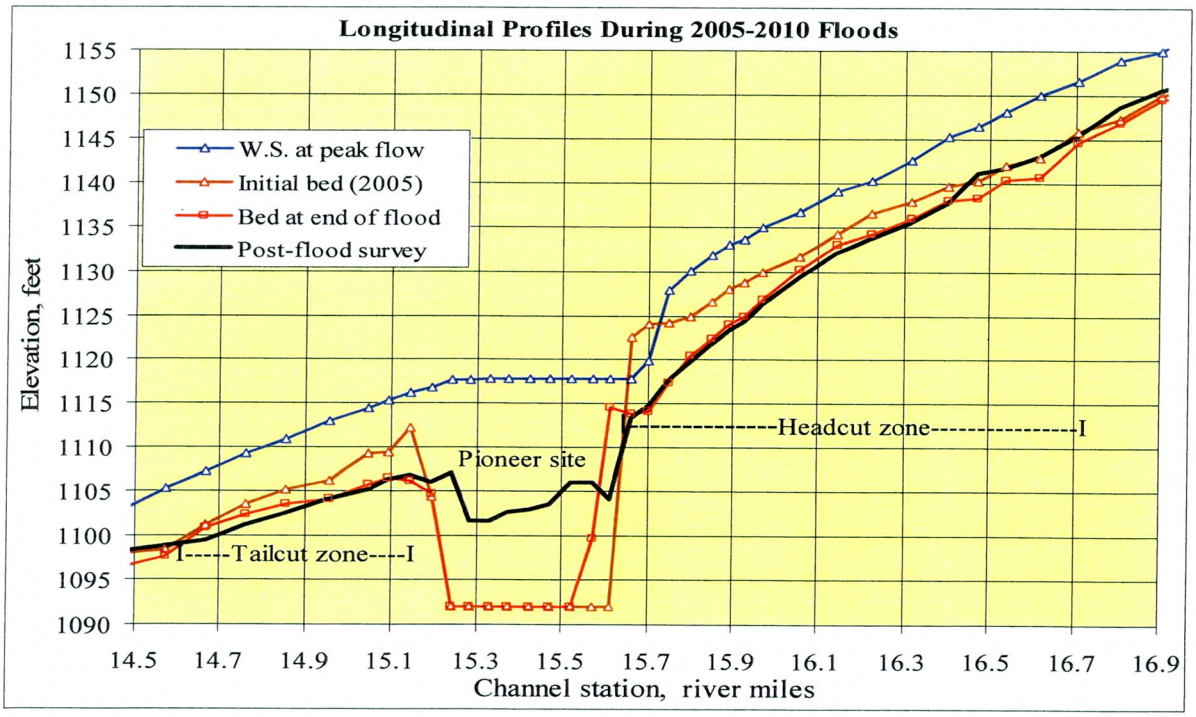
Modeling Using 2005 and 2010 Floods — Two steps were taken in modeling the February 11-12, 2005 event and January 20-21, 2010 event. The first step is to use the LHWMP-Phase I topographic data that has incorporated the mining pits configuration into the topographic data provided to Chang Consultants as HEC-RAS cross-sections. After the Fluvial-12 modeling of the 2005 flood, the original cross-section data were changed by Fluvial-12 at the end of the simulation due to river channel changes. Chang Consultants converted the output simulated by FLUVIAL-12 for the 2005 event into the input data for the 2010 flood event.

After the Fluvial-12 modeling of the 2005 flood, the original cross-section data were changed by Fluvial-12 at the end of the simulation due to river channel changes. Chang Consultants converted the output simulated by FLUVIAL-12 for the 2005 event into the input data for the 2010 flood event. Chang Consultants modeled the January 20-21, 2010 event based on the end-of-simulation cross-section data after the 2005 event. The cross-section data were then revised by incorporating the pit configuration prior to the January 2010 event.

The simulated changes in channel geometry due to headcut/tailcut are compared with the surveyed results. Headcut developed along the channel reach upstream of Pioneer pit. The headcut reach from the simulated results is from section 15.67 at the upstream edge of the mining pit to section 16.82 for a total channel length of about 1.1 miles. Tailcut developed along the channel reach downstream of the Pioneer pit. The tailcut zone is from the downstream edge of the Pioneer pit at section 15.20 down to section 14.60 for a total channel length of about 0.6 mile.



Simulated channel bed profile changes based on 2010 flood together with post-flood survey



Simulated channel bed profile changes based on both 2005 and 2010 floods together with post-flood survey

Simulated changes in longitudinal profiles near the Cemex and Hanson mining sites were compared. The comparison of the surveyed post-flood channel bed profile with the simulated bed profile changes shows no clear pattern of headcut/tailcut. It is also easy to see that the channel bed was affected by sand and gravel mining during the period from 2005 to 2010, in addition to mining activities prior to 2005. The effects of mining and headcut/tailcut induced by the mining sites can not be separated along this river reach.

Performance Indices — A Performance Index is used to assess the correlation of the simulated and surveyed results for headcut and tailcut. The Absolute Performance Index, *API*, is defined by the following equation:

$$API = \Sigma_{i=1}^{n} \frac{|M_i - C_i|}{n}$$

where M_i is the measured headcut/tailcut depth (positive values) or deposition depth (negative values), C_i is the computed headcut/tailcut depth (positive values) or deposition depth (negative values), and n is the number of cross-sections. The performance index represents the deviation of the simulated value from the surveyed value for headcut/tailcut. To assess the modeling results for the two approaches, the computed API's for the scour depths are compared as summarized in the table below.

Comparison of Absolute Performance Indices with Calibration

Cases	Absolute Performance Index API	
	Based on 2010 flood only	Based on 2005 and 2010 events
Headcut depth above Pioneer pit	1.05 feet	0.85 foot
Tailcut depth below Pioneer pit	1.02 feet	0.56 foot

The API values indicate that the differences of simulated and measured scour depths for headcut/tailcut are approximately one foot based on the results from the 2010 flood. The differences of simulated and measured scour depths are less than one foot based on the results of both the 2005 and 2010 floods. For these reasons, the correlations of simulated and measured headcut/tailcut depths near the Pioneer pit are generally good. The modeling results from both flood events have better correlations with measurement than the case of one flood only. This is expected since the scour depths developed during both floods.

The performance indices presented in the report are based on channel bed scour. In addition to the scour depth, simulated changes in cross-sectional profiles for the two cases are also presented in the report. The simulated cross-sectional changed based on both the 2005 and 2010 floods are similar to the surveyed cross sectional profiles. However the cross-sectional profiles based on the 2010 flood only are not as well correlated with the surveyed results. In summary, model study using both the 2005 and 2010 floods has improved the correlation with measurement.

Discussion of Study Results — The comparisons show that the differences between simulated and measured headcut/tailcut depths induced by the mining pits are generally small. In other words, the correlations of simulated and measured scour depth are considered good. Such results were achieved through the calibration process.

Certain sources for the discrepancy between the simulated and measured results can be cited. Channel morphology associated with headcut/tailcut is normally characterized by the formation of narrow and deep gullies. However, the channels formed by headcut/tailcut for this case are generally wider and larger in cross-sectional area than a typical gulley. The discrepancies are attributed to several factors. An important factor is the fact that the Hassayampa River has a broad floodplain with a highly braided channel pattern. Because of multiple channel branches, headcut/tailcut changes induced by the mining pit are also affected by the presence of other channel branches. The tributary inflow from Jackrabbit Wash has significant effects on channel morphology downstream of the Pioneer pit, as the large width is closely related to the lateral inflow from Jackrabbit Wash. The effects of lateral inflow on channel morphology at this location were not simulated in modeling.

Mining Pit Headcut/tailcut modeling in Lower Hassayampa River for Major Recent Flooding Events

I. INTRODUCTION

Significant flooding events on February 11-12, 2005 and January 20-21, 2010 have caused headcuts and tailcuts for the sand and gravel mining pits in the Lower Hassayampa River shown in Figures 1, 2, and 3. After the January 20-21, 2010 flooding event, new topographic data were obtained for a reach of 13 miles in the river. The purpose of this study is to use Fluvial-12 to model these flooding events using pre-2005 flooding topographic data as the initial condition to predict the headcut and tailcut and then compare the results with the new 2010 topographic data. The sand and gravel pits will be included to revise the topographic data since there were sand and gravel operations during the period. Both the original modeling results (without calibration) and the calibrated modeling results will be reported as compared with the observed new 2010 topographic data. All the results will be compiled into another report by R2D for comparison with HEC-6T and HEC-RAS sediment transport modeling results.

River Data - According to the Flood Control District of Maricopa County (FCDMC), the initial topographic data for the sediment transport modeling is based on the Lower Hassayampa River Watercourse Master Plan (JE Fuller, 2006, 2007). The topographic dates for the initial topographic data range from 4/2002 to 4/2004. This topographic data may be called Lower Hassayampa River Watercourse Master Plan Phase I (LHWMP-Phase I) topographic data. The topographic date for the new 2010 topographic data is dated 5/1/2010. The two major flooding event dates are February 11-12, 2005 and January 20-21, 2010 with the peak flows of 5500 cfs and 11600 cfs, respectively. The peak flows and flow hydrographs are based on FCDMC's stream gage at I-10. FCDMC has provided Chang Consultants the flow hydrographs.

There have been sand and gravel pit operations. Figure 2 shows the locations of the Pioneer Pit, Cemex Pit, and Hanson Pit. Figure 3 shows the river bed topography near the Pioneer pit. The following table shows the activities for these three pits.

Table 1. Estimated mine depths and areal extents (Waskowsky, 2010)

	Hanson		Cemex*		Pioneer	
	Depth (ft)	Area (acres)	Depth (ft)	Area (acres)	Depth (ft)	Area (acres)
2002 (information only)	4	0.5	12, 20	4.3	N/A	N/A
2004 (before '05 events)	5-9	15	10-15, 10-15, 15-20	1.1, 1.1, 14	N/A	N/A
2005 (after '05 events)	5-9	10	mine filled	mine filled	8-10	3.3
2009 (before Jan. 2010 event)	10	22	10	45	28-30	23

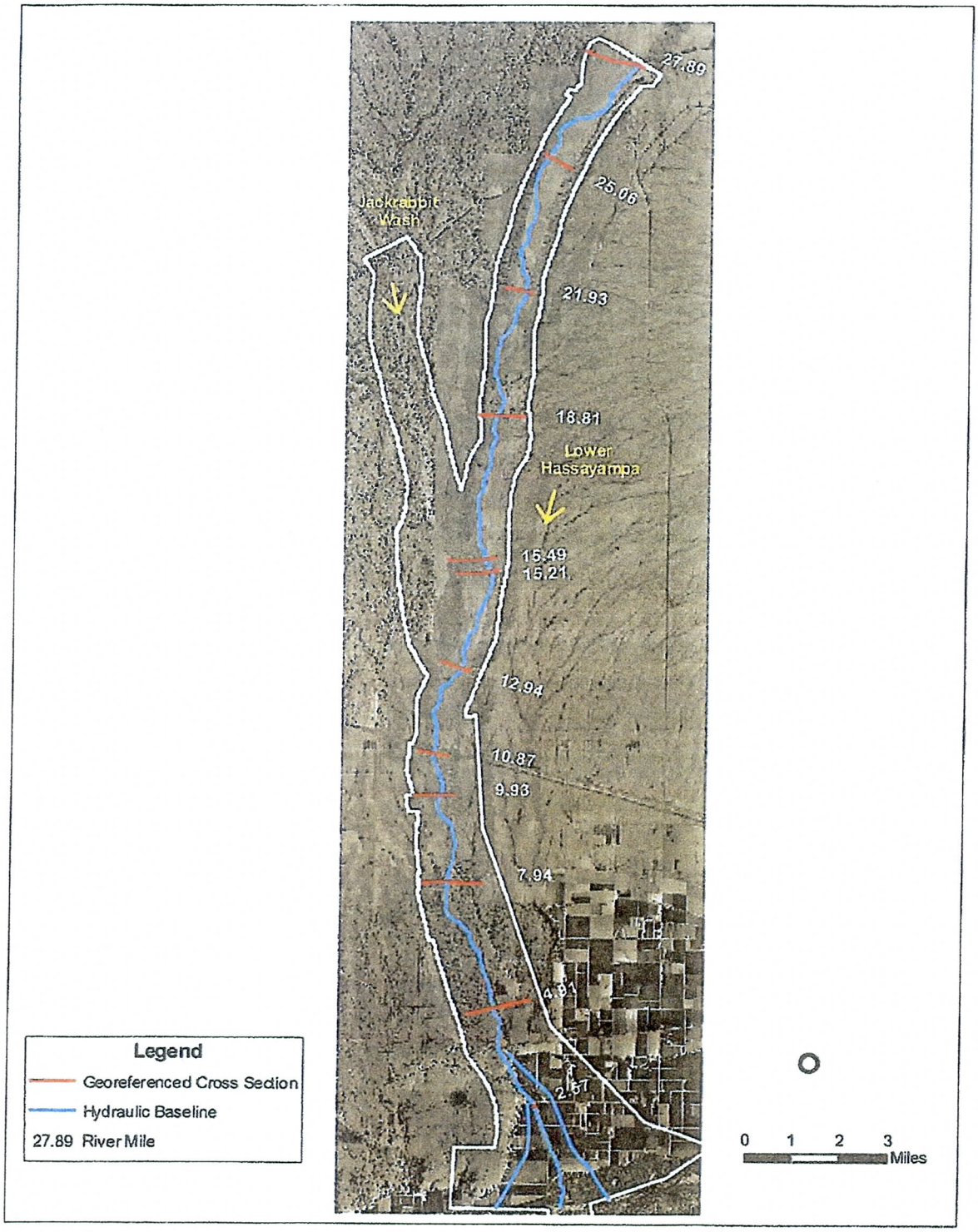


Figure 1. Lower Hassayampa River and its tributary Jackrabbit Wash

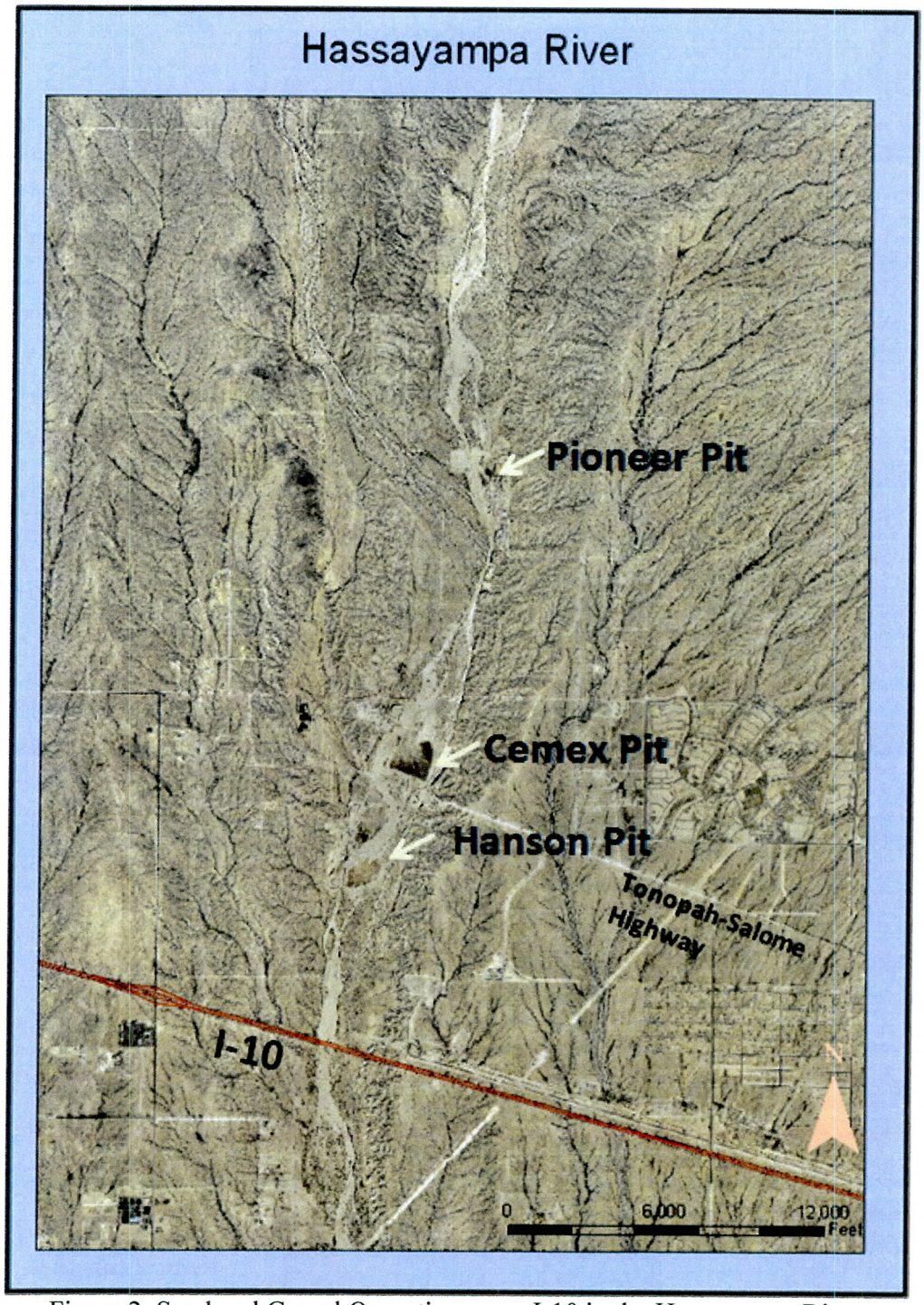


Figure 2. Sand and Gravel Operations near I-10 in the Hassayampa River

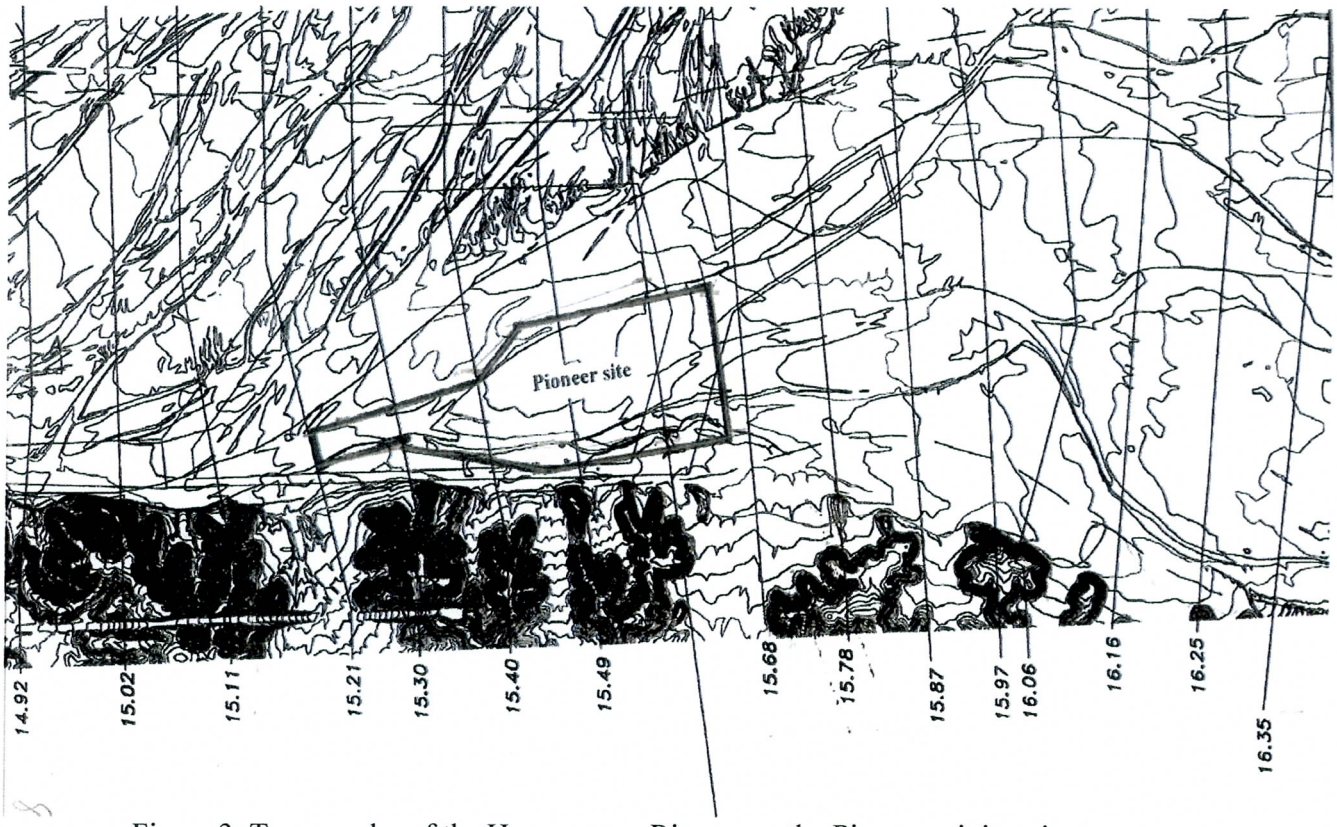


Figure 3. Topography of the Hassayampa River near the Pioneer mining site

Grain size distribution of the bed material for the study river reach is shown in Figure 4. The 2010 flood hydrograph is shown in Figure 5, and the hydrograph for the 2002 to 2010 flood series is shown in Figure 6.

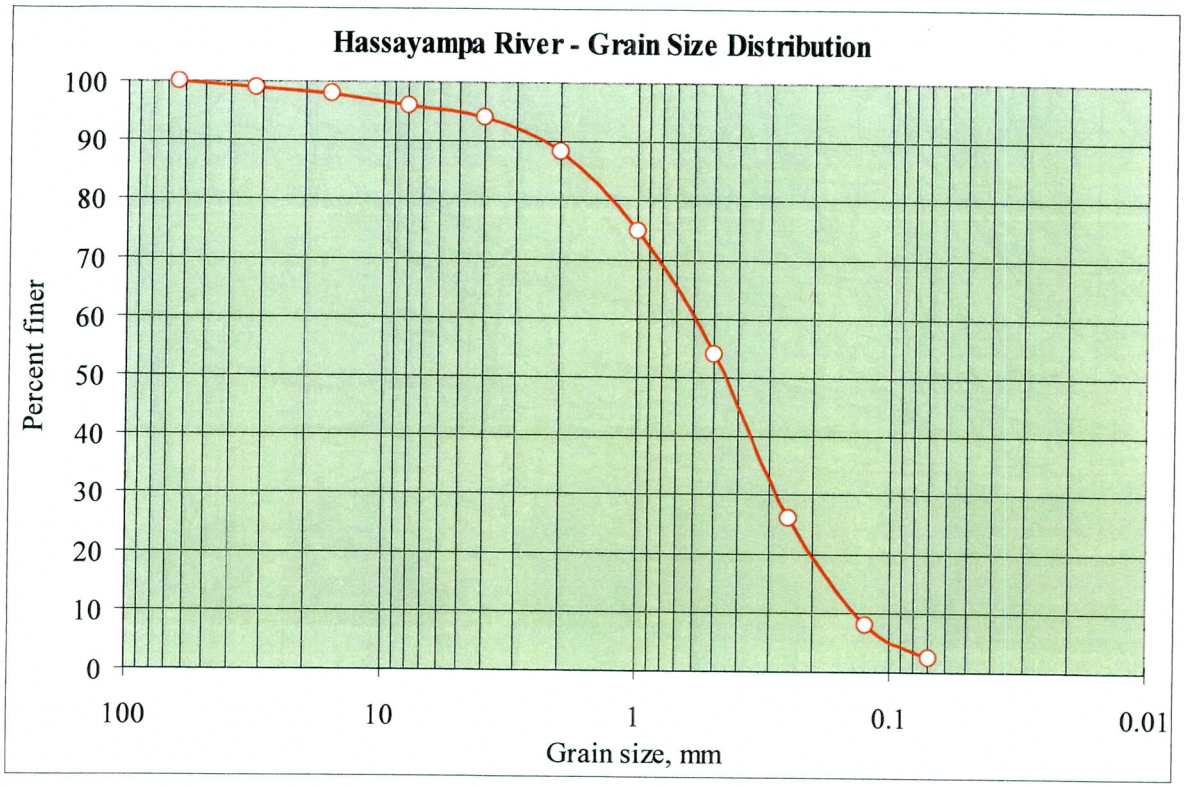


Figure 4. Grain size distribution of bed material for the study river reach

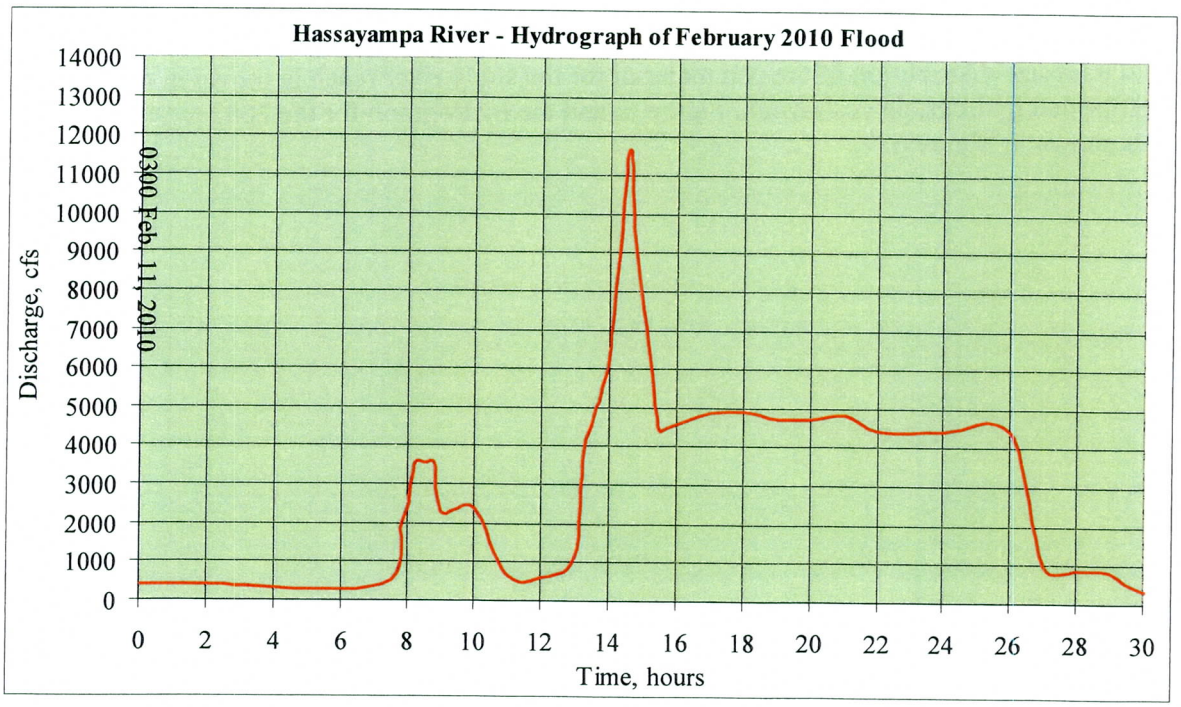


Figure 5. The 2010 flood hydrograph

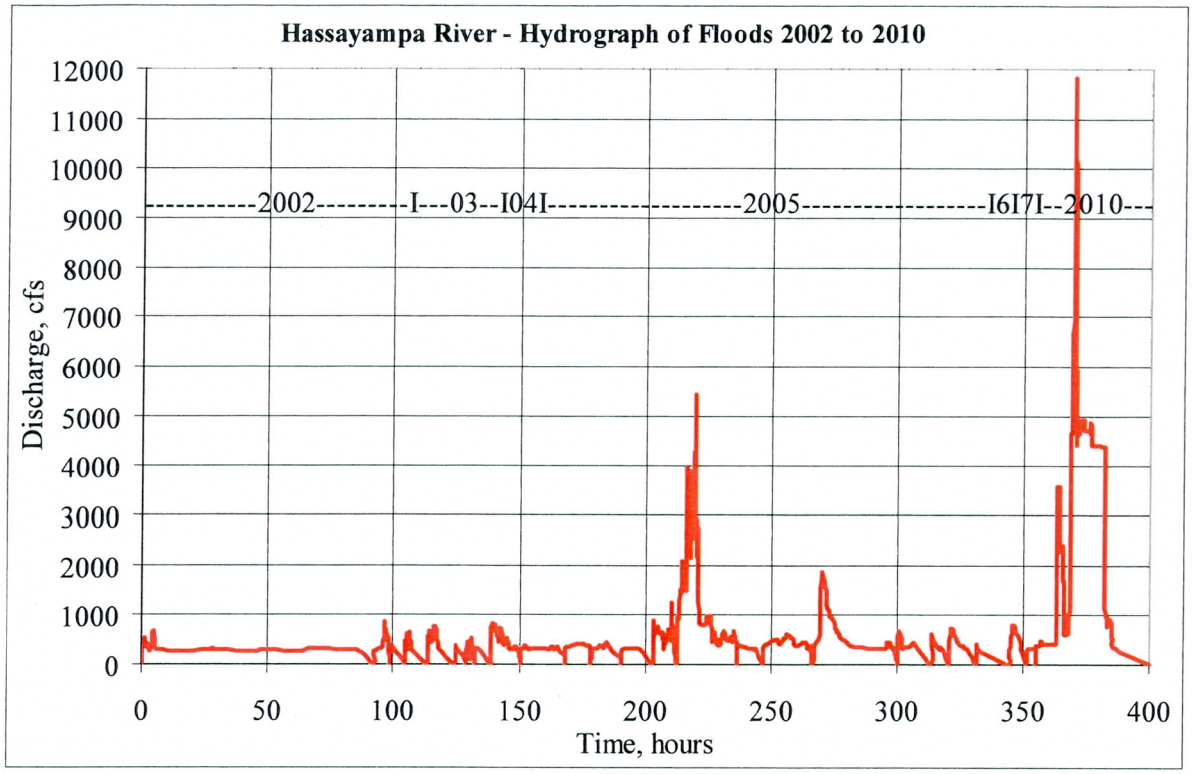


Figure 6. Hydrograph for the 2002 to 2010 flood series

Modeling Approach — There are two modeling approaches for the study. The first approach is simply to model January 20-21, 2010 event using 2002 topographic data as the basis and using the pit configuration to modify the topographic data. The pit configuration is estimated for the condition prior to the January 20-21, 2010 event. Both "without" and "with" calibration modeling will be performed.

The second approach is to model both 2005 and 2010 events using 2002 topographic data as the basis and using pit configuration to modify the topographic data. The modification of the topographic data has two steps. The first step is to modify the topographic data based on the pit configuration prior to February 11-12, 2005 event. The second step is to modify the end-of-Fluvial-12 February 11-12, 2005 event simulation cross-sections by adding the pit configurations observed prior to January 20-21, 2010 event. Both "without" and "with" calibration modeling will be performed.

II. PERFORMANCE INDEX

A Performance Index is used to assess the correlation of the simulated and surveyed results for headcut and tailcut. The Absolute Performance Index (API) is defined by Equation 1 below:

$$API = \sum_{i=1}^{n} \frac{|M_i - C_i|}{n} \quad (1)$$

where M_i is the measured headcut/tailcut depth (positive values) or deposition depth (negative values), C_i is the computed headcut/tailcut depth (positive values) or deposition depth (negative values), and n is the number of cross-sections.

III. MODEL CALIBRATION

The purpose of model calibration is to match the modeled results with measurement as closely as possible. In the process of calibration, certain parameters used in the study are selected. The modeled results using the selected parameters are compared with measurement. The selected parameters are then varied to improve the correlation of modeled results with measurement. For this study, model calibration includes the following steps:

(1) The selection of a computer model,
(2) The selection of sediment transport formula,
(3) The selection of channel roughness coefficients, and
(4) The selection of the Bank Erodibility Factor (for FLUVIAL-12 only).

The FLUVIAL-12 model was selected by Chang Consultants for the study. Model input is based on the initial topographic data called LHWMP-Phase I topographic data provided by R2D. As shown in Table 1, the Pioneer Pit has an area of 23 acres with a depth of 28-30 ft, Cemex Pit has an area of 45 acres with a depth of 10 ft, and Hanson Pit has an area of 22 acres with a depth of 10 ft. The outlines of the three pits are from the GIS Arcview shape file. R2D incorporated these pits into LHWMP-Phase I topographic data and develop HEC-RAS cross-sections. R2D provided Chang Consultants these HEC-RAS cross-sections. Before R2D cut cross-sections, R2D sent Chang Consultants the cross-sections layout for review and comments. Chang Consultants used these cross-sections to develop a Fluvial-12 model with Engelund-Hansen transport equation. All other parameters are based on the same parameters from R2D's HEC-6T and HEC-RAS sediment transport models (January 20-21, 2010 flow hydrograph, sediment inflow, time step for inflow hydrograph, sediment discharge rating curve, Manning's n, time step for computation, upstream and downstream boundary conditions…etc.). The maximum scour and scour at end of simulation will be reported. The results will be compared against the new 2010 topographic data.

Selection of Sediment Transport Formula Based on Simulated River Channel Changes near Pioneer Site — A sediment transport formula is employed in the computer model to simulate headcut/tailcut. The sediment transport formula for the study was selected based on the simulated results for headcut/tailcut induced by Pioneer pit. The Yang formula and the Engelund-Hansen formula were used separately in the study. Simulated changes in longitudinal profiles of channel reaches near the Pioneer site are shown in Figures 7 and 8, respectively. Such changes are characterized by headcut upstream of the mining site, sediment deposition in the pit, and tailcut downstream of the pit.

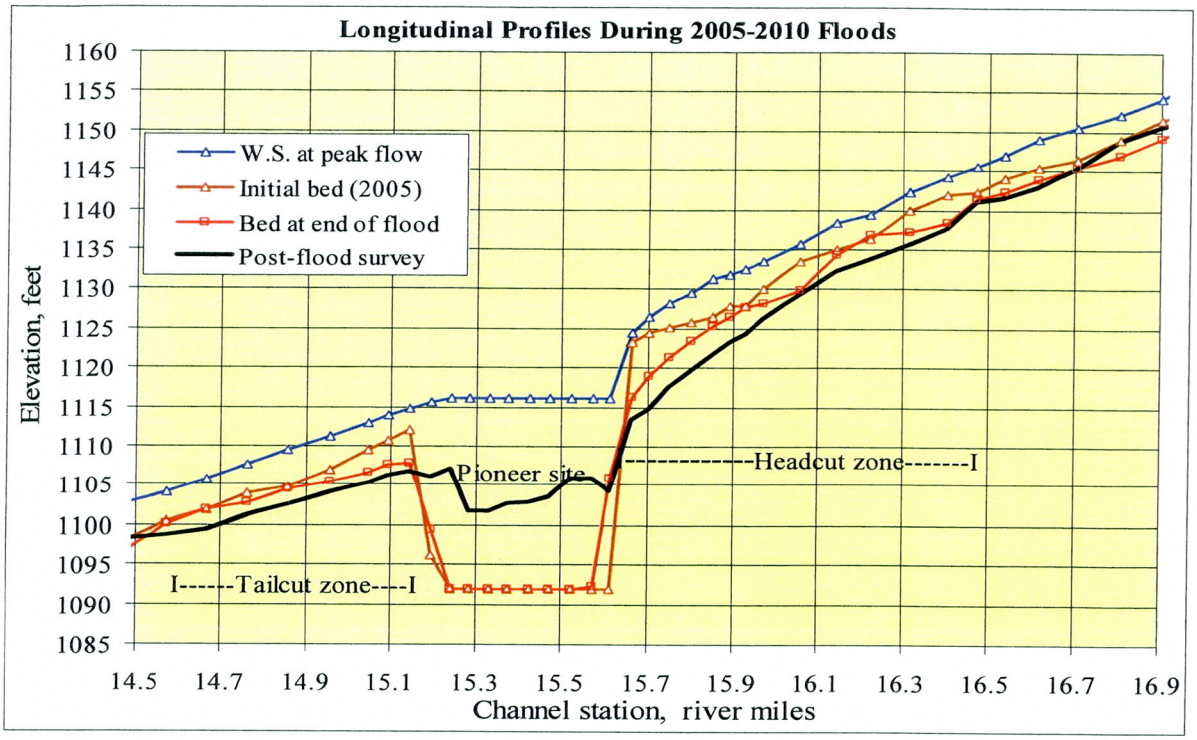


Figure 7. Simulated changes in longitudinal profiles using 2010 flood and Yang formula

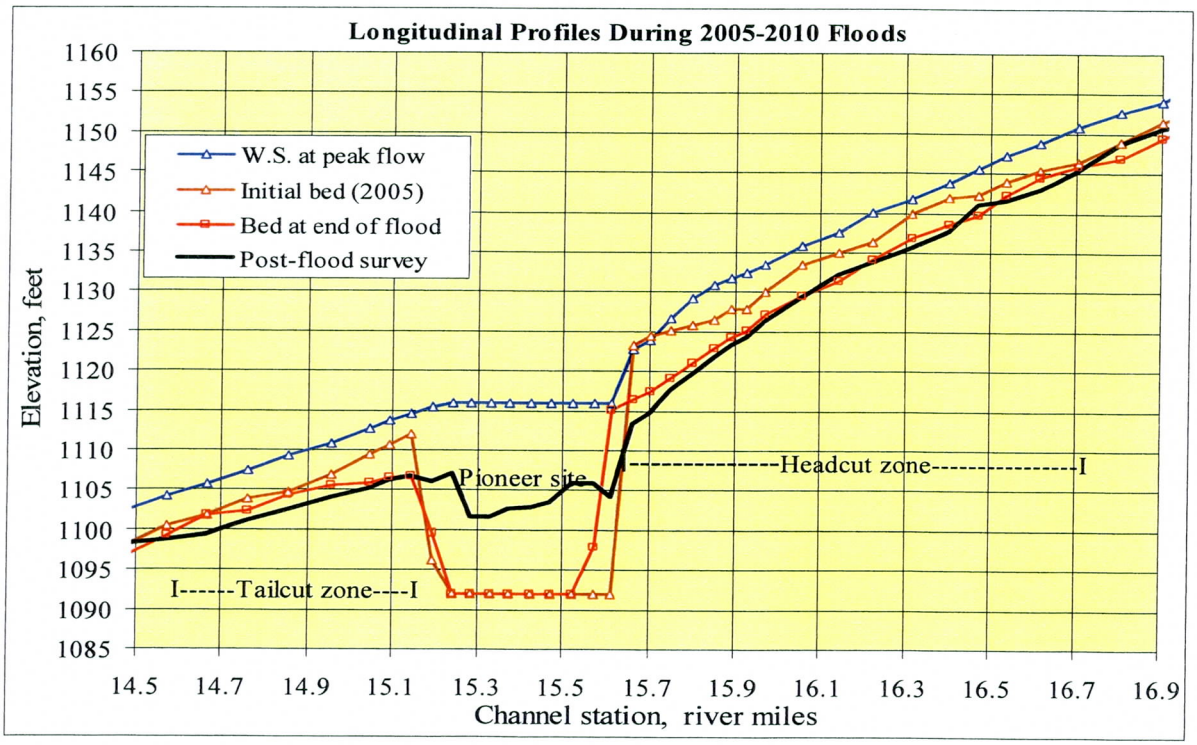


Figure 8. Simulated changes in longitudinal profiles using 2010 flood and Engelund-Hansen formula

The simulated results shown in Figures 7 and 8 are based on two different sediment transport formulas; they are used to select the sediment transport formula as a part of the calibration process. The simulated channel bed profile is now compared the post-flood survey in each figure. Since the simulated channel bed profile based on the Engelund-Hansen formula is well correlated with the survey, the Engelund-Hansen formula is therefore selected for the study.

It is clear that headcut developed along the upstream reach of Pioneer pit and tailcut developed along its downstream reach. Different scour depths due to headcut/tailcut are simulated by the Yang and Engelund-Hansen formulas. The scour depths simulated by the Yang formula are less than those by the Engelund-Hansen formula. This general trend suggests that the Yang formula calculates lower sediment transport rates than the Engelund-Hansen formula under the same conditions. The comparison for sediment transport rate prediction may also be verified by comparing sediment deliveries predicted by these two formulas as described below.

Comparison of Modeled Results on Sediment Delivery — Sediment delivery is defined as the cumulative amount of sediment that has been delivered passing a certain channel section for a specified period of time, that is,

$$Y = \int_T Q_s \, dt \tag{2}$$

Where Y is sediment delivery (yield); Q_s is sediment discharge for bed material load; t is time; and T is the duration. The sediment discharge Q_s pertains only to bed-material load of sand, gravel and cobble. Fine sediment of clay and silt constituting the wash load may not be computed by a sediment transport formula. Sediment delivery is widely employed by hydrologists for watershed management; it is used herein to keep track of sediment supply and removal along the channel reach.

Spatial variations in sediment delivery are manifested as channel storage or depletion of sediment associated stream channel changes since the sediment supply from upstream may be different from the removal. The spatial variation of sediment delivery depicts the erosion and deposition along a stream reach. A decreasing delivery in the downstream direction, i.e. downward gradient for the delivery-distance curve, signifies that sediment load is partially stored in the channel to result in a net deposition. On the other hand, an increasing delivery in the downstream direction (upward gradient for the delivery-distance curve) indicates sediment removal from the channel boundary or net scour. A uniform sediment delivery along the channel (horizontal curve) indicates that sediment inflow and outflow are in balance, i.e., no net erosion or deposition along the reach. Channel reaches with net sediment storage or depletion may thus be designated on the basis of the gradient. From the engineering viewpoint, it is best to achieve a uniform delivery, the non-silt and non-scour condition, for dynamic equilibrium.

Figure 9 shows the time and spatial variations of sediment delivery along the Hassayampa River during the 2010 flood using the Engelund-Hansen formula and the Yang formula. The simulated results of these two formulas show that the Engelund-Hansen formula predicts higher sediment transport rate than the Yang formula.

River reaches with distinct erosion and deposition are depicted in the figure. The sediment delivery increases as the flow approaches a mining site. This increase in sediment delivery indicates erosion of the river bed in the process of headcut. The sediment delivery increases as the flow leaves the mining site, indicating erosion in the process of tailcut. The sediment delivery decreases in the downstream direction through the three mining sites, indicating deposition since there is more sediment inflow than outflow. In fact, sediment delivery drops down to zero in a short distance into a mining site. This pattern indicates that sediment deposits as soon as the flow enters the mining site and it only advances for a certain distance inside the mining site. The amount of sediment deposition is a mining pit is the difference between the inflow and outflow. This figure shows that the Cemex site trapped more sediment than the other two sites. For example, the sediment inflow into the Cemex site, based on the Engelund-Hansen formula, is 184,000 tons and the outflow is zero; the net sediment deposition is 184,000 tons of bed material not including the wash load.

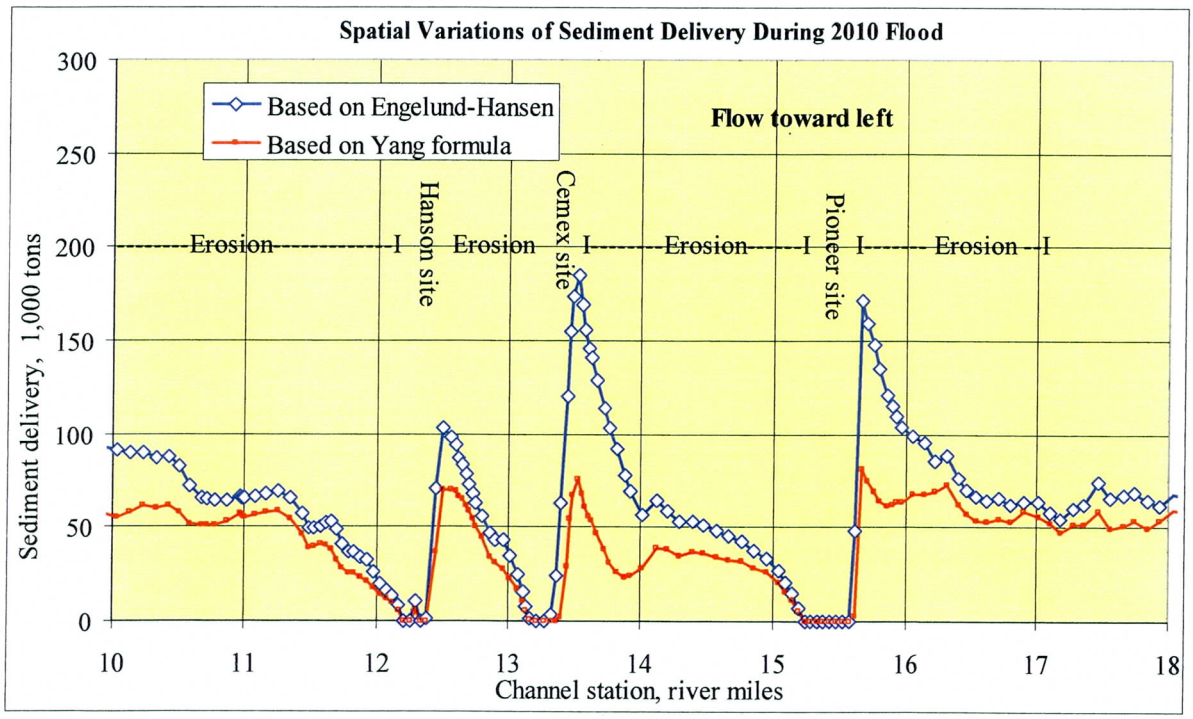


Figure 9. Time and spatial variations of sediment delivery in weight along the Hassayampa River during the 2010 flood – based on FLUVIAL-12

Selection of Channel Roughness Coefficient — The roughness coefficients provided in the HEC-RAS model by R2D were used in the initial modeling study. In the HEC-RAS file, different values of Manning's n are specified for different channel sections. The n values vary within a range and the average for the river channel is about 0.026. The simulated results shown in Figures 7 and 8 are based on n values provided by R2D. Since the simulated post-flood channel bed profile based on the Engelund-Hansen formula matches closely with the post-flood survey, the n value of 0.026 was selected as a part of the calibration process.

Performance Index for Modeled Results — The performance index, API, for the results shown in Figure 8 are computed as described below. Channel bed elevations for those cross

sections affected by headcut/tailcut shown in Figure 8 are listed in Table 2 below. In the table, the pre-flood thalweg elevation is the minimum bed elevation based on the pre-2005-flood topographic survey. The post-flood elevation from topographic survey is the minimum bed elevation from the topographic survey after the 2010 flood. The post-flood thalweg elevation from modeling is the simulated minimum bed elevation after the 2010 flood.

Table 2. Scour depths due to headcut/tailcut using 2010 flood and Engelund-Hansen formula

Location	Pre-flood thalweg elevation (feet)	Post-flood thalweg elevation from topographic mapping (feet)	Post-flood thalweg elevation from modeling (feet)	Minimum bed elevation from modeling (feet)	Scour depth from topographic mapping (feet)	Scour depth from modeling (at the end of flood simulation) (feet)
Headcut above Pioneer pit						
15.67	1123.3	1113.4	1116.4	1113.0	9.9	6.9
15.71	1124.4	1114.8	1117.4	1116.7	9.6	7.0
15.76	1125.2	1117.7	1119.1	1119.1	7.5	6.1
15.81	1125.9	1119.7	1121.0	1120.7	6.2	4.8
15.86	1126.5	1121.8	1123.0	1122.1	4.7	3.5
15.90	1127.9	T 1123.3	1124.3	1122.3	4.6	3.6
15.94	1127.9	1124.3	1125.1	1122.7	3.8	2.8
15.98	1130.9	1126.3	1127.2	1123.3	4.6	3.7
16.07	1133.4	1129.4	1129.6	1128.3	4.0	3.8
16.15	1135.0	1132.2	1131.4	1130.6	2.8	3.6
16.24	1136.4	1133.8	1134.2	1134.2	2.6	2.2
16.33	1139.9	1135.6	1136.9	1136.0	4.3	3.0
16.42	1142.0	1137.8	1138.6	1137.0	4.2	3.4
16.48	1142.3	1141.1	1139.8	1138.5	1.2	2.5
16.55	1144.0	1141.7	1142.3	1142.2	2.3	1.7

16.63	1145.3	1143.0	1144.5	1143.8	2.3	0.8
16.72	1146.5	1145.4	1145.9	1145.1	1.1	0.6
16.82	1148.9	1148.7	1147.0	1146.7	0.2	1.9
16.91	1151.5	1150.6	1149.4	1148.9	0.9	1.1
17.02	1155.5	1151.9	1152.0	1150.2	3.6	3.5
17.11	1155.6	1154.4	1154.0	1153.3	1.2	1.0
17.20	1156.8	1155.6	1156.1	1155.9	0.8	0.7
17.29	1159.0	1157.5	1159.6	1157.8	1.5	-0.6
17.38	1160.7	1159.8	1160.5	1159.9	0.9	0.2
Tailcut below Pioneer pit						
14.57	1098.8	1098.1	1100.1	1098.0	0.7	-1.3
14.67	1101.8	1099.4	1101.8	1100.9	2.4	0.0
14.77	1103.9	1101.2	1102.4	1102.1	2.7	1.5
14.86	1104.7	1102.6	1104.5	1103.7	2.1	0.2
14.96	1106.9	1104.1	1105.5	1105.4	2.8	1.4
15.06	1109.5	1105.2	1105.9	1105.8	4.3	3.6
15.10	1110.7	1106.3	1106.6	1106.5	4.3	4.1
15.15	1112.0	1106.8	1106.8	1106.7	5.2	5.2
15.20	1113.7	1106.1	1099.6	1096.2	3.6	14.1

Headcut developed along the channel reach upstream of the Pioneer site, the headcut zone may be estimated from Figure 8 and the calculated scour depths listed in Table 2. The headcut zone as estimated is from the Pioneer pit at section 15.67 to section 16.72 for a total channel length of about 1 mile. The API for the headcut scour depth is computed using the simulated and the surveyed scour depths in Table 2 as follows.

API = (3.0 + 2.6 + 0 + 1.4 + 1.2 + 1.0 + 1.0 + 0.9 + 0.2 + 0.2

$+ 0.4 + 1.3 + 0.8 + 1.3 + 0.6 + 1.5 + 0.5)/17$
$= 1.11$ feet

For the channel reach downstream of the Pioneer site, the tailcut zone may be estimated from Figure 8 and the scour depths listed in Table 2. The tailcut zone as estimated is from the downstream edge of the Pioneer pit at section 15.15 down to section 14.77 for a total channel length of about 0.6 mile. The API for tailcut scour depth is computed using the simulated and the surveyed scour depths in Table 2 as follows.

$$API = (1.2 + 1.9 + 1.4 + 0.7 + 0.2 + 0.0)/6 = 0.90 \text{ feet}$$

The computed Performance Indices for scour depths due to headcut/tailcut based on 2010 flood modeling are summarized in Table 3 below.

Table 3. Computed Performance Indices for scour depths due to headcut/tailcut using 2010 and Engelund-Hansen formula

Case	Absolute Performance Index
Headcut depth above Pioneer pit	1.11
Tailcut depth below Pioneer pit	0.90

IV. CALIBRATION AND PERFORMANCE INDEX BASED ON 2010 FLOOD ONLY

The calibration study presented in the previous section covers the selection of the sediment transport formula and the roughness coefficient. For the FLUVIAL-12 model, the Bank Erodibility Factor (BEF) is a parameter that governs the rate of bank erosion. Its value was selected in consideration of the geotechnical data for the bed material. For this calibration study, the BEF value that provides the best correlation of simulated and surveyed results was selected. The simulated cross-sectional profiles in the headcut/tailcut zones are generally smaller in width than the surveyed cross sections. The value of BEF was varied in modeling runs to select the value such that the cross sectional profiles match more closely with the measured cross-sectional profiles. Through this process, this value was determined to be 1.0 through several trial runs. This BEF value means that the bank of the headcut/tailcut channel is as erodible as the channel bed for the Hassayampa River. Input/output files for this case are as follows:

HASSA-CUTEH.FLU: FLUVIAL-12 input file for 2010 flood only using Engelund-Hansen formula

HASSA-CUTEH.OUT: FLUVIAL-12 output file for 2005 flood using Engelund-Hansen formula

Channel changes induced by mining pits during the 2010 flood was simulated. From the preliminary results, channel reaches with headcut and tailcut were first identified. The Pioneer pit has the largest depth, it induced headcut along the upstream channel reach and tailcut along the downstream reach. Headcut/tailcut also developed along channel reaches near the Cemex pit and Hanson pit. Because of instream sand/gravel mining in recent years, channel changes near the Cemex and Hanson pits were caused by headcut/tailcut as well as by mining. The effects of mining on channel changes can not be separated from the effects of headcut/tailcut.

Headcut/Tailcut near Pioneer Pit - The simulated water-surface profile and channel bed profile changes using the Engelund-Hansen formula are shown in Figures 10 and 11 for the reach upstream of the Pioneer site where headcut developed. These figures also have the following channel bed profiles:

1. Channel bed profile before the 2005 flood,
2. Simulated post-2010-flood channel bed profile, and
3. Channel bed profile from the post-2010-flood topographic survey.

Figure 12 is for the channel reach downstream of the Pioneer site with the same channel bed profiles. In addition, Figure 10 also has the simulated maximum scour profile during the 2010 flood.

Changes in channel cross-sections along the reach upstream of the Pioneer site are exemplified by those shown in Figure 13. Such changes illustrate the effects of headcut. Sample cross-sectional changes along the downstream reach of the Pioneer site are shown in Figure 14. These cross-sectional changes illustrate the effects of tailcut.

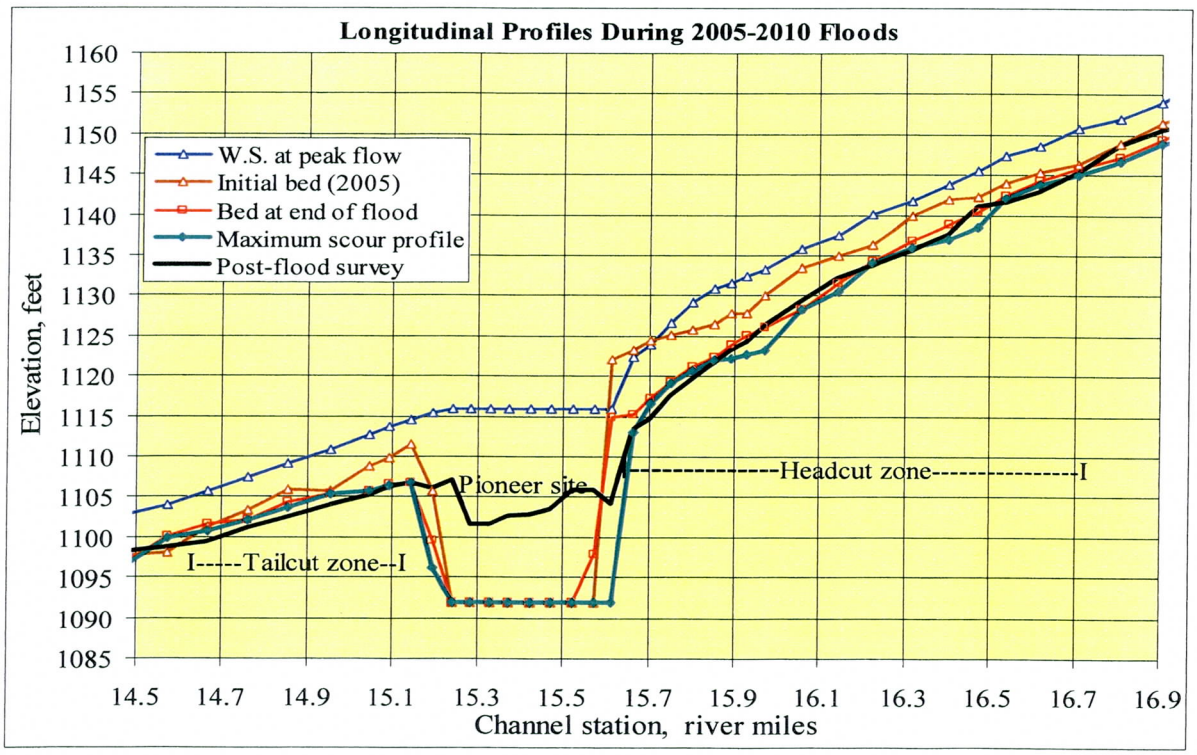


Figure 10. Simulated water-surface and channel bed profile changes near Pioneer pit using 2010 flood and Engelund-Hansen formula

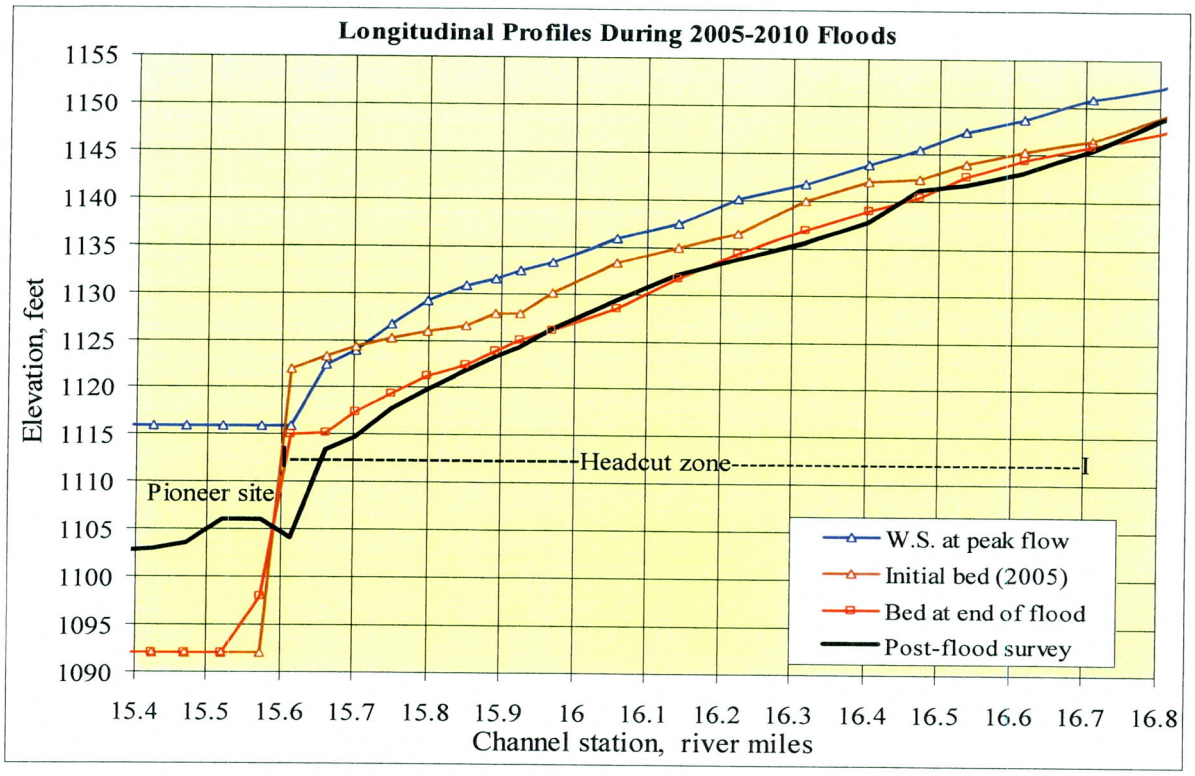


Figure 11. Water-surface and channel bed profiles for channel reach upstream of Pioneer site

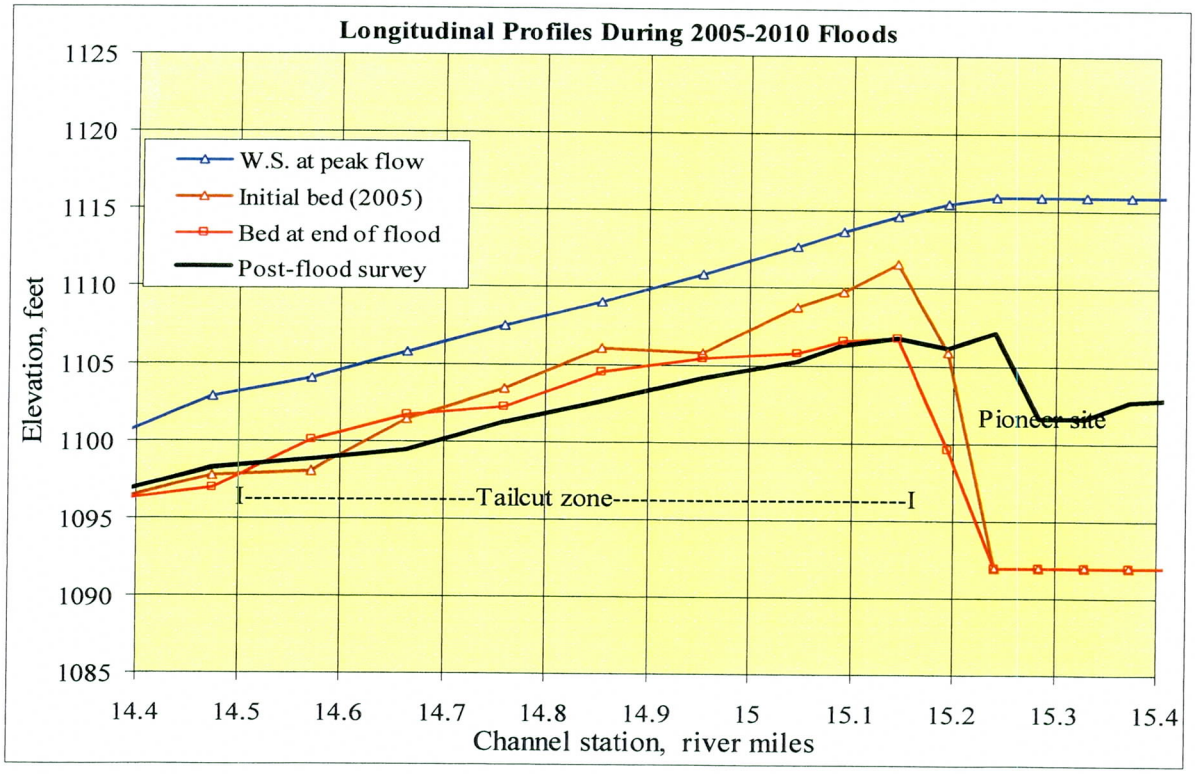


Figure 12. Water-surface and channel bed profiles for channel downstream of Pioneer site

The simulated changes in cross-sectional geometry of the channel based on the Engelund-Hansen formula due to headcut are compared with the surveyed results shown in Figure 13. The comparison is made based on those channel cross sections near the sand pit where channel geometric changes are primarily attributed to the effects of headcut or tailcut. For those cross sections away from the pit, the changes in channel geometry are also affected by several other factors such as the tributary inflows and braided channels. Because of the broad floodplain and braided channel pattern, it is sometimes difficult to identify the effective flow area during the 2010 flood. In other words, identification of the effective flow area in the broad floodplain can be somewhat inaccurate.

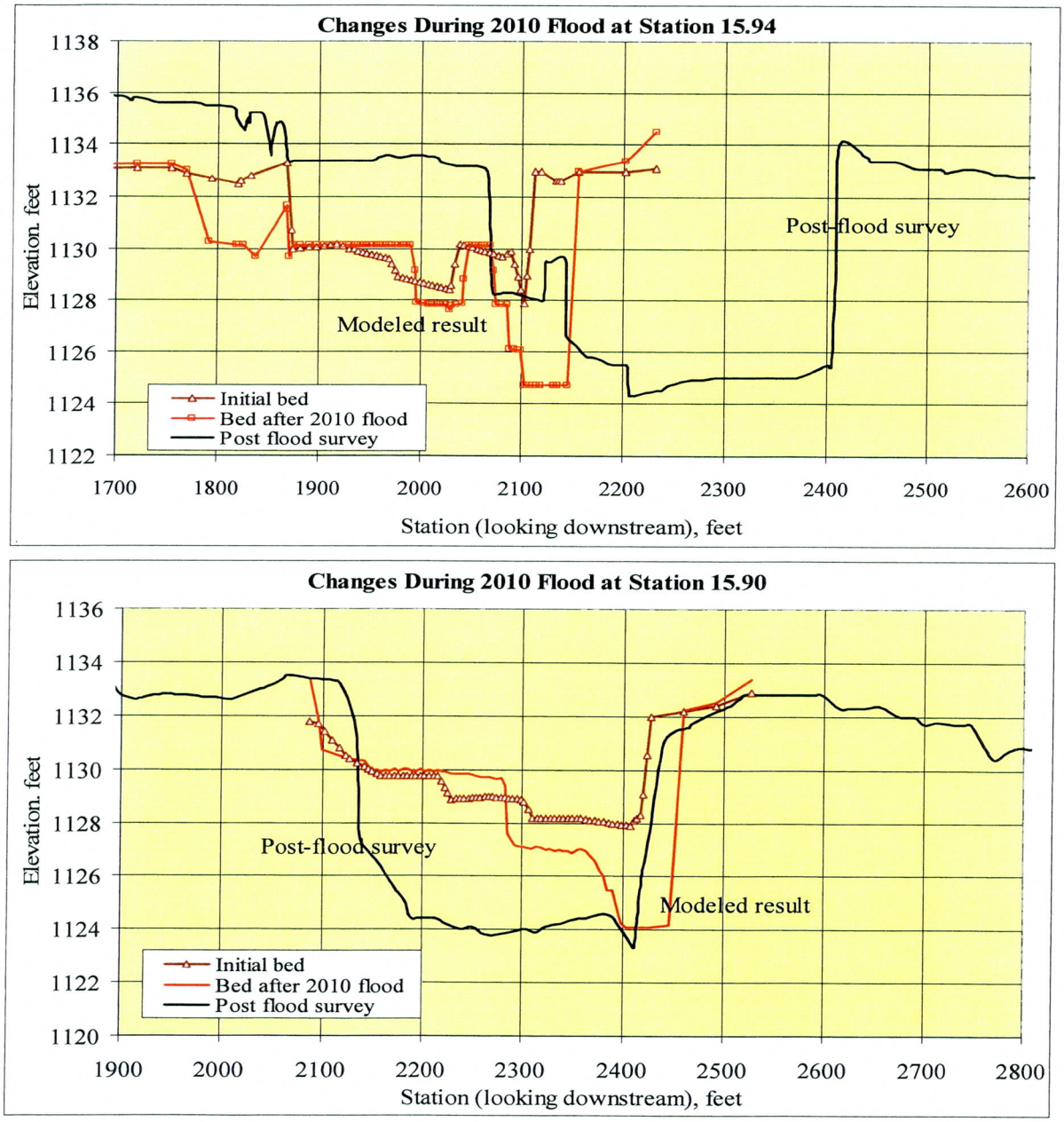
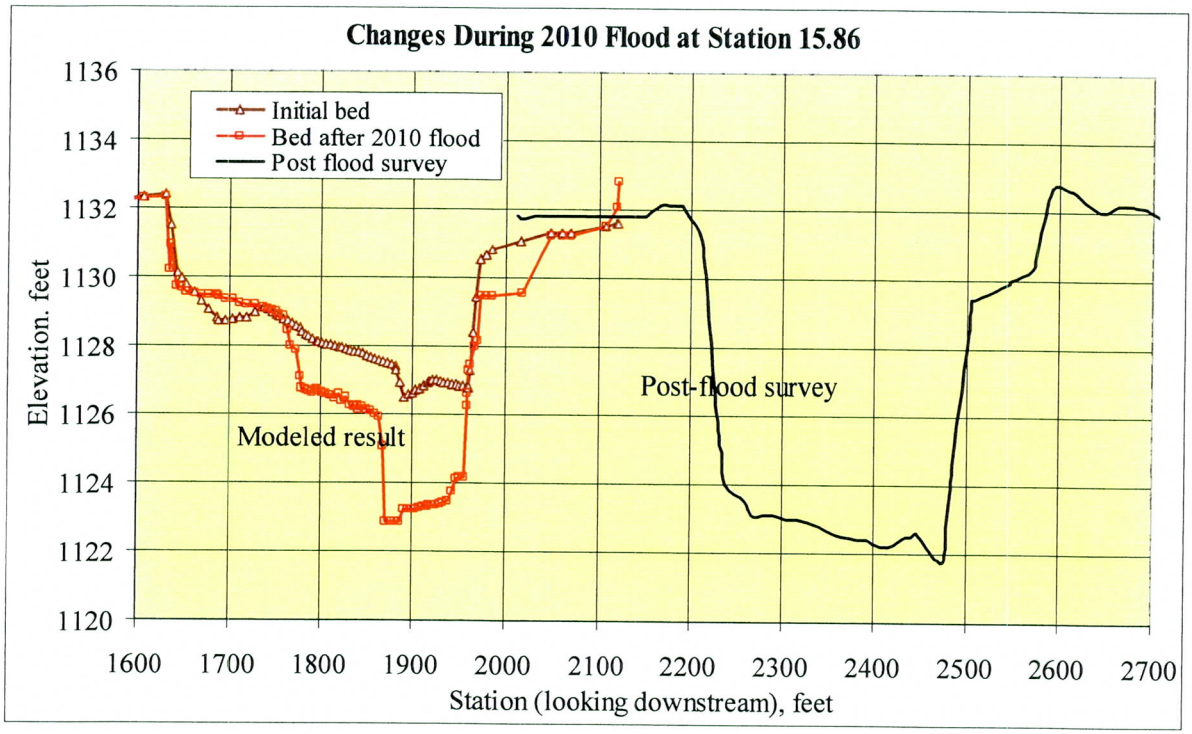


Figure 13. Simulated and surveyed channel cross sections after the 2010 flood



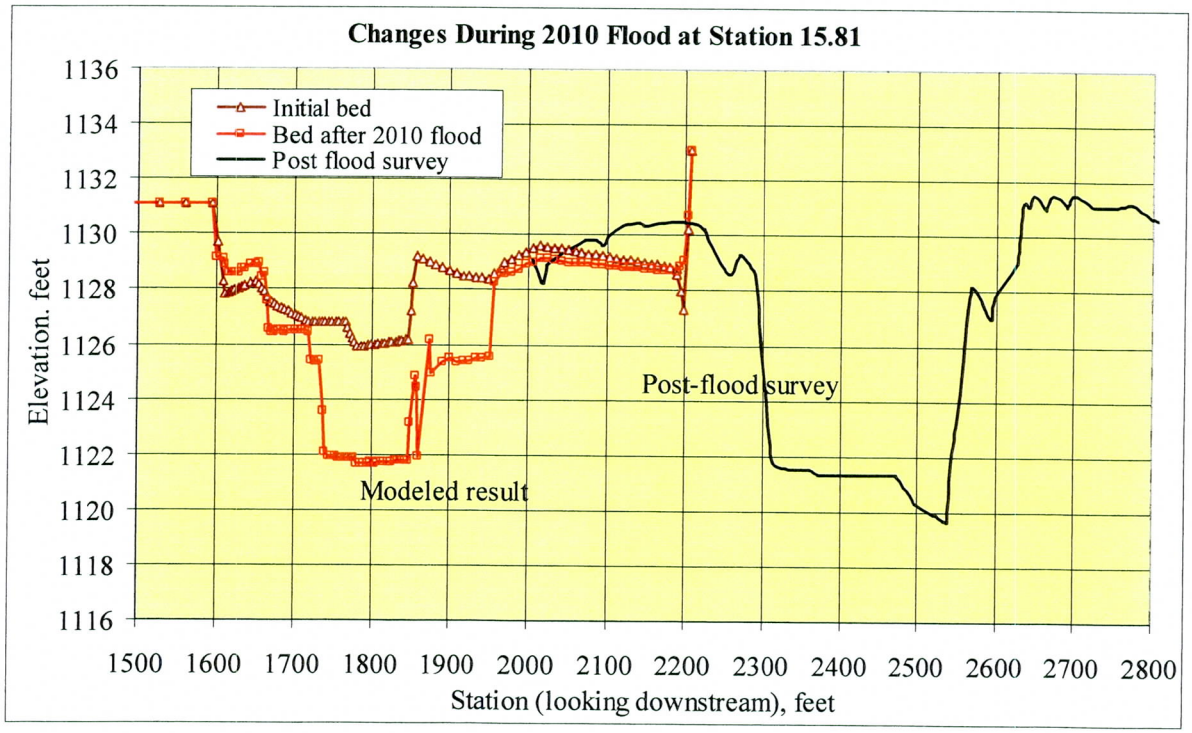


Figure 13(continued). Simulated and surveyed channel cross sections after the 2010 flood

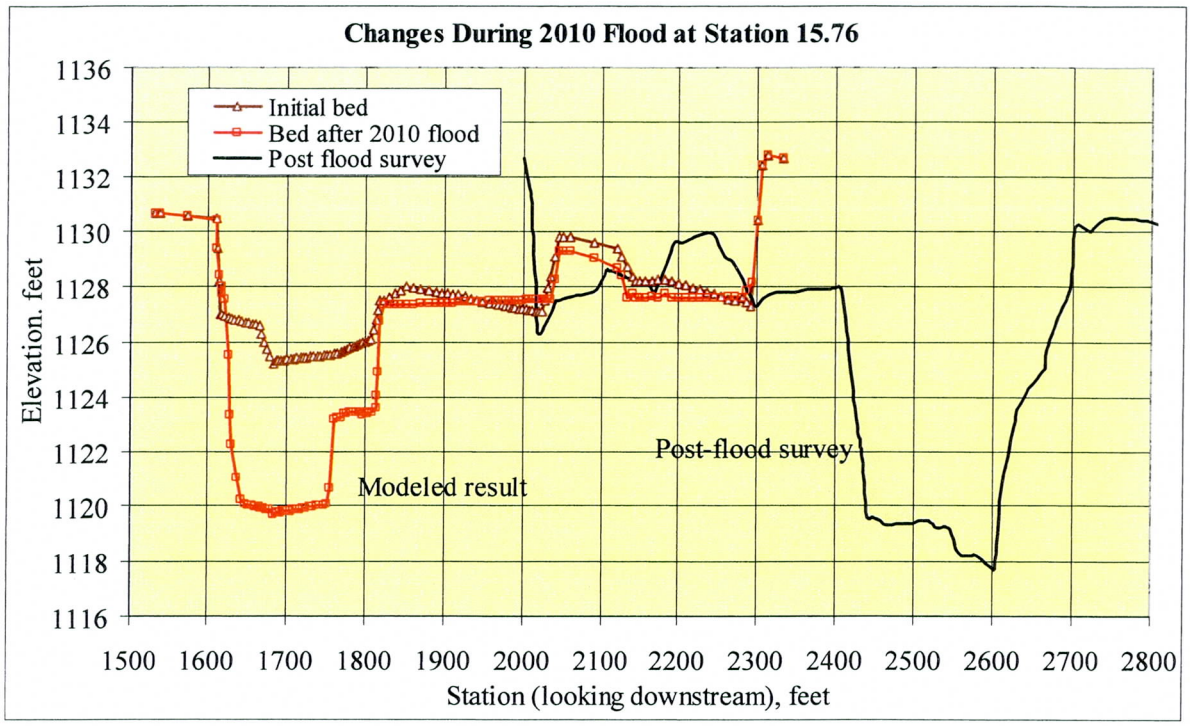


Figure 13(continued). Simulated and surveyed channel cross sections after the 2010 flood

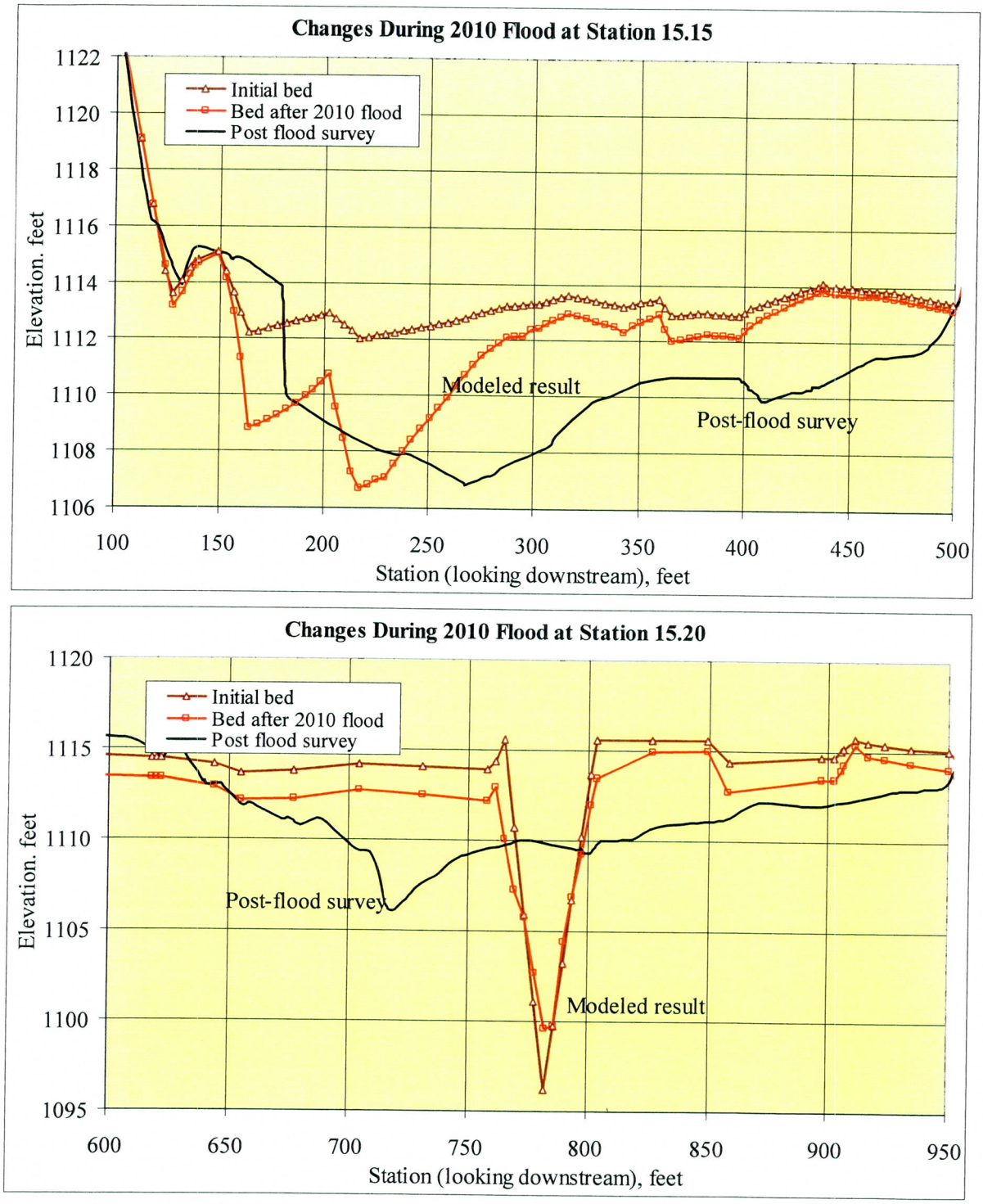


Figure 14. Simulated and surveyed channel cross sections after the 2010 flood

Simulated River Channel Changes near the Cemex and Hanson Mining Sites — Sand and gravel mining has been going on in the Hassayampa River near the Cemex and Hanson mining sites for decades. The new mining activities included in the current study are those that occurred in the effective flow area of the river channel for the time period from 2005 to 2010. There were also mining activities before this time period. In addition, deep mining at the Hanson site has created mining pits outside the effective flow area. These deep pits are separated from the main channel by a berm; therefore, they did not affect channel changes during the floods. However, other mining pits in the effective flow area of the channel had effects on headcut and tailcut changes in the river channel.

The results generated from modeling of the 2010 flood are presented in this section. Simulated waters surface profile and channel bed changes during the 2005-2010 floods using the Engelund-Hansen formula are shown in Figure 15. The uneven channel bed profiles during the time period reflect the effects of instream mining. The Cemex and Hanson mining pits, in comparison to the Pioneer mining pit, are much shallower in depth; therefore, the headcut and tailcut induced by these pits are less pronounced than those near the Pioneer site. The channel reach upstream of the Cemex site is simulated to undergo sediment deposition and channel bed aggradation during the 2010 floods. For this reason, the Cemex pit did not induce headcut along this channel reach during the 2010 flood.

Channel changes along the reach between the Cemex site and the Hanson site were caused by both mining and scour during floods. The effects of these two factors on channel changes can not be separated; therefore, no attempt is made to determine the scour depth due to headcut/tailcut.

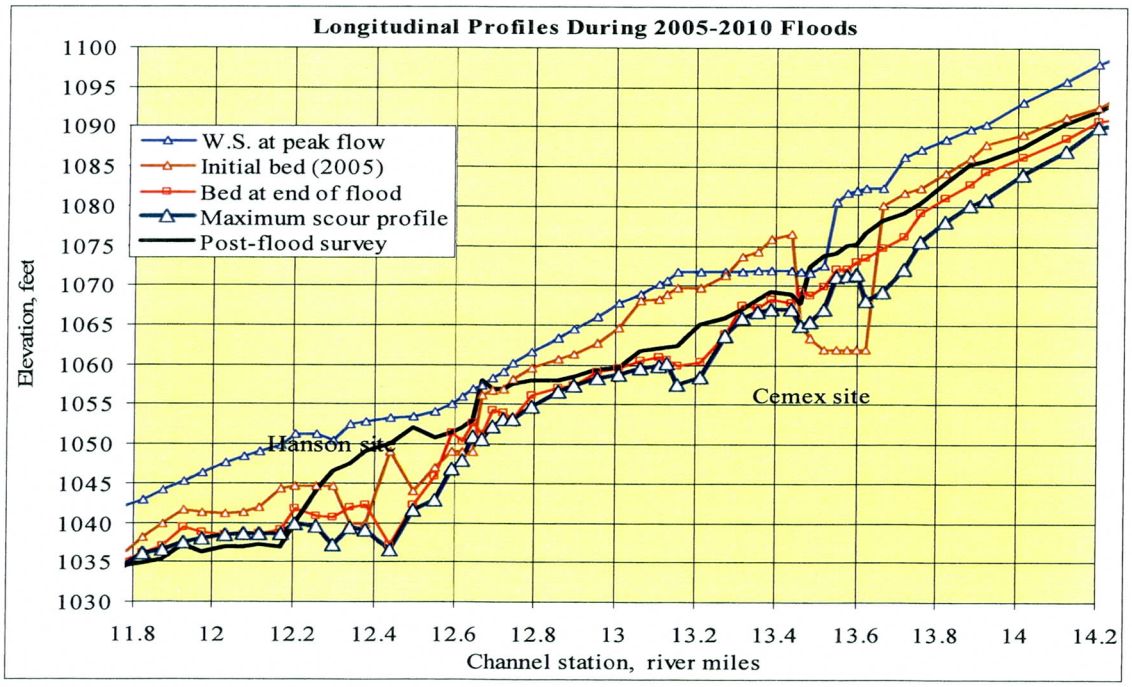


Figure 15. Water-surface and channel bed profiles for the channel reaches near the Cemex and Hanson mining sites simulated using 2010 flood and Engelund-Hansen formula

Channel bed elevations for those cross sections affected by headcut/tailcut are listed in Table 4 below. In the table, the pre-flood thalweg elevation is the minimum bed elevation based on the pre-2005-flood topographic survey. The post-flood elevation from topographic survey is the minimum bed elevation from the topographic survey after the 2010 flood. The post-flood thalweg elevation from modeling is the simulated minimum bed elevation after the 2010 flood. The minimum bed elevation from modeling is the lowest bed elevation reached by scour during the entire simulation period.

Table 4. Scour depths due to headcut/tailcut based on 2010 flood

Location	Pre-flood thalweg elevation (feet)	Post-flood thalweg elevation from topographic mapping (feet)	Post-flood thalweg elevation from modeling (feet)	Minimum bed elevation from modeling (feet)	Scour depth from topographic mapping (feet)	Scour depth from modeling (at the end of flood simulation) (feet)	Maximum scour depth from modeling during the flood (feet)
Headcut above Pioneer pit							
15.67	1123.3	1113.4	1115.2	1113.0	9.9	8.1	10.3
15.71	1124.4	1114.8	1117.4	1116.7	9.6	7.0	7.7
15.76	1125.2	1117.7	1119.3	1119.1	7.5	5.9	6.1
15.81	1125.9	1119.7	1121.2	1120.7	6.2	4.7	5.2
15.86	1126.5	1121.8	1122.5	1122.1	4.7	4.0	4.4
15.90	1127.9	T 1123.3	1123.9	1122.3	4.6	4.0	5.6
15.94	1127.9	1124.3	1125.1	1122.7	3.8	2.8	5.2
15.98	1130.9	1126.3	1126.1	1123.3	4.6	4.8	7.6
16.07	1133.4	1129.4	1128.4	1128.3	4.0	5.0	5.1
16.15	1135.0	1132.2	1131.7	1130.6	2.8	3.3	4.4
16.24	1136.4	1133.8	1134.3	1134.2	2.6	2.1	2.2
16.33	1139.9	1135.6	1136.9	1136.0	4.3	3.0	3.6
16.42	1142.0	1137.8	1139.0	1137.0	4.2	3.0	5.0

16.48	1142.3	1141.1	1140.4	1138.5	1.2	1.9	3.8
16.55	1144.0	1141.7	1142.6	1142.2	2.3	1.4	1.8
16.63	1145.3	1143.0	1144.3	1143.8	2.3	1.0	1.5
16.72	1146.5	1145.4	1145.9	1145.1	1.1	0.6	1.4
16.82	1148.9	1148.7	1147.3	1146.7	0.2	1.6	2.2
16.91	1151.5	1150.6	1149.6	1148.9	0.9	1.9	2.6
17.02	1155.5	1151.9	1152.1.	1150.2	3.6	3.4	5.3
17.11	1155.6	1154.4	1154.2	1153.3	1.2	1.4	2.3
17.20	1156.8	1155.6	1156.0	1155.9	0.8	0.8	0.9
17.29	1159.0	1157.5	1159.2	1157.8	1.5	-0.2	1.2
17.38	1160.7	1159.8	1160.4	1159.9	0.9	0.3	0.8
Tailcut below Pioneer pit							
14.67	1101.8	1099.4	1101.7	1100.9	2.4	0.1	0.9
14.77	1103.9	1101.2	1102.2	1102.1	2.7	1.7	2.8
14.86	1104.7	1102.6	1104.5	1103.7	2.1	0.2	1.0
14.96	1106.9	1104.1	1105.4	1105.4	2.8	1.5	1.5
15.06	1109.5	1105.2	1105.8	1105.8	4.3	3.7	3.7
15.10	1110.7	1106.3	1106.6	1106.5	4.3	4.1	4.2
15.15	1112.0	1106.8	1106.7	1106.7	5.2	5.3	5.3
15.20	1113.7	1106.1	1099.6	1096.2	3.6	14.1	17.5

Headcut developed along the channel reach upstream of the Pioneer site, the headcut zone may be estimated from Figure 11 and the calculated scour depths listed in Table 4. The headcut zone as estimated is from the Pioneer pit at section 15.67 to section 16.72 for a total channel length of about 1 mile. The API for the headcut scour depth is computed using the simulated and the surveyed scour depths in Table 4 as follows.

API = (3.0 + 2.6 + 0 + 1.4 + 1.2 + 1.0 + 1.0 + 0.9 + 0.2 + 0.2
+ 0.4 + 1.3 + 0.8 + 1.3 + 0.6 + 1.5 + 0.5)/17
= 1.11 feet

For the channel reach downstream of the Pioneer site, the tailcut zone may be estimated from Figure 12 and the scour depths listed in Table 4. The tailcut zone as estimated is from the downstream edge of the Pioneer pit at section 15.15 down to section 14.77 for a total channel length of about 0.6 mile. The API for tailcut scour depth is computed using the simulated and the surveyed scour depths in Table 4 as follows.

API = (1.2 + 1.9 + 1.4 + 0.7 + 0.2 + 0.0)/6 = 0.90 feet

The computed Performance Indices for scour depths due to headcut/tailcut based on 2010 flood modeling are summarized in Table 5 below.

Table 5. Computed Performance Indices for scour depths due to headcut/tailcut based on 2010 flood modeling

Case	Absolute Performance Index
Headcut depth above Pioneer pit	1.05 feet
Tailcut depth below Pioneer pit	1.02 feet

V. FLUVIAL-12 MODELING OF BOTH 2005 AND 2010 FLOOD EVENTS (for February 11-12, 2005 events and January 20-21, 2010 event modeling)

Two steps were taken in modeling the February 11-12, 2005 event and January 20-21, 2010 event. The first step is to incorporate mining pits into the LHWMP-Phase I topographic data. R2D incorporated the mining pits configuration from the GIS Arcview shape file into the topographic data and provided Chang Consultants the HEC-RAS cross-sections. Chang Consultants used these cross-sections to develop a Fluvial-12 model with Engelund-Hansen transport equation. All other parameters used in FLUVIAL-12 are consistent with the same parameters from R2D's HEC-6T and HEC-RAS sediment transport models (February 11-12, 2005 flow hydrograph, sediment inflow, time step for inflow hydrograph, sediment discharge rating curve, …etc.).

After the Fluvial-12 modeling of the 2005 flood, the original cross-section data were changed by Fluvial-12 at the end of the simulation due to river channel changes. Chang Consultants converted the output simulated by FLUVIAL-12 for the 2005 event into the input data for the 2010 flood event.

Chang Consultants modeled the January 20-21, 2010 event based on the end-of-simulation cross-section data after the 2005 event. The cross-section data were then revised by

incorporating the pit configuration prior to the January 2010 event. The Pioneer Pit has an area of 23 acres with a depth of 28-30 ft, Cemex Pit has an area of 45 acres with a depth of 10 ft, and Hanson Pit has an area of 22 acres with a depth of 10 ft. Chang Consultants modified the end-of-simulation cross-sections based on the pit configuration prior to the January 2010 event. Chang Consultants then used these cross-sections to develop a Fluvial-12 model with Engelund-Hansen transport equation. All other parameters were based on the same parameters from R2D's HEC-6T and HEC-RAS sediment transport models (January 2010 flow hydrograph, sediment inflow, time step for inflow hydrograph, sediment discharge rating curve, time step for computation, upstream and downstream boundary conditions,...etc.). R2D submitted a brief memo about the modeling parameters and assumptions to FCDMC and Chang Consultants for review. Chang Consultants then used the same parameters and assumptions.

For the purpose of model calibration, the modeling results on headcut/tailcut are documented and compared with the new 2010 topographic data. Calibration has been performed so that the modeling results would match the new 2010 topographic data as closely as possible. The morphologic parameters for headcut/tailcut include the headcut/tailcut channel length, depth, width, and cross-sectional area. In order to achieve the best correlation in calibration, the hydraulic and sediment parameters are adjusted such that the performance index is as small as possible.

The selection of the sediment transport formula can make a significant difference on the modeled results. The Engelund-Hansen formula for sediment transport was used in previous studies of the Hassayampa River for predicting scour and lateral migration of the river channel. Good correlation of modeled results with field data was obtained. For the present study, two sediment transport formulas are used and the respective results generated by them are evaluated to assess their applicability to the Hassayampa River. Yang's sediment transport equation has also been selected and used in addition to Engelund-Hansen as a separate comparison.

The bank erodibility factor (BEF) is the parameter that governs the rate of bank erosion. Its value will be selected based on the geotechnical data for the bed material. For this calibration study, the BEF value that provides the best correlation of simulated and surveyed results was selected. This value was varied in the modeling runs to select the most appropriate value and this value was determined to be 1.0, through several trial runs. This BEF value means that the bank of the headcut/tailcut channel is as erodible as the channel bed for the Hassayampa River. In addition to the sediment transport formulas and the bank erodibility factor, other hydraulic parameters for calibration include Manning's n coefficient and other parameters associated with sediment transport modeling such as sediment inflow hydrograph and boundary conditions. The n value of 0.026 was finally selected through trial runs.

Simulation of Headcut/Tailcut — Channel changes due to headcut/tailcut during the 2005-2010 floods near the Pioneer pit were simulated following the procedures described previously. The simulation includes the effects of pre-2005 mining sites included in the 2005 channel bed topography; it also includes the new mining sites existed prior to the 2010 flood.

In order to simulate the headcut/tailcut using the Engelund-Hansen formula, the following FLUVIAL-12 files were created and executed:

HASSA-EH05.FLU: This is the FLUVIAL-12 input file for the 2005 channel data and the Engelund-Hansen formula

HASSA-EH05.OUT: This is the output file produced by HASSA-EH05.FLU executed for 2005 flood

HASSA-EH10.FLU: This is the FLUVIAL-12 input file using the output channel data from HASSA-EH05.OUT plus the mining site data just before 2010 flood

HASSA-EH10.OUT: This is the FLUVIAL-12 output file produced by HASSA-EH10.FLU using the Engelund-Hansen formula and the 2010 flood

The following files were created and executed using the Yang formula:

HASSA-Y05.FLU: This is the FLUVIAL-12 input file for 2005 channel data and the Yang formula

HASSA-Y05.OUT: This is the output file produced by HASSA-Y05.FLU executed for 2005 flood

HASSA-Y10.FLU: This is the FLUVIAL-12 input file using the output channel data from HASSA-Y05.OUT plus the mining site data just before 2010 flood

HASSA-Y10.OUT: This is the FLUVIAL-12 output file produced by HASSA-Y10.FLU using the Yang formula and the 2010 flood.

VI. HEADCUT AND TAILCUT NEAR PIONEER MINING SITE

The results generated from modeling with calibration are presented in this section. Simulated water-surface and channel bed profile changes in the headcut/tailcut regions near the Pioneer pit generated by the Yang formula are shown in Figure 16; those by the Engelund-Hansen formula are shown in Figures 17 and 18. Each figure include the channel bed profiles before the 2005 flood and after the 2010 flood together with the surveyed channel-bed profile after the 2010 flood. The post-flood channel bed generated using the Yang formula has on uneven profile not supported by the post-flood survey. Model calibration using the Yang formula failed. All other results as presented in this section are based on the Engelund-Hansen formula.

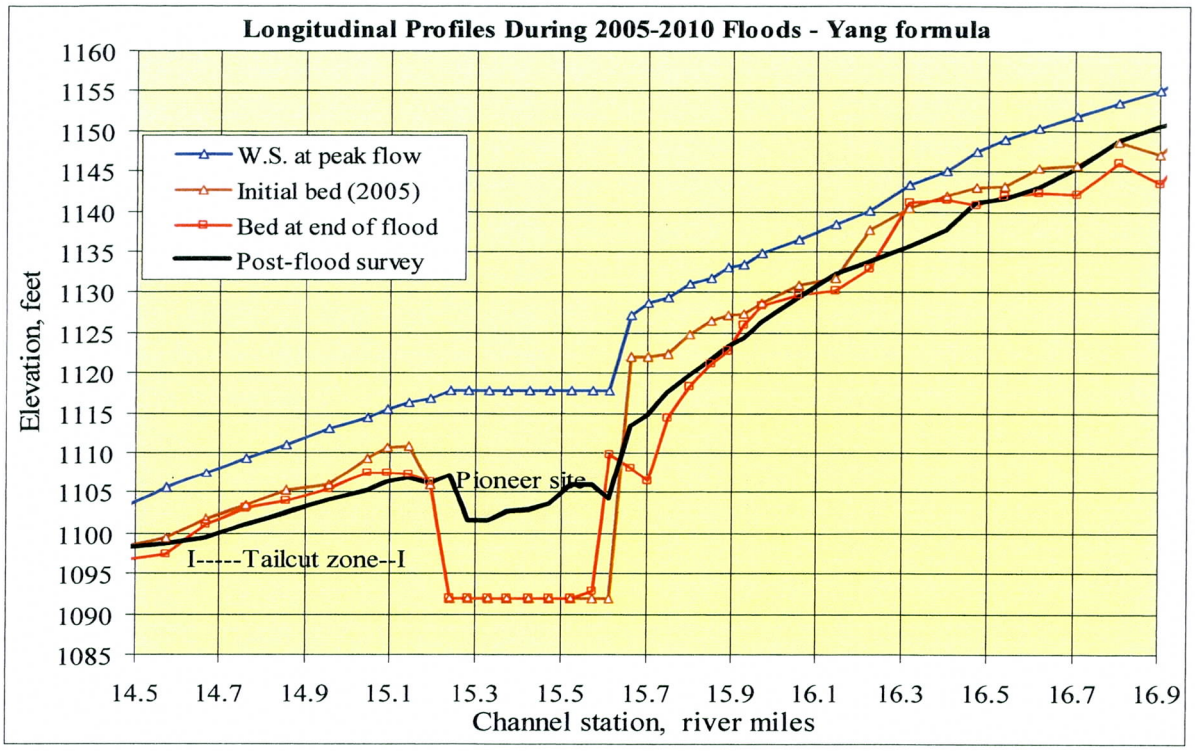


Figure 16. Simulated water-surface and channel bed profile changes near Pioneer pit using 2005 and 2010 floods and Yang formula

Channel changes due to headcut developed upstream of the Pioneer pit. Simulated water-surface profile and channel bed profile changes due to headcut during the 2005-2010 floods are shown in Figure 18, together with the surveyed channel bed profile after the floods. Channel changes due to tailcut developed downstream of the Pioneer pit. Simulated water-surface profile and channel bed profile changes due to tailcut during the 2005-2010 floods are shown in Figure 19, together with the surveyed channel bed profile after the floods. The results shown are also generated by the Engelund-Hansen formula.

The simulated changes in cross-sectional geometry of the channel due to headcut are compared with the surveyed results shown in Figure 20. The comparison is made based on those channel cross sections near the sand pit where channel geometric changes are primarily attributed to the effects of headcut or tailcut. For those cross sections away from the pit, the changes in channel geometry are also affected by several other factors such as the tributary inflows and braided channels. Because of the broad floodplain and braided channel pattern, it is sometimes difficult to identify the effective flow area during the 2005-2010 floods. In other words, identification of the effective flow area in the broad floodplain can be somewhat inaccurate. The simulated changes in channel geometry due to tailcut are compared with the surveyed results shown in Figure 21. The comparison is made based on those channel cross sections near the sand pit where channel geometric changes are primarily attributed to the effects of tailcut. For those cross sections away from the pit, the changes in channel geometry are also affected by several other factors such as the tributary inflows and braided channels. Because of the broad floodplain and braided channel pattern, it is sometimes difficult to identify the

effective flow area during the 2005-2010 floods. In other words, identification of the effective flow area in the broad floodplain with the braided channels can be somewhat inaccurate.

It should be pointed out that the changes in channel cross sections due to tailcut along the channel reach downstream of the Pioneer pit were affected by the tributary inflows from Jackrabbit Wash. As shown in Figure 3, the braided channels of Jackrabbit Wash join the Hassayampa River from the northwest and they approach the main river at a sharp angle. The tributary channels have important effects on the morphology of the main channel. In this case, the channel formed during tailcut became wider as the tributary channels joined in from the west side.

The simulated changes in channel cross sections due to tailcut are shown in Figure 21 for sections 15.15 and 15.20. For both sections, the simulated channel geometries due to tailcut are small in width, as is typical for gulley formation. However, the surveyed channel cross sections are much larger in width. Such large widths are closely related to the lateral inflow from Jackrabbit Wash. The effects of lateral inflow on channel morphology at this location were not simulated in modeling.

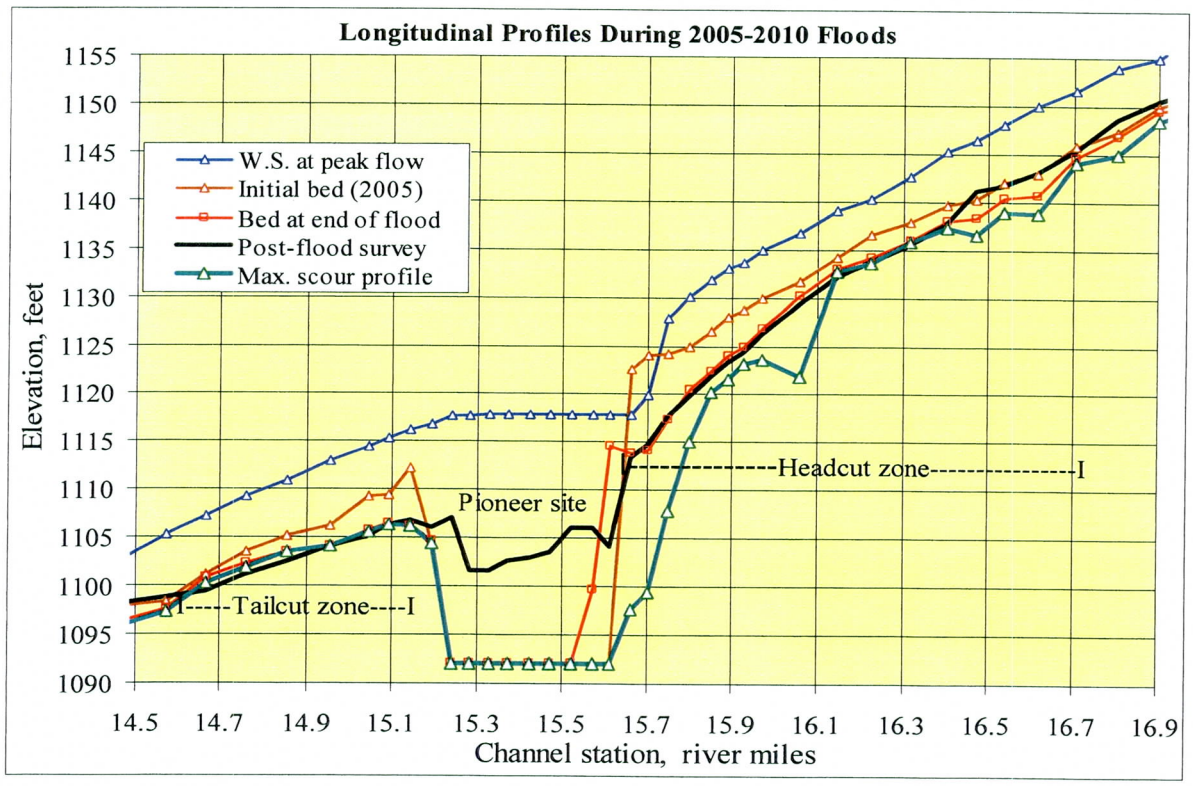


Figure 17. Simulated water-surface and channel bed profile changes near Pioneer pit using 2005 and 2010 floods and Engelund-Hansen formula

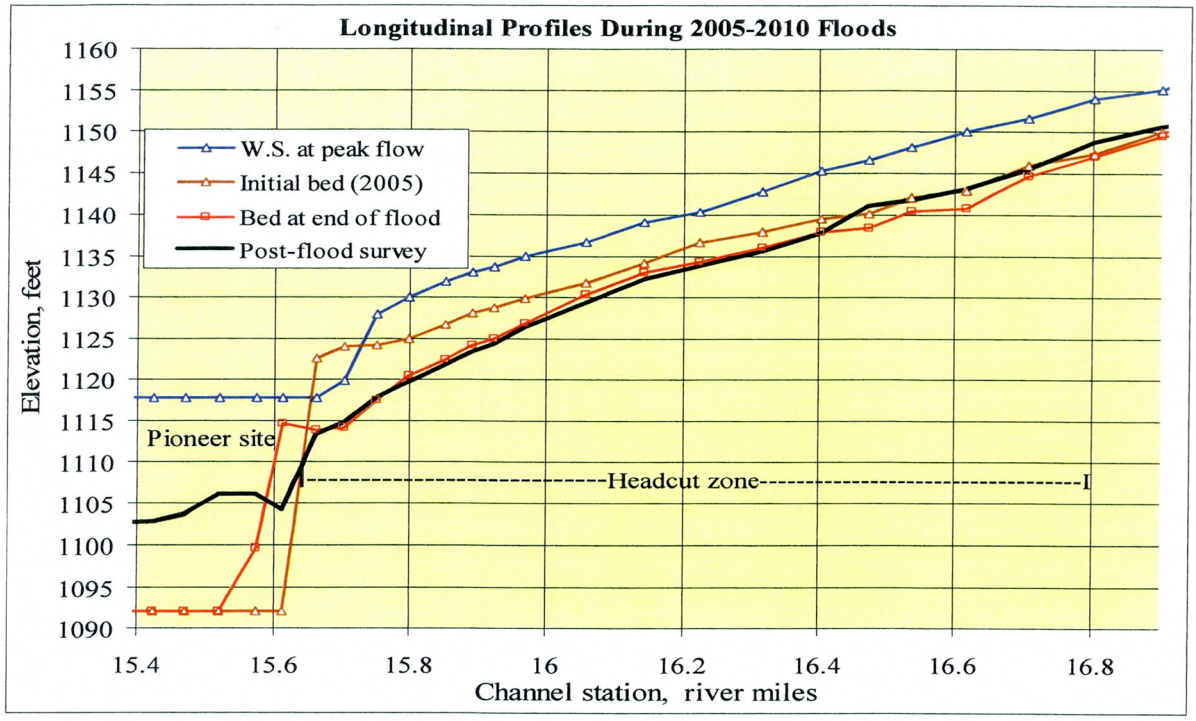


Figure 18. Simulated water-surface and channel bed profile changes upstream of Pioneer pit using 2005 and 2010 floods and Engelund-Hansen formula

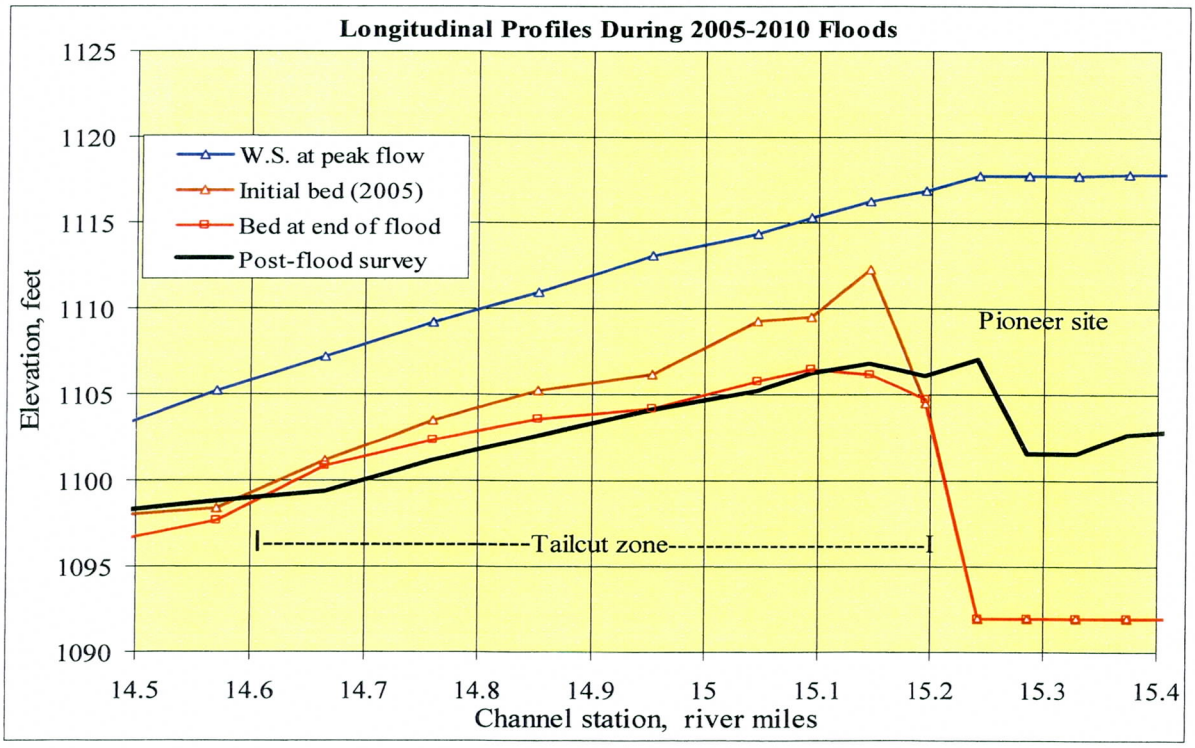
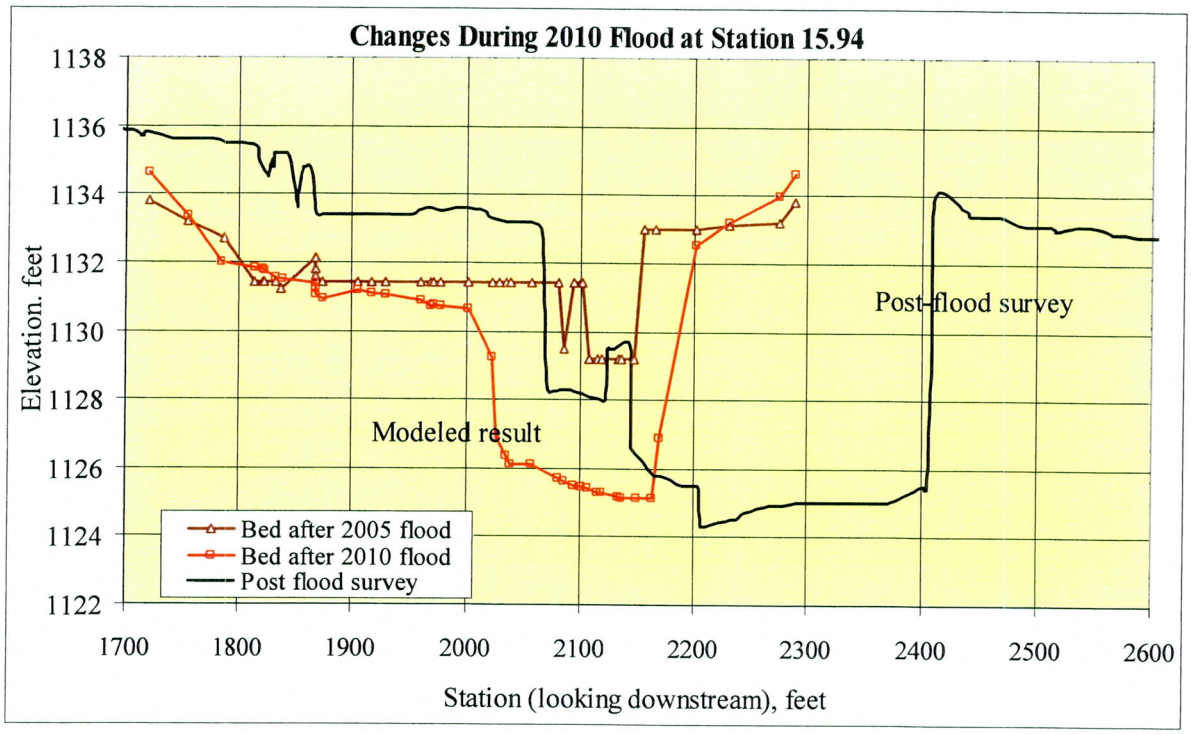


Figure 19. Simulated water-surface and channel bed profile changes downstream of Pioneer pit using 2005 and 2010 floods and Engelund-Hansen formula



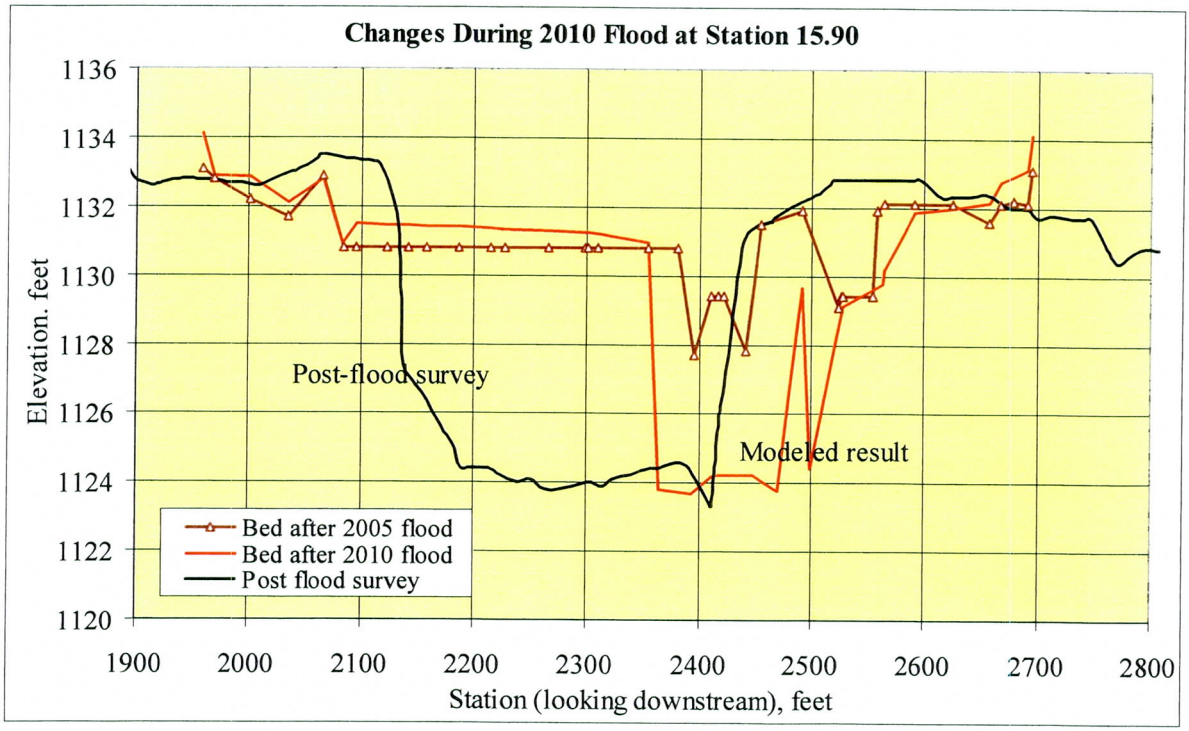
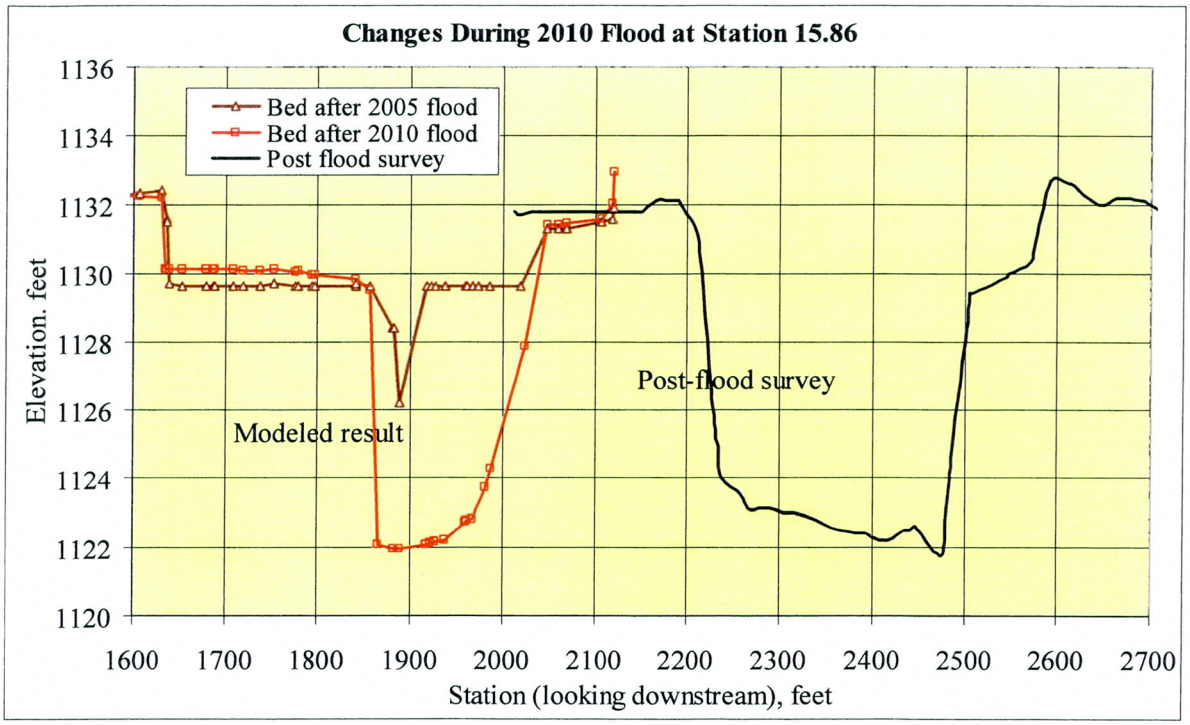


Figure 20. Simulated and surveyed cross-sectional changes due to headcut near Pioneer pit using Engelund-Hansen formula



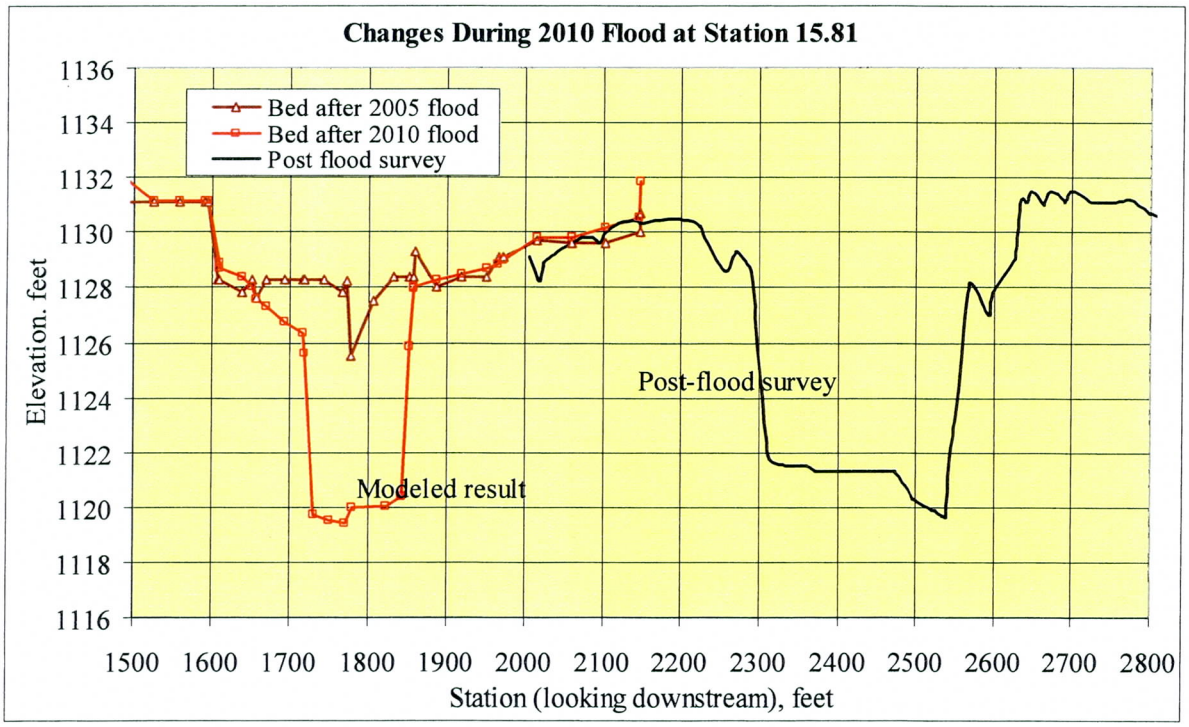


Figure 20(continued). Simulated and surveyed cross-sectional changes due to headcut near Pioneer pit using Engelund-Hansen formula

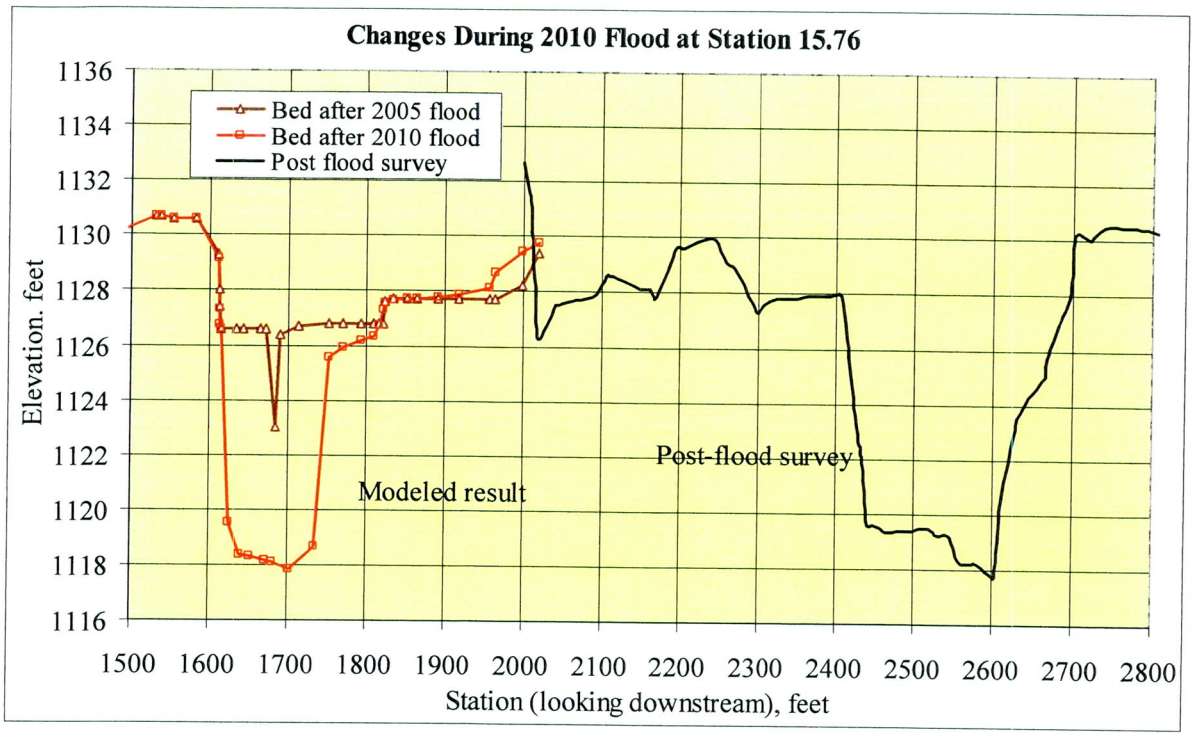
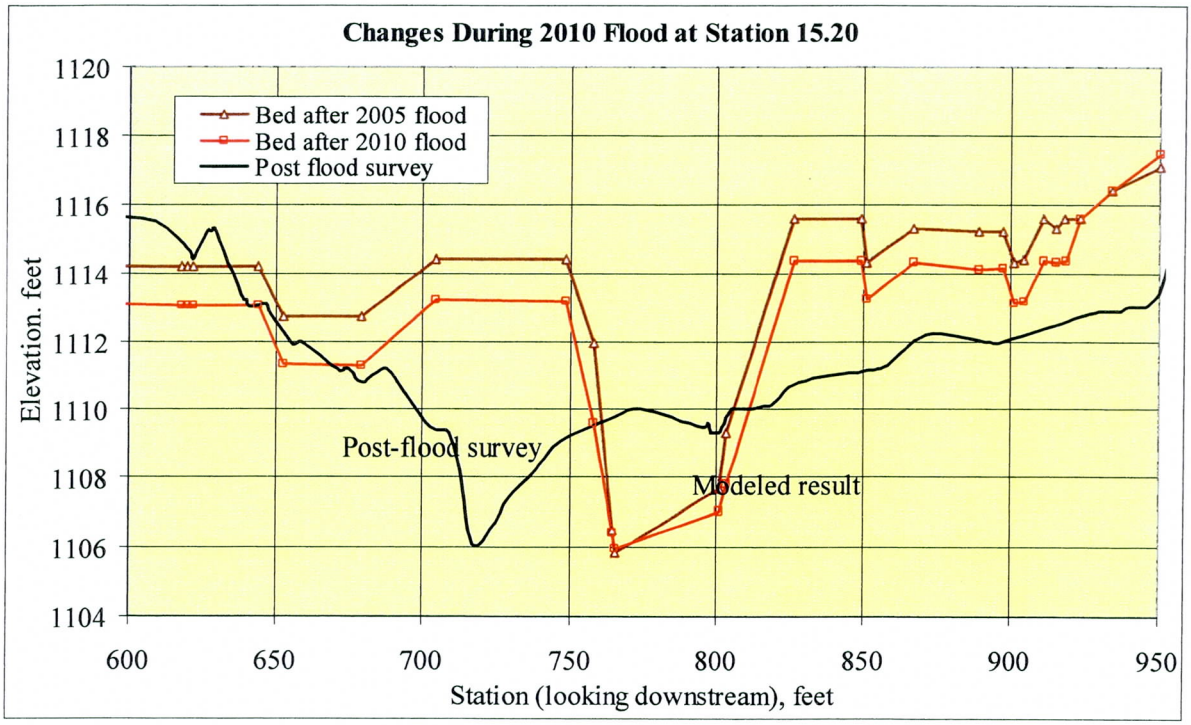


Figure 20 (continued). Simulated and surveyed cross-sectional changes due to headcut near Pioneer pit using Engelund-Hansen formula



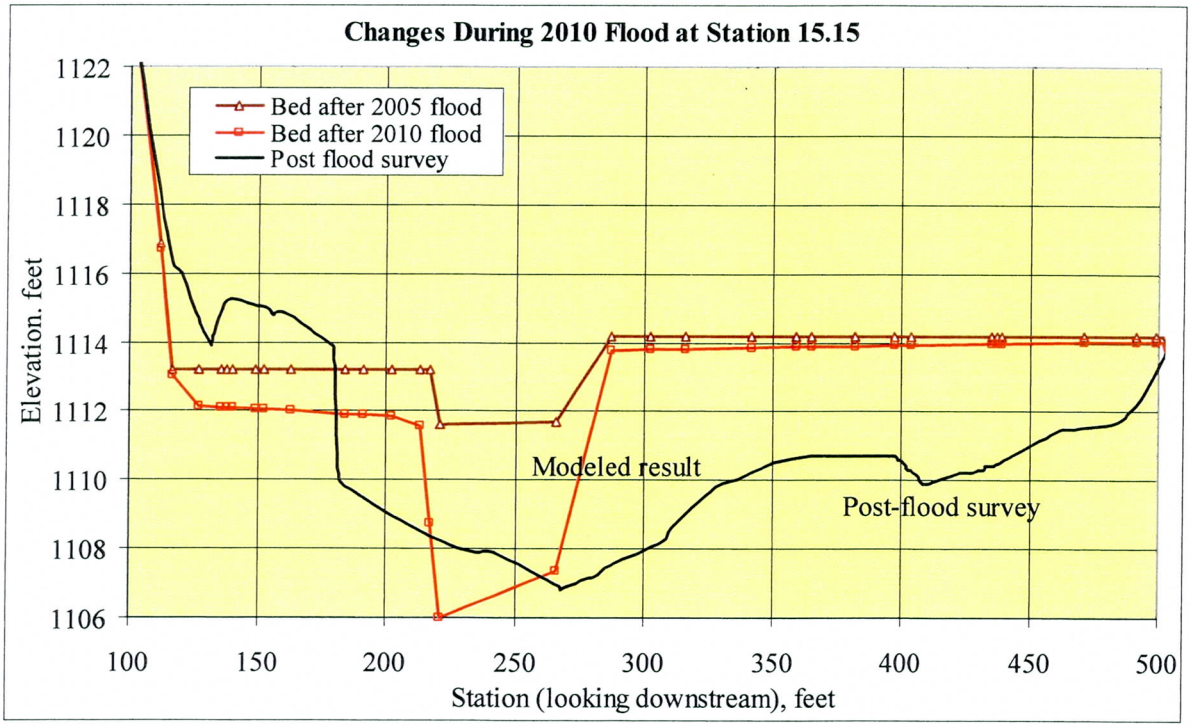


Figure 21. Simulated and surveyed cross-sectional changes due to tailcut near Pioneer pit using Engelund-Hansen formula

The simulated and surveyed results for headcut/tailcut are summarized in Table 6. The table lists the thalweg elevations at those cross sections affected by headcut/tailcut before the 2005 flood and after the 2010 flood; it also includes the thalweg elevations of cross sections from the post-flood topographic survey and the maximum scour depths of the channel bed. The scour depth is measured from the pre-flood thalweg elevation to the post-flood thalweg elevation. The maximum scour depth is measured from the pre-flood thalweg elevation to the minimum bed elevation, which is the lowest bed elevation reached by scour during the entire simulation period. The model keeps track of the channel bed profile for the entire flood period. The minimum bed elevations reached by scour are recorded in a separate file TZMIN.DAT.

Table 6. Scour depths due to headcut/tailcut for calibration case

Location	Pre-flood thalweg elevation (feet)	Post-flood thalweg elevation from topographic mapping (feet)	Post-flood thalweg elevation from modeling (feet)	Minimum bed elevation from modeling (feet)	Scour depth from topographic mapping (feet)	Scour depth from modeling (at the end of flood simulation) (feet)	Maximum scour depth from modeling during the flood (feet)
Headcut above Pioneer pit							
15.67	1123.3	1113.4	1113.3	1097.7	9.9	10.0	25.6
15.71	1124.4	1114.8	1115.5	1099.5	8.6	7.9	24.9
15.76	1125.2	1117.7	1117.9	1107.8	7.5	7.3	17.4
15.81	1125.9	1119.7	1119.4	1115.1	6.2	6.5	10.8
15.86	1126.5	1121.8	1121.9	1120.2	4.7	4.4	6.3
15.90	1127.9	T 1123.3	1123.7	1121.5	4.6	4.2	6.4
15.94	1127.9	1124.3	1125.1	1123.2	3.6	4.8	4.7
15.98	1130.9	1126.3	1127.1	1123.6	4.6	3.8	7.3
16.07	1133.4	1129.4	1130.3	1121.8	4.0	3.1	11.6
16.15	1135.0	1132.2	1133.1	1132.8	2.8	1.9	2.2
16.24	1136.4	1133.8	1134.2	1133.6	2.6	2.2	2.8
16.33	1139.9	1135.6	1135.9	1135.9	4.3	4.0	4.0

16.42	1142.0	1137.8	1138.0	1137.3	4.2	4.0	4.7
16.48	1142.3	1141.1	1138.4	1136.6	1.2	3.9	5.7
16.55	1144.0	1141.7	1140.4	1138.9	2.3	3.6	5.1
16.63	1145.3	1143.0	1140.8	1138.8	2.3	4.5	6.5
16.72	1146.5	1145.4	1144.6	1144.1	1.1	1.9	2.4
16.82	1148.9	1148.7	1147.0	1145.0	0.2	1.9	3.9
16.91	1151.5	1150.6	1149.5	1148.5	0.9	2.0	3.0
17.02	1155.5	1151.9	1150.2	1149.9	3.6	5.3	5.6
17.11	1155.6	1154.4	1155.3	1153.3	1.2	0.3	2.3
17.20	1156.8	1155.6	1156.0	1155.0	0.8	0.8	1.8
17.29	1159.0	1157.5	1157.7	1156.2	1.5	1.3	2.8
17.38	1160.7	1159.8	1160.6	1160.5	0.9	0.1	0.2
Tailcut below Pioneer pit							
14.49	1097.8	1098.2	1096.4	1096.1	-0.4	1.4	1.7
14.58	1098.1	1098.8	1097.7	1097.4	-0.6	0.4	0.7
14.67	1101.4	1099.4	1100.8	1100.3	2.0	0.6	1.1
14.77	1103.4	1101.2	1102.4	1101.9	2.2	1.0	1.5
14.86	1106.0	1102.6	1103.5	1103.5	3.4	2.5	2.5
14.96	1105.8	1104.1	1104.2	1104.1	1.7	1.6	1.7
15.06	1108.8	1105.2	1105.8	1105.6	3.6	3.0	3.2
15.10	1111.6	1106.3	1106.5	1106.4	5.3	5.1	5.2
15.15	1111.6	1106.8	1106.2	1106.2	4.8	5.4	5.4
15.20	1105.8	1106.1	1104.8	1104.5	-0.3	1.0	1.3

Headcut developed along the channel reach upstream of Pioneer pit. The headcut reach as estimated is from section 15.67 at the upstream edge of the mining pit to section 16.72 for a total channel length of about 1 mile. The performance index API for the scour depth is computed using the simulated and the surveyed scour depths in Table 6. The performance index is used to assess the correlation of simulated results on headcut with the measurement.

For headcut depth, the average deviation of the simulated scour depths from the measured scour depths for the cross sections listed in Table 6 is given below. The API as calculated represents the deviation of the simulated depth from the surveyed depth for headcut.

API = (0.1 + 0.7 + 0.2 + 0.3 + 0.3 + 0.4 + 1.2 + 0.8 + 0.9
+ 0.9 + 0.4 + 0.3 + 0.2 + 2.7 + 1.3 + 2.2 + 0.7 + 1.7 +0.8/19
= 0.85 foot

The tailcut reach downstream of the Pioneer as estimated is from section 15.20 at the downstream edge of the mining pit down to section 14.60, for a total channel length of about 0.60 mile. The value of API for the scour depth is computed using the simulated and the surveyed scour depths in Table 6 as follows.

API = (0 + 1.4 + 1.2 + 0.9 + 0.5 + 0.1 + 0.6 + 0.2 + 0.4 + 0.3)/10
= 0.56 foot

Calculated performance indices for the modeling study with calibration are summarized as listed in Table 7 below.

Table 7. Computed Performance Indices for scour depths due to headcut/tailcut with calibration

Case	Absolute Performance Index
Headcut depth above Pioneer pit	0.85 foot
Tailcut depth below Pioneer pit	0.56 foot

VII. COMPARISON OF MODELING RESULTS FOR ONE FLOOD AND TWO FLOODS

There are two modeling approaches for the study. The first approach is simply to model the January 20-21, 2010 event using 2002 topographic data as the basis and using the pit configuration to modify the topographic data. The pit configuration is estimated for the condition prior to the January 20-21, 2010 event. For the second case, both 2005 and 2010 floods were used. For both cases, calibration studies were performed.

The performance index API represents the deviation of the simulated value from the surveyed value for headcut/tailcut. To assess the modeling results for two approaches, the computed API's for the scour depths are compared as summarized in Table 8 below.

Table 8. Comparison of Absolute Performance Indices with calibration

Cases	Performance Index API	
	Based on 2010 flood only	Based on 2005 and 2010 events
Headcut depth above Pioneer pit	1.05 feet	0.85 foot
Tailcut depth below Pioneer pit	1.02 feet	0.56 foot

The comparison presented in the above table shows that the correlations of simulated and measured headcut/tailcut depths near the Pioneer pit are generally good. The modeling results from both flood events have better correlations with measurement than the case of one flood event. This is expected since the scour depths developed during both floods.

The performance indices presented in the report are based on channel bed scour. In addition to the scour depth, simulated changes in cross-sectional profiles for the two cases are also presented in the report. The simulated cross-sectional changed based on both the 2005 and 2010 floods are similar to the surveyed cross sectional profiles. However the cross-sectional profiles based on the 2010 flood only are not as well correlated with the surveyed results. In summary, model study using both the 2005 and 2010 floods has improved the correlation with measurement.

Discussion of Study Results — Certain sources for the discrepancy between the simulated and measured results can be cited. Channel morphology associated with headcut/tailcut is normally characterized by the formation of narrow and deep gullies. However, the channels formed by headcut/tailcut for this case are generally wider and larger in cross-sectional area than a typical gulley. The discrepancies are attributed to several factors. An important factor is the fact that the Hassayampa River has a broad floodplain with a highly braided channel pattern. Because of the multiple channel branches, headcut/tailcut changes induced by the mining pit are also affected by the presence of other channel branches. The tributary inflow from Jackrabbit Wash has significant effects on channel morphology downstream of the Pioneer pit, as the large width is closely related to the lateral inflow from Jackrabbit Wash. The effects of lateral inflow on the channel morphology at this location were not simulated in modeling.

VIII. SUMMARY OF COMPUTER FILES USED IN THE STUDY

Table 9 given below has been created to summarize the computer files used in the study and their respective parameters. The table lists all the parameters selected in model calibration.

Table 9. Summary of computer files and paramters

File name	Type of file	Sediment formula used	Roughness coefficient	Flood(s) used	Bank erodibility factor
HASSA-CUT.FLU	Input	Yang or Engelund-Hansen	From R2D	2010 flood	0.5
HASSA-CUTEH0.OUT	Output	Engelund-Hansen	From R2D	2010 flood	0.5
HASSA-CUTY.OUT	Output	Yang	From R2D	2010 flood	0.5
HASSA-CUTEH.FLU	Input	Engelund-Hansen	0.026	2010 flood	1.0
HASSA-CUTEH.OUT	Output	Engelund-Hansen	0.026	2010 flood	1.0
HASSA-Y05.FLU	Input	Yang	0.026	2005 flood	1.0
HASSA-Y10.FLU*	Input	Yang	0.026	2010 flood	1.0
HASSA-Y05.OUT	Output	Yang	0.026	2005 flood	1.0
HASSA-Y10.OUT*	Output	Yang	0.026	2010 flood	1.0
HASSA-EH5.FLU	Input	Engelund-Hansen	0.026	2005 flood	1.0
HASSA-EH10.FLU*	Input	Engelund-Hansen	0.026	2010 flood	1.0
HASSA-EH5.OUT	Output	Engelund-Hansen	0.026	2005 flood	1.0
HASSA-EH10.OUT*	Output	Engelund-Hansen	0.026	2010 flood	1.0

* Channel geometry output from the 2005 flood is used as the input geometry to get the cumulative effects of 2005 and 2010 floods

REFERENCES

JE Fuller Hydrology and Geomorphology, Inc., 2006. Lower Hassayampa River Watercourse Master Plan, River Behavior Report.

JE Fuller Hydrology and Geomorphology, Inc., 2007. Updated HEC-6 Model (dated May 2007) for Lower Hassayampa River Watercourse Master Plan, River Behavior Report.

Waskowsky, R., 11/22/2010. Data Collection and Modeling Approach for Selected River Mechanics Tasks of Phase II of the Lower Hassayampa Watercourse Master Plan, Memo, Submitted to Theresa Pinto of FCDMC, CC to Bing Zhao of FCDMC.

APPENDIX A. INPUT/OUTPUT DESCRIPTIONS FOR FLUVIAL-12

I. INPUT DESCRIPTION

The basic data requirements for a modeling study include (1) topographic maps of the river reach from the downstream end to the upstream end of study, (2) digitized data for cross sections in the HEC-2 format with cross-sectional locations shown on the accompanying topographic maps, (3) flow records or flood hydrographs and their variations along the study stream reach, it any, and (4) size distributions of sediment samples along the study reach. Additional data are required for special features of a study river reach.

The HEC-2 format for input data is used in all versions of the FLUVIAL model. Data records for HEC-2 pertaining to cross-sectional geometry (X1 and GR), job title (T1, T2, and T3), and end of job (EJ), are used in the FLUVIAL model. If a HEC-2 data file is available, it is not necessary to delete the unused records except that the information they contain are not used in the computation. For the purpose of water- and sediment-routing, additional data pertaining to sediment characteristics, flood hydrograph, etc., are required and supplied by other data records. Sequential arrangement of data records are given in the following.

Records	**Description of Record Type**
T1,T2,T3	Title Records
C	General Use Record
G1	General Use Record
G2	General Use Records for Hydrographs
G3	General Use Record
G4	General Use Record for Selected Cross-Sectional Output
G5	General Use Record
G6	General Use Record for Selecting Times for Summary Output
G7	General Use Record for Specifying Erosion Resistant Bed Layer
GS	General Use Records for Initial Sediment Compositions
GB	General Use Records for Time Variation of Base-Level
GQ	General Use Records for Stage-Discharge Relation of Downstream Section
GI	General Use Records for Time Variation of Sediment Inflow
X1	Cross-Sectional Record
XF	Record for Specifying Special Features of a Cross Section
GR	Record for Ground Profile of a Cross Section

SB	Record for Special Bridge Routine
BT	Record for Bridge Deck Definition
EJ	End of Job Record

Variable locations for each input record are shown by the field number. Each record has an input format of (A2, F6.0, and 9F8.0). Field 0 occupying columns 1 and 2 is reserved for the required record identification characters. Field 1 occupies columns 3 to 8; Fields 2 to 10 occupy 8 columns each. The data records are tabulated and described in the following.

T1, T2, T3 Records - These three records are title records that are required for each job.

Field	Variable	Value	Description
0	IA	T1	Record identification characters
1-10	None		Numbers and alphabetic characters for title

C Record – This is an optional record used to skip a number of lines following the C record.

Field	Variable	Value	Description
0	IA	G4	Record identification characters
1	SKIP	+	Number of lines to be skipped

G1 Record - This record is required for each job, used to enter the general parameters listed below. This record is placed right after the T1, T2, and T3 records.

Field	Variable	Value	Description
0	IA	G1	Record identification characters
1	TYME	+	Starting time of computation on the hydrograph, in hours
2	ETIME	+	Ending time of computation on the hydrograph, in hours
3	DTMAX	+	Maximum time increment at allowed, in seconds
4	ISED	1	Select Graf's sediment transport equation.
		2	Select Yang's unit stream power equation. The sediment size is between 0.063 and 10 mm.
		3	Select Engelund-Hansen sediment equation.
		4	Select Parker gravel equation.
		5	Select Ackers-White sediment equation.
		6	Select Meyer-Peter Muller equation for bed load.
5	BEF	+	Bank erodibility factor for the study reach. This value is used for each section unless otherwise specified in Field 9 of the XF and 1 may be used.
6	IUC	0	English units are used in input and output.
		1	Metric units are used in input and output.

7	CNN	+	Manning's *n* value for the study reach. This value is used for a section unless otherwise specified in Field 4 of the XF record. If bed roughness is computed based upon alluvial bedforms as specified in Field 5 of the G3 record, only an approximate *n* value needs to be entered here.
8	PTM1	+	First time point in hours on the hydrograph at which summary output and complete cross-sectional output are requested. It is usually the peak time, but it may be left blank if no output is requested.
9	PTM2	+	Second time point on the hydrograph in hours at which summary usually the time just before the end of the simulation. This field may be left blank if no output is needed.
10	KPF	+	Frequency of printing summary output, in number of time steps.

G2 Records - These records are required for each job, used to define the flow hydrograph(s) in the channel reach. The first one (or two) G2 records are used to define the spatial variation in water discharge along the reach; the succeeding ones are employed to define the time variation(s) of the discharge. Up to 10 hydrographs, with a maximum of 120 points for each, are currently dimensioned. See section II for tributaries. These records are placed after the G1 record.

Field	Variable	Value	Description
First G2			
0	IA	G2	Record identification characters
1	IHP1	+	Number of last cross section using the first (downstream most) hydrograph. The number of section is counted from downstream to upstream with the downstream section number being one. See also section II.
2	NP1	+	Number of points connected by straight segments used to define
3	IHP2	+	Number of last section using the second hydrograph if any. Otherwise leave it blank.
4	NP2	+	Number of points used to define the second hydrograph if any. Otherwise leave it blank.
5	IHP3	+	Number of last section using the third hydrograph if any. Otherwise leave it blank.
6	NP3	+	Number of points used to define the third hydrograph if any. Otherwise leave it blank.

7	IHP4	+	Number of last section using the fourth hydrograph if any. Otherwise leave it blank.
8	NP4	+	Number of points used to define the fourth hydrograph if any. Otherwise leave it blank.
9	IHP5	+	Number of last section using the fifth hydrograph if any. Otherwise leave it blank.
10	NP5	+	Number of points used to define the fifth hydrograph if any. Otherwise leave it blank.

Second G2: Note that this record is used only if more than 5 hydrographs are used for the job. It is necessary to place a negative sign in front of NP5 located in the 10th field of the first G2 record as a means to specify that more than 5 hydrographs are used.

0	IA	G2	Record identification characters
1	IHP6	+	Number of last cross section using the sixth hydrograph if any. Otherwise leave it blank.
2	NP6	+	Number of points connected by straight segments used to define
3	IHP7	+	Number of last section using the seventh hydrograph if any. Otherwise leave it blank.
4	NP7	+	Number of points used to define the seventh hydrograph
5	IHP8	+	Number of last section using the eighth hydrograph if any. Otherwise leave it blank.
6	NP8	+	Number of points used to define the eighth hydrograph
7	IHP9	+	Number of last section using the ninth hydrograph if any. Otherwise leave it blank.
8	NP9	+	Number of points used to define the ninth hydrograph
9	IHP10	+	Number of last section using the tenth hydrograph if any. Otherwise leave it blank.
10	NP10	+	Number of points used to define the tenth hydrograph

Succeeding G2 Record(s)

1	Q11, Q21 Q31	+	Discharge coordinate of point 1 for each hydrograph, in ft^3/sec or m^3/sec
2	TM11,TM21	+	Time coordinate of point 1 for each hydrograph, in hours

	TM31		
3	Q12, Q22 Q32	+	Discharge coordinate of point 2 for each hydrograph, in cfs or cms
4	TM12,TM22 TM32	+	Time coordinate of point 2 for each hydrograph, in hours

Continue with additional discharge and time coordinates. Note that time coordinates must be in increasing order.

G3 Record - This record is used to define required and optional river channel features for a job as listed below. This record is placed after the G2 records.

Field	Variable	Value	Description
0	IA	G3	Record identification characters
1	S11	+	Slope of the downstream section, required for a job
2	BSP	0	One-on-one slope for rigid bank or bank protection
		+	Slope of bank protection in BSP horizontal units on 1 vertical unit. for all cross sections unless otherwise specified in Field 8 of the XF record for a section.
3	DSOP	0	Downstream slope is allowed to vary during simulation.
		1	Downstream slope is fixed at S11 given in Field 1.
4	TEMP	0	Water temperature is 15°C.
		+	Water temperature in degrees Celsius
5	ICNN	0	Manning's n defined in Field 7 of the G1 record or those in Field 4 of the XF records are used.
		1	Brownlie's formula for alluvial bed roughness is used to calculate Manning's n in the simulation.
6	TDZAMA	0	Thickness of erodible bed layer is 100 ft (30.5 m).
		+	Thickness of erodible bed layer in ft or m. This value is applied to
7	SPGV	0	Specific gravity of sediment is 2.65.
		+	Specific gravity of sediment
8	KGS	0	The number of size fractions for bed material is 5.
		+	The number of size fractions for bed material. It maximum value is 8.
9	PHI	0	The angle of repose for bed material is 36°.
		+	Angle of repose for bed material

G4 Record - This is an optional record used to select cross sections (up to 4) to be included at each summary output. Each cross section is identified by its number which is counted from the downstream section. This record also contains other options; it is placed after the G3 record.

Field	Variable	Value	Description
0	IA	G4	Record identification characters
1	IPLI1	+	Number of cross section
		10000	All cross sections included in each summary output
2	IPLT2	+	Number of cross section
3	IPLT3	+	Number of cross section
4	IPLT4	+	Number of cross section
5	IEXCAV	+	A positive integer indicates number of cross section where sand/gravel excavation occurs.
6	GIFAC	+	A non-zero constant is used to modify sediment inflow at the upstream section.
7	PZMIN	0	Minimum bed profile during simulation run is not requested.
		1	Output file entitled TZMIN for minimum bed profile is requested.
10	REXCAV	+	A non-zero value specifies rate of sand/gravel excavation at Section IEXCAV.

G5 Record - This is an optional record used to specify miscellaneous options, including unsteady-flow routing for the job based upon the dynamic wave, bend flow characteristics. If the unsteady flow option is not used, the water-surface profile for each time step is computed using the standard-step method. When the unsteady flow option is used, the downstream water-surface elevation must be specified using the GB records.

Field	Variable	Value	Description
0	IA	G5	Record identification characters
1	DT	0	The first time step is 100 seconds.
		+	Size of the first time step in seconds.
2	IROUT	0	Unsteady water routing is not used; water-surface profiles are computed using standard-step method.
		1	Unsteady water-routing based upon the dynamic wave is used to

			compute stages and water discharges at all cross sections for each
3	PQSS	0	No output of gradation of sediment load
		3	Gradation of sediment load is included in output in 1,000 ppm by weight.
5	TSED	0	Rate of tributary sediment inflow is 1 times the discharge ratio.
		+	Rate of tributary sediment inflow is TSED times the discharge ratio.
6	PTV	0	No output of transverse distribution of depth-averaged velocity
		1	Transverse distribution of depth-averaged velocity is printed. The velocity distribution is for bends with fully developed transverse flow.
10	DYMAX	0	No GR points are inserted for cross sections.
		+	Maximum value of spacing between adjacent points at a cross

G6 Record - This is an optional record used to select time points for summary output. Up to 30 time points may be specified. The printing frequency (KPF) in Field 10 of the G1 Record may be suppressed by using a large number such as 9999.

Field	Variable	Value	Description
First G6 Record			
0	IA	G6	Record identification characters
1	NKPS	+	Number of time points
Succeeding G6 Record(s)			
0	IA	G6	Record identification characters
1	SPTM(1)	+	First time point, in hours
2	SPTM(2)	+	Second time point, in hours

Continue with additional time points.

G7 Record - This is an optional record used to specify erosion resistant bed layer, such as a caliche layer, that has a lower rate of erosion.

Field	Variable	Value	Description
First G7 Record			
0	IA	G7	Record identification characters
1	KG7	+	Number of time points used to define the known erosion rate in

			relation to flow velocity
2	THICK	+	Thickness of erosion resistant layer, in feet

Succeeding G7 Record(s)

0	IA	G7	Record identification characters
1	ERATE(1)	+	Erosion rate, in feet per hour
2	G7V(2)	+	Velocity, in feet per second

Continue with additional time points.

GS Record - At least two GS records are required for each job, used to specify initial bed-material compositions in the channel at the downstream and upstream cross sections. The first GS record is for the downstream section; it should be placed before the first X1 record and after the G4 record, if any. The second GS record is for the upstream section; it should be placed after all cross-sectional data and just before the EJ record. Additional GS records may be inserted between two cross sections within the stream reach, with the total number of GS records not to exceed 15. Each GS record specifies the sediment composition at the cross section located before the record. From upstream to downstream, exponential decay in sediment size is assumed for the initial distribution. Sediment composition at each section is represented by five size fractions.

Field	Variable	Value	Description
0	IA	GS	Record identification characters
1	DFF	+	Geometric mean diameter of the smallest size fraction in mm
2	PC	+	Fraction of bed material in this size range

Continue with other DFF's and PC's.

GB Records - These optional records are used to define time variation of stage (water-surface elevation) at a cross section. The first set of GB records is placed before all cross section records (X1); it specifies the downstream stage. When the GB option is used, it supersedes other methods for determining the downstream stage. Other sets of GB records may be placed in other parts of the data set; each specifies the time variation of stage for the cross section immediately following the GB records.

Field	Variable	Value	Description
First GB Record			
0	IA	GB	Record identification characters
1	KBL	+	Number of points used to define base-level changes

Succeeding GB Record(s)

0	IA	GB	Record identification characters
1	BSLL(1)	+	Base level of point 1, in ft or m
2	TMBL(1)	+	Time coordinate of point 1, in hours
3	BSLL(2)	+	Base level of point 2, in ft or m
4	TMBL(2)	+	Time coordinate of point 2, in hours

Continue with additional elevations and time coordinates, in the increasing order of time.

GQ Records - These optional records are used to define stage-discharge relation at the downstream section. The GQ input data may not used together with the GB records.

Field	Variable	Value	Description
First GQ Record			
0	IA	GQ	Record identification characters
1	KQL	+	Number of points used to define base-level changes
Succeeding GQ Record(s)			
0	IA	GQ	Record identification characters
1	BSLL(1)	+	Base level of point 1, in ft or m
2	TMQ(1)	+	Discharge of point 1, in cfs or cms
3	BSLL(2)	+	Base level of point 2, in ft or m
4	TMQ(2)	+	Discharge of point 2, in cfs or cms

Continue with additional elevations and discharges, in the increasing order of discharge.

GI Records - These optional records are used to define time variation of sediment discharge entering the study reach through the upstream cross section. The GI input data, if included, will supersede other methods for determining sediment inflow. The sediment inflow is classified into the two following cases: (1) specified inflow at the upstream section, such as by a rating curve; and (2) sediment feeding, such as from a dambreach or a sediment feeder. These two cases are distinguished by DXU in Field 2 of this record. For the first case, sediment discharge at the upstream section is computed using size fractions of bed-material at the section, but for the second case, the size fractions of feeding material need to be specified using the PCU values in

this record. The upstream section does not change in geometry for the first case but it may undergo scour or fill for the second case.

Field	Variable	Value	Description
First GI Record			
0	IA	GI	Record identification characters
1	KGI	+	Number of points used to define time variation of sediment inflow.
2	DXU	+ or 0	Channel distance measured from the upstream section to the and KGI signify case 2, for which PCU values are required.
3-10	PCU	+	Size fractions of inflow material. The number of size fractions is given in Field 8 of the G3 record and the sizes for the fractions are given in the second GS record.
Succeeding GI Record(s)			
0	IA	GI	Record identification characters
1	QSU(1)	+	Sediment discharge of point 1, in cubic ft or m (net volume) per second
2	TMGI(1)	+	Time coordinate of point 1, in hours
3	QSO(2)	+	Sediment discharge of point 2
4	TMGI(2)	+	Time coordinate of point 2.

Continue with additional sediment discharges and time coordinates, in the increasing order of time coordinates.

X1 Record - This record is required for each cross section (175 cross sections can be used for the study reach); it is used to specify the cross-sectional geometry and program options applicable to that cross-section. Cross sections are arranged in sequential order starting from downstream.

Field	Variable	Value	Description
0	IA	X1	Record identification characters
1	SECNO	+	Original section number from the map
2	NP	+	Total number of stations or points on the next GR records for
7	DX	+	Length of reach between current cross section and the next down-

			stream section along the thalweg, in feet or meters
8	YFAC	0	Cross-section stations are not modified by the factor YFAC.
		+	Factor by which all cross-section stations are multiplied to increase or decrease area. It also multiplies YC1, YC2 and CPC in the XF record, and applies to the CI record.
9	PXSECE	0	Vertical or Z coordinate of GR points are not modified.
		±	Constant by which all cross-section elevations are raised or lowered
10	NODA	0	Cross section is subject to change.
		1	Cross section is not subject to change.

XF Record - This is an optional record used to specify special features of a cross section.

Field	Variable	Value	Description
0	IA	XF	Record identification characters
1	YC1	0	Regular erodible left bank
		+	Station of rigid left bank in ft or m, to the left of which channel dinates in GR records but not the first Y coordinate.
2	YC2	0	Regular erodible right bank
	+		Station of rigid right bank, to the right of which channel is non-erodible. Note: This station is located at toe of rigid bank; its value must be equal to one of the Y coordinates in GR records but not the last Y coordinate.
3	RAD	0	Straight channel with zero curvature
		+	Radius of curvature at channel centerline in ft or m. Center of radius is on same side of channel where the station (Y-coordinate) starts.
		-	Radius of curvature at channel centerline in ft or m. Center of radius is on opposite side of zero station. Note: RAD is used only if concave bank is rigid and so specified using the XF record. RAD produces a transverse bed scour due to curvature.
4	CN	0	Roughness of this section is the same as that given in Field 7 of the G1 record.
		+	Manning's *n* value for this section
5	CPC	0	Center of thalweg coincides with channel invert at this section.
		+	Station (Y-coordinate) of the thalweg in ft or m
6	IRC	0	Regular erodible cross section

		1	Rigid or nonerodible cross section such as drop structure or road crossing. There is no limit on the total number of such cross sections.
8	BSP	0	Slope of bank protection is the same as that given in Field 2 of the G3 record.
		+	Slope of bank protection at this section in BSP horizontal units
		5	Slope of rigid bank is defined by the GR coordinates.
9	BEFX	0	Bank erodibility factor is defined in Field 5 of the G1 record.
		+	A value between 0.1 and 1.0 for BEFX specifies the bank erodibility factor at this section.
	RWD	+	RWD is the width of bank protection of a small channel in the specified by a value greater than 1 (ft or m) in this field. When RWD is used, BEFX is not specified.
10	TDZAM	0	Erodible bed layer at this section is defined by TDZAMA in Field
		+	Thickness of erodible bed layer in ft or m. Only one decimal place is allowed for this number.
	ENEB	±	Elevation of non-erodible bed, used to define the crest elevation of a grade-control structure which may be above or below the existing channel bed. In order to distinguish it from TDZAM, ENEB must have the value of 1 at the second decimal place. For example, the ENEB value of 365 should be inputted as 365.01 and the ENEB value of -5.2 should be inputted as -5.21. When ENEB is specified, it supersedes TDZAM and TDZAMA

CI Record - This is an optional record used to specify channel improvement options due to excavation or fill. The excavation option modifies the cross-sectional geometry by trapezoidal excavation. Those points lower than the excavation level are not filled. The fill option modifies the cross-sectional geometry by raising the bed elevations to a prescribed level. Those points higher than the fill level are not lowered. Excavation and fill can not be used at the same time. This record should be placed after the X1 and XF records but before the GR records. The variable ADDVOL in Field 10 of this record is used to keep track of the total volume of excavation or fill along a channel reach. ADDVOL specifies the initial volume of fill or excavation. A value greater or less than 0.1 needs to be entered in this field to keep track of the total volume of fill or excavation until another ADDVOL is defined.

Field	Variable	Value	Description
0	IA	G5	Record identification characters
1	CLSTA	+	Station of the centerline of the trapezoidal excavation, expressed according to the stations in the GR records, in feet or meter.
2	CELCH	+	Elevation of channel invert for trapezoidal channel, in feet or meters.

4	XLSS	+	Side slope of trapezoidal excavation, in XLSS horizontal units for 1 vertical unit.
5	ELFIL	+	Fill elevation on channel bed, in feet or meters.
6	BW	+	Bed width of trapezoidal channel, in feet or meters. This width is measured along the cross section line; therefore, a larger value should be used if a section is skewed.
10	ADDVOL	0	Volume of excavation or fill, if any, is added to the total volume already defined.
		+	Initial volume of fill on channel bed, in cubic feet or cubic meters.
		-	Initial volume of excavation from channel bed, in cubic feet or meters.

GR Record - This record specifies the elevation and station of each point for a digitized cross section; it is required for each X1 record.

Field	Variable	Value	Description
0	IA	GR	Record identification characters
1	Z1	"	Elevation of point 1, in ft or m. It may be positive or negative.
2	Y1	"	Station of point 1, in ft or m
3	Z2	"	Elevation of point 2, in ft or m
4	Y2	"	Station of point 2, in ft or m

Continue with additional GR records using up to 79 points to describe the cross section. Stations should be in increasing order.

SB Record - This special bridge record is used to specify data in the special bridge routine. This record is used together with the BT and GR records for bridge hydraulics. This record is placed between cross sections that are upstream and downstream of the bridge.

Field	Variable	Value	Description
0	IA	SB	Record identification characters
1	XK	+	Pier shape coefficient for pier loss
2	XKOR	+	Total loss coefficient for orifice flow through bridge opening
3	COFQ	+	Discharge coefficient for weir flow overtopping bridge roadway

4	IB	+	Bridge index, starting with 1 from downstream toward upstream
5	BWC	+	Bottom width of bridge opening including any obstruction
6	BWP	0	No obstruction (pier) in the bridge
		i	Total width of obstruction (piers)
7	BAREA	+	Net area of bridge opening below the low chord in square feet
9	ELLC	+	Elevation of horizontal low chord for the bridge
10	ELTRD	+	Elevation of horizontal top-of-roadway for the bridge

BT Record - This record is used to compute conveyance in the bridge section. The BT data defines the top-of -roadway and the low chord profiles of bridge. The program uses the BT, SB and GR data to distinguish and to compute low flow, orifice flow and weir flow.

Field	Variable	Value	Description
0	IA	BT	Record identification characters
1	NRD	+	Number of points defining the bridge roadway and bridge low chord to be read on the BT records
2	RDST(1)	+	Roadway station corresponding to RDEL(1) and XLCEL(1)
3	RDEL(1)	+	Top of roadway elevation at station RDST(1)
4	XLCEL(1)	+	Low chord elevation at station RDST(1)
5	RDST(2)	+	Roadway station corresponding to RDEL(2) and XLCEL(2)
6	RDEL(2)	+	Top of roadway elevation at station RDST(2)
7	XLCEL(2)	+	Low chord elevation at station RDST(2)

Continue with additional sets of RDST, RDEL, and XLCEL.

EJ Record - This record is required following the last cross section for each job. Each group of records beginning with the T1 record is considered as a job.

Field	Variable	Value	Description
0	IA	EJ	Record identification characters

1-10 Not used

II. OUTPUT DESCRIPTION

Output of the model include initial bed-material compositions, time and spatial variations of the water-surface profile, channel width, flow depth, water discharge, velocity, energy gradient, median sediment size, and bed-material discharge. In addition, cross-sectional profiles are printed at different time intervals.

Symbols used in the output are generally descriptive, some of them are defined below:

SECTION	Cross section
TIME	Time on the hydrograph
DT	Size of the time step or Δt in sec
W.S.ELEV	Water-surface elevation in ft or m
WIDTH	Surface width of channel flow in ft or m
DEPTH	Depth of flow measured from channel invert to water surface in ft or m
Q	Discharge of flow in cfs or cms
V	Mean velocity of a cross-section in fps or mps
SLOPE	Energy gradient
D50	Median size or d_{50} of sediment load in mm
QS	Bed-material discharge for all size fractions in cfs or cms
FR	Froude number at a cross section
N	Manning's roughness coefficient
SED.YIELD	Bulk volume or weight of sediment having passed a cross section since beginning of simulation, in cubic yards or tons.
WSEL	Water-surface elevation, in ft or m
Z	Vertical coordinate (elevation) of a point on channel boundary at a cross-section, in ft or m
Y	Horizontal coordinate (station) of a point on channel boundary at a cross-section, in ft or m
DZ	Change in elevation during the current time step, in ft or m
TDZ	Total or accumulated change in elevation, in ft or m.