SACRAMENTO RIVER SEDIMENT STUDY, PHASE II, CA

FOLSOM DAM MODIFICATION, WATER CONTROL MANUAL UPDATE

LOWER AMERICAN RIVER HEC-6T MODEL FINAL REPORT

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Executive Summary

The main objective of this sedimentation modeling and analysis study undertaken by Northwest Hydraulic Consultants (NHC) for the Sacramento District of the U.S. Army Corps of Engineers (USACE) was to investigate baseline sediment transport processes and geomorphic trends along the lower American River and to evaluate long-term impacts of the Folsom Dam Modification Project on bed profile vertical evolution. The analysis was conducted using the updated HEC-6T sediment transport model previously developed by Ayres and Associates (Ayres). The Ayres model includes a 22-mile reach of the American River below Nimbus Dam. The model geometry is based on the 1997 and 2006 bathymetric and overbank topographic survey data. The model was developed using vertical datum NGVD29. Bed material in the Ayres HEC-6T model was specified using Wolman Count data obtained for the bar surface material. The depth of bed sediment reservoir in the Ayres model was specified using results from geophysical data available at the time of their study.

NHC extended the Ayres HEC-6T model to include the 32-mile long reach of the Sacramento River between Verona and Freeport (in order to assess downstream changes in the American River due to tailwater control from the Sacramento River); converted the model to vertical datum NAVD88, and updated it with the most recent surface and sub-surface bed material data and results from geotechnical investigations of hard (erosion-resistant) materials. The model’s hydraulic performance was verified with high water mark data collected after the 1997 flood event. The updated model was calibrated to reproduce measured sediment loads and observed bed changes in the American River (between 1997 and 2006) and Sacramento River (between 1997 and 2008).

The calibrated model was then used to simulate long-term morphological changes in the lower American River under existing and project hydrologic conditions. The existing and project hydrographs were developed by the USACE for Water Years (WYs) 1930-2002 (73 years). The existing conditions hydrology assume regulated flow for the entire simulation period with post-Oroville Dam and Central Valley Project flow conditions in effect and reflect the existing operation of the river system. The with-project hydrology is based on simulated operation of Folsom Dam with the new auxiliary spillway for the same period of record.

The outflows from Folsom Dam provided by the USACE are estimated using the USACE Hydrologic Engineering Center's Reservoir Simulation software (HEC-RESIM) for both the existing and project conditions. The existing conditions outflows from Folsom Dam are from the HEC-RESIM E504 Existing Level of Demand (ELD) Reservoir Operation Set (ROS). The project condition outflows from Folsom Dam are from the HEC-RESIM J602P ELD ROS.

The model results indicate active degradation of the American River channel between Nimbus Dam and River Mile (RM) 14 and predominant aggradation downstream of RM 14. The upstream sediment supply to the lower American River is interrupted by Folsom and Nimbus Dams, which results in ongoing channel degradation below the dams. Bed material eroded from the upstream reach is transported to and partially deposit in the downstream reach. These model results are consistent with field observations and measurements of river profile adjustments.
Folsom Dam modification project condition flows generally increase bed material transport through the study reach of the American River. The total bed material inflow from the American River to the Sacramento River during the 73-year long simulation period is 333,000 tons for the existing hydrology and 382,000 tons (15% increase) for the project hydrology.

Simulated changes in invert elevations vary significantly along the study reach of the American River. This variability is attributed to complex channel adjustments in the model caused by a variety of factors including local channel geometry, successive wetting and drying of different parts of the river channel during high and low flow periods, varying sediment transport capacity at different flows, and alternating aggradation and degradation processes in different parts of the channel during different flow periods. Maximum channel invert degradation computed for the lower American River with the existing hydrology is about 8-10 ft upstream of RM 19, 6-7 ft between RMs 12-19, and 4-6 ft between RMs 5.5-7. Up to 2-3 ft of localized invert aggradation is computed in between RMs 10.5-11.5, at RM 6.7, and at RM 5. The lower 4 miles of the American River are in a slight aggradational state, with 1-3 ft of localized invert aggradation. Project flows increase (by about 1 ft) invert degradation upstream of RM 14 and between RMs 5.5-6.5, and do not affect significantly invert profile in the other reaches.

Potential implications of the simulated long-term changes in the American River bed profile can be increased stress along the toe of the project levees in the degradational reaches, which may result in increased scour along unrevetted channel sections. In the aggradational reaches, increases in bed elevations may result in higher flood stages and reduced flood conveyance.

Net bed material erosion in the 22-mile long study reach of the American River is about 265,000 cubic yards for the existing hydrology and 304,000 cubic yards (15% increase) for the project hydrology. The additional erosion of bed material under project conditions is relatively small and is equivalent to about 0.03 ft of reach-averaged increase in bed degradation.

According to the HEC-6T model results, the hard cohesive materials beneath the American River channel can become exposed at several locations between RMs 6.9-10.5 and upstream of RM 20 over the model simulation time period. The latter location is somewhat uncertain as the hard surface elevations upstream of RM 11.5 were not measured and were assumed to be 10 ft below the 2006 invert. In general, the project hydrology does not increase significantly the overall exposure of the hard materials in the study reach of the American River.

The exposed hard material becomes subject to erosion by flowing water. However, modeling results indicate that the shear stress computed using the smooth wall law for the American River between RMs 6.9-10.5 is below the critical for erosion of the moderately resistant materials (clay and cemented sand with silt) for all the flows modeled in this study. Upstream of RM 20, hard materials can be eroded only during extreme flows exceeding 100,000 cfs. However, the exact location of the hard material in this reach is presently unknown. The elevation of the hard surface needs to be more accurately determined in this reach to evaluate the risk of hard material exposure. Erosion of the hard material can be higher than estimated due to the scouring effects of moving sediment impacting the hard material surface.
For the Sacramento River between Verona and Freeport, predominant degradation is obtained upstream of the Sacramento Weir and predominant aggradation downstream of the weir. Project hydrology flows in the lower American River increase bed material loads in the Sacramento River downstream of about RM 70. Total bed material load at Freeport during the simulation period is 43,180,000 tons under existing conditions and 43,280,000 tons (less than 1% increase) under project conditions.

Long-term changes in the Sacramento River invert profile simulated with the existing hydrology range from about 2-3 ft of degradation to 3-8 ft of aggradation. The model results indicate an overall slight degradational trend upstream of the Sacramento Weir and a slight aggradational trend downstream of the weir. In general, however, the study reach of the Sacramento River appears to be stable. The project hydrology does not have a significant effect on long-term changes in the Sacramento River profile.

Net deposition of bed material in the 32-mile long study reach of the Sacramento River is about 839,000 cubic yards for the existing condition hydrology and 791,000 cubic yards (6% reduction) for the project condition hydrology. This decrease in net deposition is equivalent to about 0.01 ft of reach-average bed degradation.

A series of model sensitivity runs was performed for both the existing and project hydrology to evaluate the effects of potential widening of the American River channel on sediment transport processes and geomorphic trends in the lower American River. The sensitivity analyses were conducted for the channel width increased by 50 ft and by 100 ft. The results of the sensitivity runs generally show less significant bed degradation in the widened channel of the American River, particularly upstream of about RM 13. Invert profiles in the widened channel are up to about 1-3 ft higher than the invert profile simulated for the existing channel width. The wider the channel, the less bed degradation in the study reach of the American River. As a result, depth to the hard surface in the widened channel upstream of RM 13 is about 1-3 ft greater compared to the existing channel width. At the same time, the channel widening does not change the potential exposure of the hard materials between RMs 6.9-10.5. In general, the modeled channel widening does not change the overall bed material transport and bed material deposition/erosion patterns in the lower American River and has an insignificant effect on the Sacramento River.
List of Abbreviations

1-d  One-dimensional
Ayres  Ayres and Associates, Inc.
Comp Study  Comprehensive Study
CRP  Continuous Resistivity Profiling
D₈₄, D₉₀  Grain size for which 84%, 90% of sediment is finer
DWR  Department of Water Resources
EFA  Erosion Function Apparatus
ELD  Existing Level of Demand
ERDC  U.S. Army Engineer Research and Development Center
Fugro  Fugro Consultants
GIS  Geographic Information System
HEC  Hydrologic Engineering Center
HEC-6  Hydrologic Engineering Center’s 1-d sediment transport model
HEC-6T  Mobile Boundary Hydraulics’ 1-d sediment transport model (enhanced HEC-6)
HEC-RAS  Hydrologic Engineering Center’s River Analysis System, 1-d hydraulic model
HEC-RESIM  Hydrologic Engineering Center's Reservoir Simulation software
JET  Jet Erosion Test
LAR  Lower American River
MBH  Mobile Boundary Hydraulics, PLLC
MPM  Meyer-Peter and Muller bed load transport formula
NAVD88  North American Vertical Datum of 1988
NEMDC  Natomas East Main Drainage Canal
NGVD29  National Geodetic Vertical Datum of 1929
NHC  Northwest Hydraulic Consultants
RM  River Mile
ROS  Reservoir Operation Set
SPI  Sorting and armoring time interval or exchange increment in HEC-6T
USACE  U.S. Army Corps of Engineers
USGS  U.S. Geological Survey
WY  Water Year
# Table of Contents

1. Introduction ........................................................................................................................1
2. Description of Computer Model HEC-6T .........................................................................3
5. Lower American River Model Update ..............................................................................7
   5.1. Model Extension .......................................................................................................7
   5.2. Datum Conversion ....................................................................................................7
   5.3. Bed Material .............................................................................................................8
   5.4. Hard Surface .............................................................................................................9
   5.5. Sediment Diversion ................................................................................................10
   5.6. Hydraulic Boundary Conditions ..............................................................................10
   5.7. Computational Time Step .........................................................................................12
   5.8. Exchange Increment ................................................................................................12
   5.9. Sediment Transport Function ....................................................................................12
   5.10. Upstream Sediment Inflow .....................................................................................13
6. Model Calibration and Verification ...................................................................................14
   6.1. Fixed-Bed, Steady Flow Tests ..................................................................................14
   6.2. Movable-Bed, Steady Flow Test .............................................................................16
   6.3. Movable-Bed, Quasi-Unsteady Flow Test ..............................................................17
      6.3.1. Bed Material Transport ....................................................................................18
      6.3.2. Invert Profile ....................................................................................................19
      6.3.3. Bed Material Volume .......................................................................................20
      6.3.4. Bed Surface Gradation .....................................................................................21
   6.4. Sediment Transport Function Selection ....................................................................21
7. Channel Widening .............................................................................................................23
8. Existing Hydrology Model Results ....................................................................................24
   8.1. Bed Material Transport .............................................................................................24
   8.2. Invert Profile .............................................................................................................24
   8.3. Bed Material Volume ...............................................................................................26
   8.4. Bed Surface Gradation .............................................................................................26
9. Project Hydrology Model Results ......................................................................................28
  9.1. Bed Material Transport .............................................................................................28
  9.2. Invert Profile .............................................................................................................29
  9.3. Bed Material Volume ...............................................................................................29
  9.4. Bed Surface Gradation ............................................................................................30
10. Erosion of Hard Material ...............................................................................................31
11. Effect of Channel Widening ..........................................................................................33
  11.1. Bed Material Transport ........................................................................................33
  11.2. Invert Profile .........................................................................................................34
  11.3. Bed Material Volume ............................................................................................34
  11.4. Bed Surface Gradation ........................................................................................34
12. Summary .........................................................................................................................36
  12.1. Model Update .......................................................................................................36
  12.2. American River ......................................................................................................36
  12.3. Sacramento River ...................................................................................................38
  12.4. Effect of American River Widening .......................................................................38
References ..............................................................................................................................39

Appendix A. Study Reach of American River
Appendix B. Study Reach of Sacramento River
Appendix C. 1997 and 2006 Cross Sections in HEC-6T Model of American River
Appendix D. Modified 2006 Cross Section (for Sensitivity Analyses)
List of Tables

Table 1. Hard surface in American River in HEC-6T model (based on Fugro 2012 geophysical data) .................................................................................................................................42
Table 2. Sediment concentration diversion ratios at Sacramento Weir in HEC-6T model (calculated using Rouse equation; from NHC 2012) .................................................................43
Table 3. Stage-discharge rating curve for Sacramento River at Freeport ........................................43
Table 4. Roughness coefficients in HEC-6T model ................................................................................44
Table 5. Measured and computed bed material yields in Sacramento River at Freeport (movable-bed model calibration) .................................................................................44
Table 6. Measured and computed bed volume changes (movable-bed model calibration) ......................................................... .................................................................45
Table 7. Computed bed volume changes (long-term simulations) .................................................................46
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1</td>
<td>Study area and vicinity map</td>
<td>47</td>
</tr>
<tr>
<td>Figure 2</td>
<td>Schematic of HEC-6T model stream network</td>
<td>48</td>
</tr>
<tr>
<td>Figure 3</td>
<td>Conversion factors from vertical datum NGVD29 to vertical datum NAVD88 (provided by USACE)</td>
<td>49</td>
</tr>
<tr>
<td>Figure 4</td>
<td>Relationship between USACE stationing and HEC-6T stationing for American River</td>
<td>50</td>
</tr>
<tr>
<td>Figure 5</td>
<td>Conversion factor from USACE stationing to HEC-6T stationing for American River</td>
<td>51</td>
</tr>
<tr>
<td>Figure 6</td>
<td>Measured and modeled sub-surface bed material gradations (American River; NHC data)</td>
<td>52</td>
</tr>
<tr>
<td>Figure 7</td>
<td>Measured surface bed material gradations (American River; NHC and Ayres data)</td>
<td>53-54</td>
</tr>
<tr>
<td>Figure 8</td>
<td>Surface bed material gradations adjusted for sand content (American River; NHC and Ayres data)</td>
<td>55-56</td>
</tr>
<tr>
<td>Figure 9</td>
<td>Measured bed material gradations (Sacramento River; NHC data)</td>
<td>57</td>
</tr>
<tr>
<td>Figure 10</td>
<td>Invert and hard surface elevations in American River in HEC-6T model</td>
<td>58</td>
</tr>
<tr>
<td>Figure 11</td>
<td>Daily flow hydrographs used for model calibration against observed bed changes</td>
<td>59</td>
</tr>
<tr>
<td>Figure 12</td>
<td>Existing conditions hydrographs developed by USACE for long-term simulations</td>
<td>60-61</td>
</tr>
<tr>
<td>Figure 13</td>
<td>Project conditions hydrographs (preliminary) developed by USACE for long-term simulations</td>
<td>62-63</td>
</tr>
<tr>
<td>Figure 14</td>
<td>Downstream stage-discharge rating curve for Sacramento River at Freeport used for test runs based on 1997 geometry</td>
<td>64</td>
</tr>
<tr>
<td>Figure 15</td>
<td>Downstream stage-discharge rating curve for Sacramento River at Freeport used for long-term with-project simulations (from USACE 2014)</td>
<td>65</td>
</tr>
<tr>
<td>Figure 16</td>
<td>Upstream total bed material inflows in Sacramento River at Verona computed by NHC (2012) model for 1997-2008</td>
<td>66</td>
</tr>
<tr>
<td>Figure 17</td>
<td>Total bed material load gradations in Sacramento River at Verona computed by NHC (2012) model for 1997-2008</td>
<td>67</td>
</tr>
<tr>
<td>Figure 18</td>
<td>Comparison of measured and computed stage-discharge relationships (fixed-bed model test)</td>
<td>68</td>
</tr>
<tr>
<td>Figure 19</td>
<td>Computed and observed water surface elevations for January 2-3, 1997 flood event (fixed-bed model test)</td>
<td>69</td>
</tr>
<tr>
<td>Figure 20</td>
<td>Water surface profiles computed for American River (fixed-bed model test)...</td>
<td>70</td>
</tr>
</tbody>
</table>
Figure 21. Water surface profiles computed for Sacramento River (fixed-bed model test) .....................................................................................................................71

Figure 22. Channel discharge profiles computed for American River (fixed-bed model test) .....................................................................................................................72

Figure 23. Channel discharge profiles computed for Sacramento River (fixed-bed model test) .............................................................................................................73

Figure 24. Channel velocity profiles computed for American River (fixed-bed model test) .....................................................................................................................74

Figure 25. Channel velocity profiles computed for Sacramento River (fixed-bed model test) .....................................................................................................................75

Figure 26. Comparison of measured and computed suspended bed material loads for American River at Sacramento (RM 6.6) ........................................................................76

Figure 27a. Comparison of bed loads (gravel and cobble) computed for American River at Sacramento (RM 6.6). ....................................................................................77

Figure 27b. Comparison of bed loads by size class (very fine gravel) computed for American River at Sacramento (RM 6.6). ........................................................................78

Figure 27c. Comparison of bed loads by size class (fine gravel) computed for American River at Sacramento (RM 6.6). ..........................................................................79

Figure 27d. Comparison of bed loads by size class (medium gravel) computed for American River at Sacramento (RM 6.6). ........................................................................80

Figure 27e. Comparison of bed loads by size class (coarse gravel) computed for American River at Sacramento (RM 6.6). ........................................................................81

Figure 27f. Comparison of bed loads by size class (very coarse gravel) computed for American River at Sacramento (RM 6.6). ........................................................................82

Figure 27g. Comparison of bed loads by size class (small cobbles) computed for American River at Sacramento (RM 6.6). ........................................................................83

Figure 28a. Comparison of measured and computed suspended bed material loads for Sacramento River at Verona (RM 78.8) ........................................................................84

Figure 28b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Verona (RM 78.8) ...............85

Figure 28c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Verona (RM 78.8) .....................86

Figure 28d. Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Verona (RM 78.8) ..............87

Figure 29a. Comparison of measured and computed suspended bed material loads for Sacramento River at Sacramento (RM 59.7). ......................................................88

Figure 29b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Sacramento (RM 59.7).....89
Figure 29c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Sacramento (RM 59.7) ..........90
Figure 29d. Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Sacramento (RM 59.7) .....91
Figure 30a. Comparison of measured and computed suspended bed material loads for Sacramento River at Freeport (RM 46.4) .................................................................92
Figure 30b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Freeport (RM 46.4) ..........93
Figure 30c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Freeport (RM 46.4) ...................94
Figure 30d. Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Freeport (RM 46.4) ............95
Figure 31. Computed total bed material load in American River (movable-bed model calibration) ..........................................................................................................96
Figure 32. Computed total bed material load in Sacramento River (movable-bed model calibration) ...............................................................................................97
Figure 33. Computed total bed material deposition in American River (movable-bed model calibration) ...............................................................................................98
Figure 34. Computed total bed material deposition in Sacramento River (movable-bed model calibration) ...............................................................................................99
Figure 35. Computed cumulative bed material deposition in American River from upstream to downstream (movable-bed model calibration) ...............................100
Figure 36. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (movable-bed model calibration) ...............................101
Figure 37. Measured and computed invert profiles in American River (movable-bed model calibration) ......................................................................................................................102-103
Figure 38. Measured and computed invert profiles in Sacramento River (movable-bed model calibration) ......................................................................................................................104-105
Figure 39. Measured and computed net changes in invert elevations in American River (movable-bed model calibration) ......................................................................................................................106-107
Figure 40. Measured and computed net changes in invert elevations in Sacramento River (movable-bed model calibration) ......................................................................................................................108-109
Figure 41. Measured and computed bed volume changes in American and Sacramento Rivers (movable-bed model calibration) ......................................................................................................................110
Figure 42. Measured and computed initial and final surface bed material gradations in American River (movable-bed model calibration) ......................................................................................................................111-113
Figure 43. Measured and computed initial and final surface bed material gradations in Sacramento River (movable-bed model calibration) ......................................................................................................................114-115
Figure 44. Computed total bed material load in American River (long-term simulations, existing hydrology) ................................................................. 116

Figure 45. Computed total bed material load in Sacramento River (long-term simulations, existing hydrology) ........................................................................ 117

Figure 46. Computed total bed material deposition in American River (long-term simulations, existing hydrology) ........................................................................ 118

Figure 47. Computed total bed material deposition in Sacramento River (long-term simulations, existing hydrology) ........................................................................ 119

Figure 48. Computed cumulative bed material deposition in American River from upstream to downstream (long-term simulations, existing hydrology) ........ 120

Figure 49. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (long-term simulations, existing hydrology) .... 121

Figure 50. Computed invert profiles in American River (long-term simulations, existing hydrology) .................................................................................. 122

Figure 51. Computed invert profiles in Sacramento River (long-term simulations, existing hydrology) .................................................................................. 123

Figure 52. Computed net changes in invert elevations in American River (long-term simulations, existing hydrology) ................................................................ 124

Figure 53. Computed net changes in invert elevations in Sacramento River (long-term simulations, existing hydrology) ................................................................ 125

Figure 54. Computed depth to hard surface below invert in American River (long-term simulations, existing hydrology) ................................................................ 126

Figure 55. Timeline progression of degradation and aggradation trends at selected cross sections in American River (long-term simulations, existing hydrology) ................................................................. 127

Figure 56. Computed bed volume changes in American and Sacramento Rivers (long-term simulations, existing hydrology) ........................................................................ 128

Figure 57. Computed surface bed material gradations in American River (long-term simulations, existing hydrology) ........................................................................ 129-131

Figure 58. Computed surface bed material gradations in Sacramento River (long-term simulations, existing hydrology) ........................................................................ 132-133

Figure 59a. Computed total bed material load in American River (long-term simulations, project hydrology) .................................................................................. 134

Figure 59b. Comparison of total bed material loads in American River computed for existing and project hydrology ................................................................. 135

Figure 60a. Computed total bed material load in Sacramento River (long-term simulations, project hydrology) ........................................................................ 136

Figure 60b. Comparison of total bed material loads in Sacramento River computed for existing and project hydrology ........................................................................ 137
Figure 61a. Computed total bed material deposition in American River (long-term simulations, project hydrology)..................................................................................138
Figure 61b. Comparison of total bed material depositions in American River computed for existing and project hydrology .................................................................139
Figure 62a. Computed total bed material deposition in Sacramento River (long-term simulations, project hydrology)........................................................................140
Figure 62b. Comparison of total bed material depositions in Sacramento River computed for existing and project hydrology .............................................................141
Figure 63a. Computed cumulative bed material deposition in American River from upstream to downstream (long-term simulations, project hydrology) ........142
Figure 63b. Comparison of cumulative bed material depositions in American River (from upstream to downstream) computed for existing and project hydrology .............................................................................................................143
Figure 64a. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (long-term simulations, project hydrology) ....144
Figure 64b. Comparison of cumulative bed material depositions in Sacramento River (from upstream to downstream) computed for existing and project hydrology .............................................................................................................145
Figure 65a. Computed invert profiles in American River (long-term simulations, project hydrology) ..............................................................................................146
Figure 65b. Comparison of invert profiles in American River computed for existing and project hydrology .........................................................................................147
Figure 66a. Computed invert profiles in Sacramento River (long-term simulations, project hydrology) ..............................................................................................148
Figure 66b. Comparison of invert profiles in Sacramento River computed for existing and project hydrology .........................................................................................149
Figure 67a. Computed net changes in invert elevations in American River (long-term simulations, project hydrology)........................................................................150
Figure 67b. Comparison of net changes in invert elevations in American River computed for existing and project hydrology .................................................................................151
Figure 68a. Computed net changes in invert elevations in Sacramento River (long-term simulations, project hydrology)........................................................................152
Figure 68b. Comparison of net changes in invert elevations in Sacramento River computed for existing and project hydrology .................................................................................153
Figure 69a. Computed depth to hard surface below invert in American River (long-term simulations, project hydrology)........................................................................154
Figure 69b. Comparison of depths to hard surface in American River computed for existing and project hydrology .........................................................................................155
Figure 70. Comparison of timeline progression of degradation and aggradation trends in American River computed for existing and project hydrology ......................156

Figure 71a. Computed bed volume changes in American and Sacramento Rivers (long-term simulations, project hydrology) .................................................................157

Figure 71b. Comparison of bed volume changes in American and Sacramento Rivers computed for existing and project hydrology ............................................................................158

Figure 72. Computed surface bed material gradations in American River (long-term simulations, project hydrology) .......................................................................159-161

Figure 73. Comparison of surface bed material gradations in American River computed for existing and project hydrology .................................................................162-164

Figure 74. Computed surface bed material gradations in Sacramento River (long-term simulations, project hydrology) ............................................................................165-166

Figure 75. Comparison of surface bed material gradations in Sacramento River computed for existing and project hydrology .................................................................167-168

Figure 76. Bed shear stress for cohesive materials computed for American River (1997 bathymetry) ..............................................................................................169

Figure 77. Bed shear stress for cohesive materials computed for American River (2006 bathymetry) ..............................................................................................170

Figure 78. Bed shear stress for cohesive materials computed for American River (long-term simulations, existing hydrology, final bathymetry) .......................171

Figure 79. Bed shear stress for cohesive materials computed for American River (long-term simulations, project hydrology, final bathymetry) .............................172
1. Introduction

The main objective of this study undertaken by Northwest Hydraulic Consultants (NHC) for the Sacramento District of the U.S. Army Corps of Engineers (USACE) was to investigate baseline sediment transport processes and geomorphic trends along the lower American River and to evaluate long-term impacts of the Folsom Dam Modification Project. The Folsom Dam Modification Project is revising the Water Control Manual to account for the increased release capability of the new auxiliary spillway. Changes to the controlled releases of flood waters could change the channel width and cause vertical erosion and/or deposition for the Lower American and Sacramento Rivers. The study area map is shown in Figure 1.

The present study is concerned with the American River channel vertical evolution (degradation and/or aggradation). The analysis was conducted using the updated HEC-6T sediment transport model previously developed by Ayres and Associates (Ayres 2010). The Ayres model includes a 22-mile reach of the American River below Nimbus Dam. The model geometry is based on the 1997 and 2006 bathymetric and overbank topographic survey data. The model was developed using the National Geodetic Vertical Datum of 1929 (NGVD29). Bed material in the Ayres HEC-6T model was specified using Wolman Count data obtained for the bar surface bed material in 2006. The depth of bed sediment reservoir in the Ayres model was specified using results from geophysical data available at the time of their study.

NHC extended the Ayres HEC-6T model to include the Sacramento River between Verona and Freeport in order to assess downstream changes in the American River. This reach was taken from the Sacramento River HEC-6T model previously developed by NHC (2012). The NHC (2012) model was developed using the 1997 bathymetry and NGVD29 vertical datum. The extended model of the American River was converted to the North American Vertical Datum of 1988 (NAVD88) using conversion factors provided by the USACE. The American River segment of the model was updated with surface and sub-surface bed material data collected by NHC in the study reach of the river in November 2011. Also incorporated in the model were results (locations and elevations) from the most recent geotechnical investigations of erosion-resistant materials provided by the USACE.

The model hydraulic performance was tested against stage-discharge data measured at the U.S. Geological Survey (USGS) gages and high water mark data collected after the 1997 flood event. The updated model was calibrated using measured sediment loads and observed bed changes in the American River (between 1997 and 2006) and Sacramento River (between 1997 and 2008). The calibrated model was then used to simulate long-term morphological changes in the lower American River under existing hydrologic conditions and project hydrologic conditions based on simulated operation of Folsom Dam with the new auxiliary spillway. The existing and with-project hydrology was developed by the USACE. In addition, sensitivity analyses were performed to evaluate the effects of potential widening of the American River channel on sediment transport processes and geomorphic trends in the lower American River.

This report describes the development of the HEC-6T model of the lower American River, derivation of input data used in the model, updated parameters, key assumptions, model calibration, results from existing and project conditions long-term simulations, and sensitivity
analyses of the effect of the American River channel widening. If not otherwise noted, River Miles (RMs) along the American River in this report refer to the HEC-6T stationing which is based on the 2006 channel alignment and which differs from USACE stationing. For the Sacramento River reach, the HEC-6T model and report use USACE stationing. All water surface and channel elevations reported herein are referenced to the NAVD88 vertical datum.
2. Description of Computer Model HEC-6T

HEC-6T (MBH 2009) is a one-dimensional (1-d), movable boundary, open channel flow and sediment model designed to simulate changes in river profiles resulting from erosion and deposition over fairly long time periods (typically years). Mr. William A. Thomas initiated development of this computer program at the Little Rock District of the USACE in 1967. Further development at the USACE Hydrologic Engineering Center (HEC) by Mr. Thomas produced the widely used HEC-6 generalized computer program for calculating scour and deposition in rivers and reservoirs (USACE 1993). Additional modification and enhancement to the basic program by Mr. Thomas and his associates at the U.S. Army Engineer Research and Development Center (ERDC) led to the HEC-6W program. The HEC-6T program used in this study is the product of additional modification and enhancement conducted by Mr. Thomas at Mobile Boundary Hydraulics, PLLC (MBH). The model is proprietary and can be obtained from MBH.

HEC-6T is a state-of-the-art program for use in mobile bed channels. The numerical model computations account for all the basic processes of sedimentation including erosion, entrainment, transportation, deposition, and bed compaction. The model calculates aggradation and degradation of the streambed profile over the course of a hydrologic event. It does not simulate local scour or local deposition, bank erosion, natural adjustments in channel widths, or lateral movement of the channel. When applied by experts using good engineering judgment, the HEC-6T program will provide good insight into the hydraulic and bed profile behavior of mobile bed rivers.

The channel geometry is modeled by cross sections spaced along the modeled channel. Hydraulic roughness is described by Manning’s roughness coefficients and can vary with discharge, with stationing across the cross section, and from section to section. The model uses a sequence of steady flows of variable durations to represent discharge hydrographs. For each flow a water surface profile is computed using the standard-step method to solve the energy and continuity equations thereby providing hydraulic parameters such as energy slope, velocity, depth, and wetted width at each cross section. The sediment mixture is described by a set of discrete grain size fractions for a particular reach. Potential sediment transport rates are computed for the main channel from flow parameters at each section. These rates, combined with the duration of the flow, permit a volumetric accounting of sediment within each channel reach. The amount of scour or deposition at each section is computed by means of the Exner equation for sediment continuity. The sediment computations are performed by grain size fraction thereby allowing the simulation of hydraulic sorting and armoring. Computed information includes the cumulative sediment load passing each cross section, the volume and gradation of deposits (or erosion) accumulated at each cross section from the beginning of the simulation, and the cross section elevations. In addition, sediment outflow at the downstream end of the modeled reach is computed.

HEC-6T simulates sediment transport and vertical bed changes using section-average hydraulics and it does not simulate sedimentation processes related to meandering (such as erosion of the outside bank of a bend, deposition at the point bar and bank accretion on the inside of the bend, formation of pools at the outside of the bend and riffles between channel bends). Therefore, the primary intent of HEC-6T is to simulate long-term, reach-averaged vertical changes in river profiles rather than to quantify precise values of local channel changes.
Data input requirements for the model include: (1) geometry information, including cross section geometry, cross section spacing, bridge geometry, and bed roughness; (2) hydraulic information, including a continuous sequence of flows and durations, and specification of hydraulic controls and/or boundary conditions; and (3) sediment information, including bed material characteristics, inflowing sediment loads, grain size distribution of inflowing sediments, sediment size diversion ratios, and selection of the sediment transport function to be used for simulating sediment transport.

HEC-6T is based on the following assumptions: (1) the channel is sufficiently straight and uniform in the reach so that the flow characteristics may be physically represented by a 1-d gradually varying flow model; (2) the velocity is uniformly distributed over sub sections of the cross section; (3) hydrostatic pressure prevails at every point in the channel; (4) the water surface slope is small; (5) the density of the sediment-laden water is constant over the cross section; and (6) the unsteady flow resistance coefficient is assumed to be the same as for steady flow in alluvial channels.

HEC-6T has the following restrictions: (1) the model is based on 1-d, gradually varied flow hydraulics and sediment transport theory; (2) the model does not compute the entire water surface profile for the supercritical flow case, but it does compute supercritical hydraulic parameters; (3) there is no provision for simulating the development of meanders or specifying a lateral distribution of sediment load across a cross section; (4) bed forms are not directly simulated; however, channel roughness values can be input as function of discharge, which indirectly permits consideration of the effects of bed forms; and (5) the processes and loading contributions due to bank caving are not simulated; however, it is possible to add sediment loading from bank failure to the computations.

None of these model restrictions limit the applicability of HEC-6T for evaluating sediment transport dynamics in the lower American and Sacramento Rivers. While channel planform migration cannot be reproduced in the 1-d model, the existence of levees along channel banks and absence of significant lateral channel shifting since the 1950’s (according to the Ayres (2010), NHC (2012a), and NHC (2012) bank erosion analyses) indicate that lateral processes have an insignificant impact on sediment transport, bed elevation changes, and longitudinal profile adjustment in the study reaches of the American and Sacramento Rivers.

The HEC-6T model of the lower American River (LAR) was originally developed by Ayres and Associates (Ayres 2010). The model includes a 22-mile long reach of the river and extends from just downstream of Nimbus Dam (RM 22.3) to just upstream of the confluence with the Sacramento River (RM 0.3). Stationing is based on the 2006 channel alignment. The model includes two channel geometries – one is based on the 1997 bathymetric and overbank topographic survey data and the other is based on the 2006 bathymetric survey data merged with the 1997 overbank topographic data. The Ayres model has 84 cross sections. The cross sections were placed to represent the hydraulic characteristics of the study reach and include both the main channel and overbank areas between the levees. Manning roughness coefficients in the model were taken from their previously calibrated 1992 HEC-6T model and updated with field review. The study reach of the lower American River and location of the model cross sections are shown in Appendix A.

Bed material gradations were developed from the Ayres Wolman Count data. Bed sediment reservoir depth in the model was developed from the Continuous Resistivity Profiling (CRP) geophysical data collected between RM 6.02-11.46 as part of that investigation (USGS 2008). Assumed bed sediment reservoir depths were used in areas not included in CRP testing. Erosion boundaries in the model were defined within the main channel where most of sediment load is conveyed. Deposition in the model is allowed to occur both in the main channel and overbank areas confined by project levees.

The Yang method was selected to model sediment transport through the study reach of the river. Zero sediment load (clear-water) conditions were assumed for inflows since the upstream boundary was set immediately below Nimbus Dam. The model was validated using the historic bed changes between 1997 and 2006. The validated model was then run for multiple hydrologic scenarios, including single event storms, multiple storm events over many years, and actual historic flow data to determine locations where the river is degrading and potentially threatening the levees. Downstream stage for each flow was determined from a stage-discharge rating curve provided by the USACE.

The maximum bed degradation predicted by the Ayres LAR model was about 2 ft between RM 6.9 and RM 7.8 (Guy West reach) and 1.8 ft between RM 7.9 and 10.2 (Howe Avenue to Watt Avenue reach). The model predictions were used in conjunction with the results of the Erosion Function Apparatus (EFA) testing to assess the potential for vertical and lateral channel movement. The combined HEC-6T and EFA analysis identified the reach between RM 6.9 and RM 7.3 as having particularly deep potential degradation (up to 15 ft) as reported by Ayers.
4. NHC (2012) Model of Sacramento River

Previously, NHC developed a HEC-6T model of the 98-mile long reach of the Sacramento River between Colusa (approximate RM 144) and Freeport (approximate RM 46) including the lower 9 miles of the Feather River and 22 miles of the American River below Nimbus Dam. The model was developed using cross section geometry from the USACE HEC-RAS model of the Sacramento River basin (developed as part of the Common Features Project) and from the Ayres HEC-6T model of the lower American River. Overbank bypasses were modeled as local water and sediment inflow or outflow points. Sediment initial and boundary conditions were developed using measured sediment data.

Model roughness was calibrated using measured stage-discharge data. The Laursen-Copeland method was selected to model sediment transport through the study reach of the river. The movable-bed model was calibrated using the actual changes between the 1997 and 2008 bathymetries of the Sacramento River, observed changes in stage-discharge rating curves, and measured sediment loads. The American River segment was used as in the original Ayres model, without any modifications. The calibrated model was used to simulate long-term and flood event aggradation and degradation potential along the study streams. According to the model results, the Sacramento River appeared to be generally stable, with a slight degradational trend. This trend is in agreement with stage-discharge rating curve measurements and measured bed profiles.

A portion of the Sacramento River between Verona and Freeport from the NHC (2012) HEC-6T model was used in the present study to extend the Ayres model of the lower American River. Modifications to the Ayres model implemented by NHC are discussed in detail in the following sections.
5. Lower American River Model Update

5.1. Model Extension

The downstream extent of the original Ayres (2010) LAR model is located at the confluence with the Sacramento River. Ayres determined the downstream stage for each model flow from the USACE stage-discharge rating curve. This stage-discharge relationship did not change during the simulations, which did not allow for accurate modeling of channel profile evolution in the most downstream reach of the American River.

In order to assess downstream changes in the lower American River, NHC extended the Ayres model by adding a 32-mile long reach of the Sacramento River from the Verona gage to the Freeport gage. This reach was extracted from the NHC (2012) HEC-6T model of the Sacramento River. The extended portion has 75 cross sections. The study reach of the Sacramento River and location of the model cross sections are shown in Appendix B. A model stream network schematic is shown in Figure 2.

The extended model includes two channel geometries for the American River (based on the 1997 and 2006 bathymetries) and one channel geometry for the Sacramento River (based on the 1997 bathymetry). The lower American River is the main subject of this modeling study. The Sacramento River reach was included in the HEC-6T model to eliminate the effect of the downstream model hydraulic boundary on sediment transport computations in the study reach of the American River. Accurate simulation of the bed profile in the Sacramento River reach is of secondary importance in this modeling study. Sediment transport modeling of the Sacramento River between Colusa and Freeport was previously undertaken by NHC (2012).

5.2. Datum Conversion

The original Ayres (2010) LAR HEC-6T model was developed using the NGVD29 vertical datum. NHC converted the model to the NAVD88 vertical datum (now a common datum for the USACE) using spatially variable datum conversion factors provided by the USACE (Ethan Thompson, USACE Sacramento District, personal communications). The datum conversion factor varies with location and ranges from 2.15-2.20 ft near Nimbus Dam to 2.25-2.30 ft in the mouth reach of the American River. Variation of the USACE’s datum conversion factor along the lower American River is shown in Figure 3.

NHC determined the appropriate datum conversion factor for each cross section in the LAR HEC-6T model and used it to adjust (increase) bed elevations to the NAVD88 vertical datum. The difference between the HEC-6T and USACE stationing was taken into account by comparing river miles shown on the maps in the Ayres (2010) report and in the USACE HEC-RAS model at bridge crossings and using linear interpolation when applying the USACE conversion factors. Relationship between the USACE stationing and HEC-6T stationing along the American River is shown in Figure 4. Conversion factors from the USACE stationing to HEC-6T stationing are shown in Figure 5. The 1997 and 2006 LAR cross sections converted to the NAVD88 vertical datum are compared in Appendix C.
The original NHC (2012) Sacramento River HEC-6T model uses cross sections from the USACE HEC-RAS model, which was developed from the 1997 topographic and bathymetric data collected in support of the Comprehensive Study (Comp Study). The Comp Study geometry data is close to, but not exactly in the NGVD29 vertical datum and requires its own unique spatially varied conversion factors for adjustment to the NAVD88 datum (Todd Rivas, USACE Sacramento District, personal communications). The USACE developed conversion factors for their HEC-RAS model, which are shown for the Sacramento River between Verona and Freeport in Figure 3. NHC used these conversion factors to adjust (increase) bed elevations at each cross section in the Sacramento River segments of the HEC-6T model.

5.3. Bed Material

The LAR model originally developed by Ayres (2010) uses bed material gradations developed from the Wolman Count data obtained for surface bar deposits. As a result, the model includes only gravel and cobble size particles and lacks sand-size sediment. No sub-surface material data are included in the Ayres model.

Field sampling conducted on the American River by NHC (2011) in November 2011 indicated that (1) the surface and sub-surface bed materials are mostly composed of gravels and cobbles; (2) the surface bed material is appreciably coarser than the sub-surface material; (3) the surface material contains small amounts of sand (1-8%) which cannot be measured using the Wolman Count method; and (4) significant amounts of sand (11-18%) are contained in the sub-surface material. Disruption of the armor layer during high flow events will expose finer-grained sub-surface material, which will increase sediment loading and may result in accelerated bed scour. Therefore, it was decided to include both the surface and sub-surface bed material in the model for more accurate simulation of sedimentation processes in the study reach of the river.

The NHC’s sampling data were used to update bed material composition in the LAR HEC-6T model. The measured sub-surface bed material gradations were used to specify gradations of the bed sediment reservoir in the model. Measured maximum grain size in NHC’s sub-surface bed material samples ranged from 63 mm to 100 mm. For sediment continuity, grain size distribution curves for the sub-surface bed material in the model were extended to 180 mm (maximum grain size at nearby locations from the Ayres 2010 report). Bed material gradations in the model were recalculated for size classes used in HEC-6T. The measured and modeled sub-surface bed material gradations are shown in Figure 6.

The Ayres (2010) pebble count data collected in 2006 and NHC’s surface bed material data collected in 2011 were used to specify the active layer gradations in the model. Ayres surface bed material data do not include sand. Therefore, Ayres gradations were adjusted for sand content using NHC’s sieve data for the surface material sampled at nearby locations. The measured and adjusted surface bed material gradations are shown in Figures 7 and 8, respectively. Gradations shown in Figure 8 were used to calculate percentage for each grain size class used in the HEC-6T model.

The active layer thickness in the LAR model was set to 0.6 ft and corresponded to the geometric mean of the largest grain size class in the bed material (large cobbles, grain size 128-256 mm,
median size 181 mm). This thickness is between the values of $D_{90}$ and $2D_{84}$ suggested for the surface armor layer in the literature (Parker 1991, Hoey and Ferguson 1994, Seal et al. 1998). The Exner 7 method was used instead of the default Exner 5 method for the surface layer armoring calculations in the lower American River, based on recommendations from the HEC-6T developer (William Thomas, personal communications).

Bed material gradations in the Sacramento River reach were extracted from the NHC (2012) HEC-6T model. These bed gradations were developed using field sampling data collected by NHC in October 2009 (NHC 2012). The measured bed material gradations in the Sacramento River between Verona and Freeport are shown in Figure 9. The field data indicated that bed material in the study reach of the Sacramento River is mostly composed of sand, with small amounts of silt, clay, and fine gravel. Silt and clay represent wash load, which is not present in appreciable amounts in the bed material deposits, has poor correlation with flow hydraulics, and has insignificant effect on channel morphology of these rivers (particularly the gravel-bed American River). Therefore, silt and clay were excluded from all the bed material data and were not simulated in this modeling study.

5.4. Hard Surface

Hard surface (erosion-resistant material) data were collected by Fugro Consultants in the study reach of the American River between RM 5.5 and RM 11.5 (Fugro 2012). They utilized the geotechnical boring logs and geologic survey data to develop continuous surfaces representing hard material elevations and depths from the channel bottom to the hard material. These surfaces were provided to NHC by the USACE in GIS format. According to Fugro (2012), the thickness of the hard material in the study reach is several tens of feet.

NHC used the Fugro geotechnical data to develop hard material elevation and depth profiles at locations of the HEC-6T model cross sections. Section-average hard surface elevations were determined and used to prescribe the bottom elevation of the bed material sediment reservoir in the HEC-6T model. If a hard surface average elevation at a cross section exceeded either the 1997 or 2006 invert elevation, the hard material was assumed to be 1.0 ft below the lowest invert (to provide a thin initial layer of movable bed material for sediment transport computations). For reaches with no measured hard surface data, the depth to hard surface was assumed to be 10 ft and 20 ft below the 2006 invert upstream of RM 11.5 and downstream of RM 5.5, respectively. These depth values are based on the hard surface data at the upstream and downstream ends of the measured reach.

A comparison of measured hard surface elevations and hard surface elevations adopted in the HEC-6T model for the American River reach (elevations of model bottom) is provided in Table 1. The section-average hard surface profile used in the HEC-6T model and the 1997 and 2006 invert profiles are shown in Figure 10. Also shown on this figure is the hard surface profile from the original Ayres model of the lower American River. It is seen that downstream of about RM 12 the most recent hard surface is up to 20-40 ft higher than the surface used in the original Ayres model, which may have implications for prediction of bed scour. The reason for such large differences between the previous and present hard material elevation data is not clear and may be related to measurement errors and different geophysical methods used in the field assessments.
An unlimited sediment reservoir was assumed along the study reach of the Sacramento River.

5.5. Sediment Diversion

Sediment diversion suspended sediment concentrations into the distributaries are specified as boundary conditions in the numerical model. The ratio of diverted sediment concentration to the main channel sediment concentration upstream from the diversion is specified for each sediment size class. Typically, outlet/inlet channels at diversions are at a higher elevation than the average bed of the river and draw flow from the upper portion of the water column in the river. Coarse sediment concentrations are higher at the bottom of the water column, while fine sediment is more evenly distributed in the water column. Thus, the concentration diversion ratios will be higher for finer sediment than for coarser sediment. The diversion ratio also varies with flowrate, as bed material concentration profiles become more uniform through the water column at higher flows.

Sediment outflow in the extended HEC-6T model of the American River occurs over the Sacramento Weir to Yolo Bypass. Sediment size diversion ratios at this location were determined using the Rouse (1937) equation. Comparison with the available measured suspended sediment data indicated that this equation can be used to approximately estimate sediment diversion ratios in the study area (NHC 2012). Sediment concentration diversion ratios are summarized in Table 2. Diversion ratios for gravel fractions were assumed to be 0.0.

There are no data on sediment inflow from the Natomas East Main Drainage Canal (NEMDC) which enters the Sacramento River just upstream of the American River confluence. Given that flow in the NEMDC is relatively small and occurs only occasionally, sediment inflow from the canal is expected to be insignificant and composed mainly of silt and clay (which are not modeled in this study). This assumption does not affect sediment transport processes in the American River, which is the main subject of this study.

5.6. Hydraulic Boundary Conditions

HEC-6T requires that hydraulic boundary conditions are specified at all inflow and outflow control points that bracket the study area. Upstream inflow locations in the model are the American River below Nimbus Dam and Sacramento River at Verona. Local outflow is over the Sacramento Weir to Yolo Bypass. Downstream outflow is the Sacramento River at Freeport.

A range of flows including the 1986 and 1997 flood peak flows were specified at the upstream inflow and local outflow locations for testing model hydraulic performance and sediment transport computations. Daily flow hydrographs published for the USGS gages on the American River at Fair Oaks, Sacramento River at Verona, and Sacramento Weir for Water Years (WYs) 1998-2008 (11 years) were used as upstream water inflows/local outflows for movable-bed model calibration against observed bed changes. Inflows from the NEMDC during the calibration period are unknown and were assumed to be insignificant compared to the inflows from the other sources. The WYs 1998-2008 daily hydrographs are shown in Figure 11.
The USACE developed existing and project conditions hourly hydrographs for the American River below Folsom Dam, Sacramento River at Verona, and NEMDC, and 12-hour snapshots of flow over the Sacramento Weir for WYs 1930-2002 (73 full years). The existing conditions hydrology assume regulated flow for the entire simulation period with post-Oroville Dam and Central Valley Project flow conditions in effect and reflect the existing operation of the river system. The with-project hydrology is based on simulated operation of Folsom Dam with the new auxiliary spillway which allows greater flood peak flow releases into the lower American River.

The outflows from Folsom Dam provided by USACE are estimated using the USACE Hydrologic Engineering Center's Reservoir Simulation software (HEC-RESIM) for both the existing and with-project conditions. The existing conditions outflows from Folsom Dam are from the HEC-RESIM E504 Existing Level of Demand (ELD) Reservoir Operation Set (ROS). The project outflows from Folsom Dam are from the HEC-RESIM J602P ELD ROS. The existing conditions Folsom Dam outflows are from the E504 ELD ROS dated June 9, 2015. The project condition Folsom Dam outflows are from the J602P ELD ROS dated June 10, 2015.

The project hydrology is preliminary and is being updated at the time of the preparation of this report. This modeling study used preliminary with-project hydrology due to the schedule and availability of the updated hydrology. The USACE existing and project conditions hydrographs are shown in Figures 12 and 13, respectively. The USACE hydrographs were used to specify mean daily upstream water inflows/local outflows in the HEC-6T model for long-term simulations. The simulations assumed non-failure conditions along system levees.

A stage-discharge rating curve was fitted to the USGS daily mean streamflow data published for the Sacramento River at Freeport for WYs 1997 and 1998 and used to determine downstream stages for model test runs based on the 1997 geometry (Figure 14). Daily mean stages measured in the Sacramento River at the Freeport gage during WYs 1998-2008 represented the downstream hydraulic boundary condition for movable-bed model calibration to measured bed changes. A stage-discharge rating curve developed by the USACE for the Freeport gage was used for long-term with-project simulations (USACE 2014). NHC (2012) showed that the stage-discharge rating has not changed appreciably since the 1980’s, so utilizing a time invariant stage discharge relationship for this boundary condition is reasonable for long-term simulations. The USACE stage-discharge rating data are presented in Table 3 and the rating curve is shown in Figure 15. The USACE rating curve represents an average downstream boundary for a given flow over the course of an average water year (USACE 2014).

The Sacramento River at Freeport is subject to tidal action at low flows. However, the downstream model boundary is located sufficiently far (about 14 miles) from the American River confluence and therefore is assumed to have insignificant effect on sediment transport and morphological processes in the study reach of the American River (the main subject of this modeling study). Since little bed material is mobilized during low flow conditions this modeling assumption has little effect on the long-term bed profile adjustments computed by HEC-6T.

It must be remembered that HEC-6T does not hydrodynamically route flood waves. The model uses a sequence of steady flows of variable durations to represent discharge hydrographs and applies the standard-step method to solve the energy and continuity equations for open channel
flow. In large river systems (such as the American and Sacramento Rivers), such a numerical approach may result in some discrepancies between actual and model flows at a given instance, especially for large and relatively short duration flood events. However, given that in the long term most sediment is transported by channel forming flows (which typically have a recurrent interval of 1.5-2 years), this model assumption will have a relatively insignificant effect on the simulation of long-term sedimentation processes.

Monthly average water temperatures developed in NHC (2012) were used for each inflowing/outflowing water discharge for model calibration and long-term simulations.

5.7. Computational Time Step

The computational time step needs to be short enough so that changes in bed elevation, due to deposition or erosion, do not significantly change the hydraulic parameters during the event. In this study a computational time step of 0.001 day was used for calculation of instantaneous transport rates in model test runs and one day was used for calibration runs and long-term simulations. A one-day time step is not necessary to meet the requirement of insignificant bed change, but was chosen for convenience, because flow data used in the model for calibration runs and long-term simulations were reported as mean daily flows.

5.8. Exchange Increment

The sorting and armoring time interval or exchange increment (SPI) is the parameter that determines how many times the Exner equation is solved during the computational time step. If sediment transport capacity is greater than the sediment load entering the control volume defined by the upstream and downstream cross sections, sediment (if available) is removed from the bed to satisfy bed material continuity. Since sediment transport capacity for a given size class depends on the fraction of that size class on the bed, it is necessary to frequently recalculate fractions present as sediment is exchanged with the bed. The HEC-6T program will calculate SPI as a function of the computational time step $\Delta t$, average channel velocity $V$, and the reach length $\Delta L$: $SPI = \frac{\Delta t V}{\Delta L}$. Usually, the number of exchange increments can be less than calculated using this equation without inducing bed change and sediment yield oscillations from one time step to the next. Fewer exchange increments relates to less computational intensity, i.e. shorter computer runs. The original Ayres model used $SPI=20$, which is usually satisfactory (according to the HEC-6T manual). In this study SPI=50 was used for greater numerical stability. The same SPI=50 was previously used in the Sacramento River HEC-6T model (NHC 2012).

5.9. Sediment Transport Function

The following sediment transport functions were selected for testing against the observed sediment loads and bed changes in the study reaches of the American and Sacramento Rivers:

(1) Yang (1973, 1984)
(2) Toffaleti (1969) – Meyer-Peter and Muller (1948) combination
(3) Wilcock (Wilcock and Crowe 2003)
(4) Laursen-Copeland (Copeland and Thomas 1989)
These transport functions were developed using both sand and gravel data. The Yang, Toffaleti and Meyer-Peter and Muller combination (Toffaleti-MPM), and Laursen-Copeland functions compute the total bed material load (suspended load plus bed load). The Wilcock function computes bed load only. Although some of these functions were developed to compute bed material load using a median grain size, all have been modified in HEC-6T to calculate sediment transport by size class as advocated by Einstein (1950).

The USACE (1994) provides tentative guidance for sand and gravel-bed rivers based on experience at the USACE Waterways Experiment Station and various USACE Districts, primarily with simulations involving the HEC-6 computer program. Recommended sediment transport functions are the Yang function and Toffaleti-MPM combination. Therefore, these two functions were selected for the present analysis. The Yang function was used in the original Ayres HEC-6T model and demonstrated reasonable agreement with the observed bed changes. The Wilcock function was selected because it was specifically derived for sand/gravel mixtures and accounts for inter-granular effects in mixed-size sediment. The Laursen-Copeland function was selected because it was used in the NHC (2012) Sacramento River Basin HEC-6T model and showed good agreement with the measured sediment load and bed changes in the Sacramento River.

5.10. Upstream Sediment Inflow

HEC-6T requires that sediment inflows are specified for all the upstream boundaries. Similar to the original Ayres model, zero sediment load (clear-water) conditions were specified at the upstream boundary on the American River, which is located immediately below Nimbus Dam. It is assumed that all the bed material inflow from the upper watershed is trapped upstream of Nimbus and Folsom Dams and therefore sediment transport in the lower American River is generated only from the river bed itself.

Sediment transport data collected at the Verona gage by the USGS between 1979 and 1998 and by NHC in 2010 (described in the NHC (2012) report) are insufficient to define the upstream bed material inflow for the Sacramento River reach. According to the NHC (2012) analysis, the Verona stage-discharge rating curve shows no significant change over the last several decades, which indicates that this location is in overall state of equilibrium with respect to bed profile adjustments. Therefore, the NHC (2012) Sacramento River HEC-6T model was used to develop a sediment inflow rating curve at Verona. The NHC (2012) model was based on the Laursen-Copeland transport function and reasonably replicated sediment transport processes in the Sacramento River.

Daily total bed material loads at Verona computed by the NHC (2012) HEC-6T model for the 11-year period 1997-2008 are shown in Figure 16. Computed daily total bed material load gradations are shown in Figure 17. The scatter in the computed data is quite typical and reflects the complexity of natural sediment transport processes. The power regression equation calculated in EXCEL for the total bed material load data computed by the NHC (2012) model was used to develop an average sediment inflow rating curve at Verona. A statistical correction factor was applied to the regression equation to account for bias created by using a least-squares regression (similar to the NHC (2012) study). Linear regression equations were calculated for the size class fractions. These regression equations were used to determine average gradations for sediment inflows at Verona.
6. Model Calibration and Verification

Calibration is the process of selecting model parameters and sediment transport functions that allow the model to reconstitute measured stages, sediment loads, and trends in bed aggradation and degradation. The following sections describe calibration and verification procedures used for the sediment transport model of the lower American River developed in this study. The calibration procedure adopted for this study is generally based on the accepted USACE methodology described in HEC (1992) and Chapter 14 of ASCE Manual 110 (ASCE 2008). The calibration included the following steps: (1) fixed-bed, steady flow tests; (2) movable-bed, steady flow tests; and (3) movable-bed, quasi-unsteady flow test. These tests are discussed below.

6.1. Fixed-Bed, Steady Flow Tests

The fixed-bed test included verification of channel and overbank roughness coefficients specified for the American River by Ayres (2010) and Sacramento River by NHC (2012). Manning roughness coefficient in the Ayres (2010) model of the American River ranges from 0.035 to 0.04 for the main channel and is 0.07 for overbank areas. For comparison, roughness coefficients in the lower American River in the USACE basin-wide HEC-RAS model range from 0.0359 to 0.0512 for the main channel and from 0.0461 to 0.0871 for overbank areas. In the NHC (2012) model, roughness coefficient in the Sacramento River between Verona and Freeport ranges from 0.025 to 0.035 for the main channel and from 0.04 to 0.08 for overbank areas. Table 4 summarizes the roughness coefficients in the modeled reaches.

To verify model roughness coefficients, water surface elevations were computed with the HEC-6T model for a range of flows under fixed-bed conditions. Model tests were conducted using the 1997 channel geometry for both the American and Sacramento Rivers. Therefore, roughness coefficients for these rivers were verified using streamflow data measured in WYs 1997 and 1998. The following gages were used to verify model roughness coefficients:

- American River at Fair Oaks (USGS gage 11446500) at RM 22.3
- Sacramento River at Verona (USGS gage 11425500) at RM 78.8
- Sacramento River at I Street Bridge (Department of Water Resources (DWR) gage IST) at RM 59.7
- Sacramento River at Freeport (USGS gage 11447650) at RM 46.4

Stages from these gages were converted to the NAVD88 vertical datum using conversion factors provided in USACE (2013). Comparison of measured and computed stage-discharge relationships is shown in Figure 18. The computed water surface elevations are generally within 0.5 ft of the measured stage-discharge relationships. According to HEC (1992), such accuracy of hydraulic calculations is usually satisfactory for movable bed studies of natural rivers.

An additional test run was performed for the January 2-3, 1997 flood event. During this event, the peak flow was 117,000 cfs in the American River at Fair Oak, 102,000 cfs in the Sacramento River at Verona, 116,000 cfs over the Sacramento Weir Spill to the Yolo Bypass, and 115,000 cfs in the Sacramento River at Freeport. However, these peak flows were not coincident. According to the streamflow data published by the USGS and Department of Water Resources (DWR), peak flow
in the American River occurred about half a day earlier than in the Sacramento River at Verona and about a day earlier than in the Sacramento River at Freeport. Therefore, separate test runs were conducted to simulate flood peak profiles in the American and Sacramento Rivers. Model test for the American River was conducted using the published peak flow of 117,000 cfs. According to the observed streamflow data included in the USACE basin-wide HEC-RAS model, flows in the American River in the evening of January 2, 1997 and morning of January 3, 1997 were around 106,000 cfs – this value was used to compute flood peak profiles in the Sacramento River reach.

Water surface elevations computed for the 1997 flood event are shown in Figure 19. Also shown in this figure are observed high water marks and peak stages measured at the USGS gages. The high water marks were extracted from the USACE basin-wide HEC-RAS model and re-projected to the HEC-6T stationing along the American River using conversion factors shown in Figure 5.

The difference between the computed peak stages and observed high water marks along the lower American River range from about 0.1 to 1.0 ft and is generally less than 0.5 ft. The scatter in the high water marks measured at several adjacent locations (near RMs 3.9, 6.6, 7.1, and 7.8) is up to almost 1.0 ft. Therefore, the difference between the computed and observed water surface elevations is generally within the measured data noise.

The peak water surface elevation computed for the American River at the Fair Oaks gage for the 1997 flood is about 2.4 ft higher than the measured peak stage. The reason for such a difference is not clear. It should be noted that the peak stage computed at this location by the USACE HEC-RAS model (which was calibrated to the 1997 flood event) is about 7 ft higher than the HEC-6T model. At the same time, the HEC-6T model shows reasonable agreement with the high water marks observed on the American River at about RM 20. Overall, the roughness coefficients specified by Ayres (2010) in the HEC-6T model are satisfactory for the purpose of sediment transport analysis.

The 1997 peak water surface profile computed for the Sacramento River generally follows the rather scattered high water marks. Exception is the most downstream 5 miles of the study reach, where computed stages are consistently 0.5-1 ft higher than the observed high water marks. The reason for this discrepancy is that the downstream water surface elevation in the model was specified using the peak stage observed at the Freeport gage, which appears to be about 0.6 ft higher than adjacent high water marks. At the same time, computed peak stage at the Verona gage is very close to the observed stage. Given that the peak flows in the study reach of the Sacramento River did not occur at all sites simultaneously and that this reach in the HEC-6T model essentially acts as a receiving reservoir for the flows and sediment from the American River (which is the main subject of this modeling study), the overall hydraulic performance of the Sacramento River portion of the model is reasonable.

In addition to reconstituting the measured water surface elevations, water surface profiles, channel discharge profiles, and channel velocity profiles in the study reach of the American River were also analyzed for a range of discharges to ascertain that the model was producing acceptable hydraulic results and to identify reaches where instability might occur. Computations were conducted using USGS streamflow and stage data measured during the 1986 and 1997 flood events. Flows selected for the analysis range from 24,400 cfs to 131,000 cfs for the American
River at Fair Oaks, from 21,400 cfs to 94,700 cfs for the Sacramento River at Verona, and from 0 cfs to 96,100 cfs over the Sacramento Weir to Yolo Bypass.

The water surface profiles computed for the American River (see Figure 20) generally follow the invert profile and show an abrupt change in longitudinal slopes at rapids at about RM 13.5. The average water surface slope is about 0.0008-0.0010 upstream of the rapids and reduces to 0.0001-0.0004 downstream of the rapids.

The water surface profiles computed for the Sacramento River between Verona and Freeport (see Figure 21) are relatively uniform, with the average slope of less than 0.0001.

The channel discharge plots are used to identify reaches with significant overbank flow. Sediment transport is calculated using channel hydraulic parameters and an abrupt reduction in channel discharge could lead to significant aggradation. The channel discharge profiles computed for the American River (see Figure 22) indicate that flows less than about 30,000 cfs are mostly contained in the channel, while higher flows overtop channel banks and inundate overbank areas. Large decreases in channel discharge occur at high flows at RMs 4-6, 12-13.5, and 17-19, where there is significant overbank flow.

The channel discharge profiles computed for the Sacramento River between Verona and Freeport (see Figure 23) indicate that flow is contained in the channel for the full range of tested discharges. Reduction of discharge between the Sacramento Weir (RM 63.5) and American River confluence (RM 60.5) computed for flows of 79,500 cfs and 94,700 cfs is due to outflow over the Sacramento Weir to Yolo Bypass.

Channel velocity profile plots are used to identify reaches where significant changes in velocity occur. Spikes in computed channel velocity may lead to numerical channel instability. The channel velocity profiles computed for the American River (see Figure 24) indicate overall increases in channel velocity at RMs 6-7, 10, 14, 15.7, 16.5, 19.8, 20.6, and 22.1. The main channel at these locations tends to be more confined which results in the increased velocity and may be indicative of the potential for channel erosion.

The channel velocity profiles computed for the Sacramento River between Verona and Freeport (see Figure 25) do not show significant velocity spikes for flows below 50,000-60,000 cfs. At the higher flows, the Sacramento Weir was open and there is a significant reduction in stream velocities between the Sacramento Weir (RM 63.5) and American River confluence (RM 60.5). When outflow over the Sacramento Weir exceeds inflow at Verona, a portion of flows from the American River is conveyed upstream to the Sacramento Weir.

6.2. Movable-Bed, Steady Flow Test

The USACE methodology suggests running a steady bankfull flow test with a movable bed for rivers in regime. However, the American River is not in regime because upstream sediment supply is interrupted by Nimbus and Folsom Dams. The stage-discharge data for the Fair Oaks gage analyzed in NHC (2012) suggest continuing channel degradation below Nimbus Dam.
NHC conducted computations of instantaneous bed material loads for a range of flows and initial bed material gradations to evaluate performance of the sediment transport functions selected for testing. HEC-6T does not allow use of different transport functions for different segments within a river network. Therefore, each function was tested for both the gravel-bed American River and sand-bed Sacramento River. As mentioned previously, wash load (silt and clay) was excluded from the computations. For comparison purposes, it was assumed that suspended bed material load in the American River consists of sand (grain size 0.062-2 mm) and bed load primarily consists of gravel (grain size 2-64 mm) and cobbles (grain size 64-256 mm). Some coarse sand can be transported as bed load (mainly at low flows), but its amount is likely to be relatively small compared to suspended sand load and will not affect model testing results. According to the USGS measurements (discussed in NHC (2012)), suspended bed material load in the study reach of the Sacramento River primarily consists of fine to medium sand (grain size 0.062-0.5 mm). Coarse sand was assumed to be transported mainly as bed load.

Suspended bed material loads computed for the 1997 channel geometry are compared with the limited USGS data measured in the American River at the Sacramento gage at RM 6.6 in Figure 26. No measured transport data by size class are available for this gage. The measured data indicate that very small amount of suspended sand (less than 15 tons per day) is transported at flows less than 10,000 cfs. The Toffaleti-MPM combination and Laursen-Copeland functions tend to overestimate suspended sand loads at these flows. The Yang transport function envelops the highest measured data, while the Wilcock function shows practically no sand load for flows less than 10,000 cfs.

Bed loads (gravel and cobble) computed at this location are compared in Figure 27. There are no measured bed load data. The Yang, Wilcock, and Laursen-Copeland functions show generally similar results for bed loads. The Toffaleti-MPM combination shows an order of magnitude higher bed load at low flows compared to the other functions tested. Computed bed loads by size class (particularly for very fine gravel and cobbles) vary significantly depending on the transport equation used. However, there are no measured data to verify computed bed loads.

Suspended bed material loads computed for the Sacramento River are compared with the USGS and NHC data measured at the Verona, Sacramento, and Freeport gages in Figures 28-30. The collection of the NHC’s sediment data is described in the NHC (2012) report. Reasonable agreement with the measured data is shown by the Toffaleti-MPM and Laursen-Copeland transport functions. The Yang function tends to underestimate transport of fine and very fine sand at Sacramento and Freeport. The Wilcock functions significantly underestimates bed material loads along the entire Sacramento River reach.

The performance of the sediment transport functions was further tested during movable-bed, quasi-unsteady flow test discussed below.

6.3. Movable-Bed, Quasi-Unsteady Flow Test

The movable-bed model developed for the lower American River was tested using each of the four selected sediment transport methods against the actual changes in channel bed between 1997 and 2006. The actual bed changes were approximately determined by comparing the 1997 and 2006
model geometries developed by Ayres (2010) from the bathymetric and overbank survey data (see Appendix C). The model was run using the 1997 starting geometry and continuous daily flow hydrographs (shown in Figure 11) and daily stages determined from the USGS data for WYs 1998-2006.

The model performance for the Sacramento River reach was tested against observed bed changes between 1997 and 2008 and sediment yield measured at Freeport. Bed changes were determined by comparing the 1997 and 2008 topographic data (see Section 3.3 in Chapter 3 in NHC (2012)). The model was run using the 1997 starting geometry and daily streamflow data from the USGS gages for WYs 1998-2008.

**6.3.1. Bed Material Transport**

The total bed material yields computed for the lower American River (1997-2006) and Sacramento River (1997-2008) are shown in Figures 31 and 32, respectively. The bed material yield measured in the Sacramento River at Freeport during 1997-2008 (as determined in NHC 2012) is also shown in Figure 32. Bed material yields computed for the Sacramento River at Freeport are compared with the measured data in Table 5. Total bed material deposition computed for the study reaches of the American and Sacramento Rivers is shown in Figures 33 and 34, respectively. The cumulative bed material deposition computed for the American and Sacramento Rivers is shown in Figures 35 and 36, respectively.

Of the four transport functions tested, the Laursen-Copeland function shows the greatest bed material yield and bed material erosion/deposition volumes in the lower American River between 1997 and 2006, while the Wilcock function shows the lowest bed material yield and bed material erosion/deposition. There are no measured sediment transport data to verify bed material yields computed for the lower American River. All the transport functions show predominant bed material erosion in the upstream reach (between RMs 13-22) and deposition in the downstream reach (between RMs 0-13) of the lower American River.

For the Sacramento River between Verona and Freeport, the greatest bed material yield between 1997 and 2008 is shown by the Laursen-Copeland transport function and the lowest yield is shown by the Wilcock function. The Laursen-Copeland function predominantly shows bed material erosion between Verona and the Sacramento Weir (RMs 63-79) and deposition between the Sacramento Weir and Freeport (RMs 46-63). The Toffaleti-MPM function shows no significant change upstream and deposition downstream of the American River confluence. The Yang function predominantly shows deposition along the entire study reach of the Sacramento River, particularly downstream of the American River. The Wilcock function shows unrealistically high deposition between Verona and the American River and little change downstream of the American River confluence.

The measured bed material yield in the Sacramento River at Freeport during the 11-year period is 5.6 million tons, the average annual amount being 0.51 million tons/year. The computed bed material yields at this location range from 0.6 to 6.6 million tons, with average annual values ranging from 0.05 to 0.60 million tons/year. The Yang and Wilcock transport functions underestimate bed material yield by about 37% and 89%, respectively. The Laursen-Copeland
function overestimates bed material yield by about 18%. The best agreement with the measured bed material yield at Freeport is shown by the Toffaleti-MPM combination.

The difference between the measured and computed sediment yields can be related to the overall complexity of natural fluvial sediment transport (which is difficult to model one-dimensionally), insufficient accuracy of existing sediment calculation methods, and measurement errors. Existing sediment calculation methods provide a very simplistic representation of actual sediment transport phenomenon. Most methods are based on experimental flume data, are derived for uniform sediment and do not account for size-fraction interaction in mixed-size sediments (reduced mobility of fine fractions due to shielding from coarse grains and increased mobility of coarse grains due to greater exposure to flow compared to uniform sediment). Existing sediment transport methods also do not account for sediment transport by means of spatial evolution of various channel forms (meanders and bars). Published assessments of different sediment transport formulas (e.g. Gomez and Church 1989, Nakato 1990, Barry et al. 2004) indicate that the current state of knowledge of sediment transport phenomenon is such that error of sediment transport prediction of up to 25-50% can be considered as reasonable.

6.3.2. Invert Profile

Measured and simulated invert profiles are compared for the American River in Figure 37 and for the Sacramento River in Figure 38. Measured and computed net changes in invert elevations in the American and Sacramento Rivers are compared in Figures 39 and 40, respectively.

Measured net changes in the American River between 1997 and 2006 range from about 5 ft of aggradation to 16 ft of degradation. According to Ayres (2010), areas of major differences between the 1997 and 2006 profiles are regions where the channel has shifted laterally or where there were gaps in the 1997 survey data. In general, however, the channel profile has not significantly changed over the 9-year period.

The variability in the measured channel changes in the American River appears to be greater compared to the simulated channel changes. This variability in the measured data is likely related to localized channel scour/aggradation and lateral channel shifts. HEC-6T is a 1-d model primarily designed to predict vertical bed changes and does not simulate lateral channel shifts. The overall trend in invert profile predicted by all the four transport methods appears to be in agreement with the measured data.

For the Sacramento River, measured net changes in invert elevations between 1997 and 2008 range from about 12 ft of aggradation to 9 ft of degradation. The measured data reveal highly non-uniform distribution of aggradation and degradation areas. However, despite the generally noisy channel bed evolution pattern, the channel of the Sacramento River between Verona and Freeport appears to be in an overall slight degradational state.

Changes in the Sacramento River invert profile computed using the Yang, Toffaleti-MPM, and Laursen-Copeland transport functions are in overall agreement with the measured data. The Wilcock transport method shows excessive aggradation in the upstream part and reasonable agreement with the measured data in the downstream part of the study reach.
It should be noted that the invert represents the deepest locations in cross sections and therefore measured changes in invert elevations may not accurately represent overall morphological changes (i.e. decrease in invert elevation in a cross section may be accompanied by aggradation in other areas of the cross section, and vice versa). Therefore, model performance was evaluated against measured changes in bed volumes. These results are discussed below.

6.3.3. Bed Material Volume

Measured and computed net changes in bed volumes in the American River (between 1997 and 2006) and Sacramento River (between 1997 and 2008) are compared for different sub-reaches in Figure 41 and summarized in Table 6.

For the lower American River, the measured data show a general degradational trend in the upper reach approximately between RMs 13-22 and an aggradational trend downstream of RM 13. The greatest degradation is observed between RMs 20-22 (129,000 cubic yards) and the greatest aggradation is observed between RMs 0-5 (183,000 cubic yards). In general, the channel of the lower American River appears to be in an overall slight degradational state. The total measured degradation volume in the lower American River downstream of Nimbus Dam between 1997 and 2006 is about 10,000 cubic yards, with is equivalent to about 0.01 ft of reach-average depth of bed degradation.

The bed volume changes simulated for the lower American River by the Yang, Toffaleti-MPM, and Laursen-Copeland transport methods generally follow the measured data trend. The Wilcock method shows unrealistically low bed volume changes. For the entire reach downstream of Nimbus Dam, the Yang method shows about 2,000 cubic yards of degradation, Toffaleti-MPM combination shows 30,000 cubic yards of degradation, Laursen-Copeland method shows 64,000 cubic yards of degradation, and Wilcock method shows 3,000 cubic yards of degradation. The Yang, Toffaleti-MPM, and Laursen-Copeland methods generally show reasonable agreement with the measured bed volume changes.

For the Sacramento River, the measured data demonstrate a predominantly degradational trend between RMs 64-79 and predominantly aggradational trend downstream of RM 79. The greatest degradation is observed between RMs 75-79 (1,350,000 cubic yards) and the greatest aggradation is observed between RMs 55-60 (1,010,000 cubic yards). Overall, the channel of the Sacramento River between Verona and Freeport is in a slight degradational state. The total measured degradation volume in this reach between 1997 and 2008 is 890,000 cubic yards, which is equivalent to about 0.23 ft of reach-average depth of bed degradation.

The bed volume changes in the Sacramento River reach computed using the Yang, Toffaleti-MPM, and Laursen-Copeland transport functions generally follow the observed data. All these transport methods tend to underestimate channel degradation between RMs 65-79 and show reasonable agreement with the measured data between RMs 46-65. The Wilcock method shows unrealistically high deposition of the bed material along the entire study reach of the Sacramento River. For the entire reach between Verona and Freeport, the Yang method shows 3,240,000 cubic yards of aggradation, Toffaleti-MPM shows 1,540,000 cubic yards of aggradation, Laursen-Copeland
method shows 870,000 cubic yards of degradation, and Wilcock method shows 5,590,000 cubic yards of aggradation. The Laursen-Copeland function shows the best overall agreement with the observed bed changes in the Sacramento River reach.

The Toffaleti-MPM and Laursen-Copeland transport functions were also tested in the NHC (2012) modeling study and generally showed similar results. Some differences in the computed bed volumes between the NHC (2012) and present study is due to the different model extents and different upstream sediment inflow boundaries. The NHC (2012) system-wide model was developed to provide the best correspondence between the measured and simulated sediment loads and morphological changes for a large and complex area which included the Sacramento River between Colusa and Freeport, Feather River downstream of Nicolaus, American River downstream of Nimbus Dam, and portions of Sutter and Yolo Bypasses. In the NHC (2012) modeling study the sediment discharge rating curve at Verona was not constant (as in the present study) and varied depending on complex interaction of sediment inflows from several tributaries and overbank bypasses, as well as bed sorting and associated transport processes. Also, a different sediment inflow from the American River (which did not have sand bed material in the previous model) was utilized in the NHC (2012) study. In general, however, morphological changes in the Sacramento River between Verona and Freeport simulated by the NHC (2012) system-wide model and the present model are quite similar.

### 6.3.4. Bed Surface Gradation

Initial and final bed material surface gradations computed by the four sediment transport functions are shown for selected cross sections in the American and Sacramento Rivers in Figures 42 and 43, respectively. For most locations, computed final surface bed material gradations generally do not differ significantly from the initial gradations. All the sediment transport functions show quite similar prediction of bed surface gradations.

Initial gradations used in the model for the test run are based on the bed material sampling data collected by Ayres in 2006 and NHC in 2009 and 2011. Actual bed material gradations in 1997 (start of model calibration period) are not known. However, comparison of the present-day and historic bed material data (reviewed for the American River in NHC (2011) and Sacramento River in NHC (2012)) did not reveal obvious trends (coarsening or fining) with time over the last several decades. This justifies the use of the present-day bed material data to describe the 1997 bed conditions.

### 6.4. Sediment Transport Function Selection

The model test runs demonstrate that none of the transport functions used in the model provide a perfect fit to all the observed data. The Yang sediment transport function generally provides reasonable prediction of sediment loads and bed changes in the American River, but tends to underestimate sediment loads and bed degradation in the Sacramento River. The Toffaleti-MPM and Laursen-Copeland functions provide reasonable prediction of sediment loads in the Sacramento River and satisfactorily replicate observed bed changes in the study reaches of the American and Sacramento Rivers. The Wilcock transport function significantly underestimates sediment loads and shows unrealistic bed changes in both the American and Sacramento Rivers.
It should be noted that the study reaches of the American and Sacramento Rivers are very different, particularly with respect to the channel slope and size of the bed material. The bed material mostly consists of gravel in the American River and is almost entirely sand in the Sacramento River. HEC-6T uses a single transport function for different river segments to prevent discontinuities in the solutions. Therefore, a transport function may show reasonable results for gravel-bed material and poor performance for sand-bed material, and vice versa. Also, it should be remembered that channel degradation or aggradation are caused by the imbalance between inflowing and outflowing sediment and not the magnitude of sediment load. As a result, a transport function may overestimate sediment load magnitude, but show reasonable agreement with bed changes observed over relatively short time periods.

The main subject of this modeling study is the lower American River, while the Sacramento River reach was added to provide a more accurate simulation of the time-variant characteristics in the mouth reach of the American River. Accurate simulation of the bed profile in the Sacramento River is of secondary importance in this modeling study. However, simulated morphological changes in the Sacramento River reach ideally should be consistent with the NHC (2012) system-wide modeling study.

According to the NHC (2012) study and results from the present model test runs, the Laursen-Copeland sediment transport method provides the best overall fit with the observed sediment loads and bed changes in the Sacramento River and shows reasonably conservative predictions of sediment loads and bed degradation in the American River. Given that channel degradation and scour of erosion-resistant materials in the American River is one of the main concerns for the USACE in the analysis and design of flood control improvements on the lower American River, the Laursen-Copeland function was selected for the subsequent long-term simulations to provide conservative estimates of channel scour.
7. Channel Widening

One of the tasks of this modeling study included a sensitivity analysis of simulated long-term bed morphological adjustments to potential channel widening in the lower American River. For a given water discharge, widening of the channel will reduce flow depth and, at the same time, increase active bed width. Combined effect of these opposing factors on sediment load is site-specific and depends on local bed material characteristics, channel geometry, and bed slope.

According to the Ayres (2010) and NHC (2012a) bank erosion analyses, the study reach of the American River had not exhibited significant lateral shifting due to natural river processes from 1957 to 2010 (a total of 53 years). Large shifts (over 200 ft) in bankline location were the result of historic sand and gravel mining operations. In areas unaffected by sand and gravel mining, banklines had not shifted more than 1/20th of one channel width or about 25 ft.

Therefore, it was decided to conduct HEC-6T sensitivity analysis with the channel width in the entire study reach of the American River increased (1) by 25 ft on both channel sides (50 ft total channel widening) and (2) by 50 ft on both channel sides (100 ft total channel widening). These values bracket long-term channel width adjustments that may occur during the modeled 73-year long period, based on the observed historic bank migration.

NHC modified the 2006 geometry previously developed for the American River by Ayres (2010) to account for the 50-ft and 100-ft widening. Channel widening for most cross sections was accomplished by moving both left and right channel banks away from the river by 25 ft and 50 ft, respectively. In the upper 6 miles of the study reach where the right bank is composed of erosion-resistant materials, the left bank was moved by 50 ft and 100 ft, respectively. Bank stations, erosion limits, and lateral distribution of roughness coefficients in the HEC-6T model were adjusted accordingly.

The modified channel cross sections are shown in Appendix D. These cross sections were used for sensitivity analyses for both the existing and project hydrology simulations.
8. Existing Hydrology Model Results

This chapter discusses HEC-6T model results from long-term movable-bed simulations (WYs 1930-2002) using the existing conditions inflow hydrographs. The results include the existing starting channel geometry and widened (by 50 ft and 100 ft) channel of the lower American River. Discussion of the effect of the American River widening is presented in Chapter 11.

8.1. Bed Material Transport

Total bed material yields computed for the existing hydrology for WYs 1930-2002 are shown for the study reaches of the American and Sacramento Rivers in Figures 44 and 45, respectively. Computed bed material transport varies along the study reaches in response to local geomorphic, hydraulic, and sediment supply conditions. In the lower American River, computed bed material transport rapidly increases in the sediment supply-deficient reach downstream of Nimbus Dam until about RM 14 and gradually reduces downstream of RM 14. In the Sacramento River, bed material transport generally increases from Verona to the Sacramento Weir and declines between the Sacramento Weir and Freeport.

Computed total bed material deposition in the American and Sacramento Rivers is shown in Figures 46 and 47, respectively. Negative values in these figures indicate channel degradation. Computed cumulative (from upstream to downstream) bed material deposition is shown for the American River in Figure 48 and for the Sacramento River in Figure 49. Model results show highly variable deposition/degradation pattern which reflects varying sediment transport capacity and sediment availability along the study reaches. In general, a predominantly degradational trend is obtained for the lower American River upstream of about RM 14 and an aggradational trend downstream of RM 14. Bed material eroded from the upstream reach of the American River is transported to and partially deposit in the downstream reach. In the study reach of the Sacramento River, predominant degradation is obtained upstream of the Sacramento Weir and predominant aggradation downstream of the weir. For the entire study reaches, net overall erosion is obtained for the lower American River and net deposition for the Sacramento River between Verona and Freeport.

8.2. Invert Profile

Simulated invert profiles in the American and Sacramento Rivers are shown in Figures 50 and 51, respectively. Simulated long-term changes in invert elevations are shown for the American River in Figure 52 and for the Sacramento River in Figure 53. Computed depths to hard surface below the American River invert (or thickness of movable-bed deposits) are shown in Figure 54. A timeline progression of degradation and aggradation trends in the lower American River is shown for selected cross sections in Figure 55.

Simulated changes in invert elevations vary significantly along the study reaches of the American and Sacramento Rivers. This variability is attributed to complex channel adjustments in the model caused by a variety of factors including local channel geometry, successive wetting and drying of different parts of the river channel during high and low flow periods, varying sediment transport.
capacity at different flows, and alternating aggradation and degradation processes in different parts of the channel during different flow periods.

The model results indicate that the upstream part of the 22-mile long study reach of the American River is actively degrading. The greatest channel invert degradation occurs in the 3-mile long reach downstream of Nimbus Dam. Upstream sediment supply on the American River is interrupted by Folsom and Nimbus Dam, which results in channel degradation below the dams. Computed maximum invert degradation in this reach is about 8-10 ft. Active invert degradation (up to 4-7 ft) is also computed between RMs 12-19 and between RMs 5.5-7. Up to 2-3 ft of localized invert aggradation is computed in between RMs 10.5-11.5, at RM 6.7, and at RM 5. The lower 4 miles of the American River are in a slight aggradational state, with 1-3 ft of localized invert aggradation. The results from the updated model of the lower American River are generally consistent with the original Ayres (2010) model.

The degradation trends simulated for the American River are relatively constant in reaches with thick bed material deposits and become asymptotic when approaching the hard material surface. The degradation accelerates abruptly during high flood events and slows down during low flow periods. A continuous but slow aggradation trend is obtained for the mouth reach of the American River.

It should be noted that the channel of the lower American River is highly irregular at many locations (especially at RMs 5.5, 10-11, 12-13.5, and 18-19.4). These irregular reaches may not be adequately represented in the 1-d HEC-6T model. Therefore, results obtained for the irregular reaches may be subject to simulation errors and should be treated with caution. In general, however, degradational trends predicted by the model immediately below Nimbus Dam agree with the USGS stage-discharge records obtained for the American River at Fair Oaks which show ongoing channel degradation (NHC 2012).

Potential implication of the simulated long-term changes in the American River bed profile can be increased stress along the toe of the project levees in the degradational reaches, which may result in increased scour along unrevetted channel sections. In the aggradational reaches, increase in bed elevations may result in higher flood stages and reduced flood conveyance. It should be noted that this study does not consider risk to project levees from other sources such as boat wakes, wind waves, local scour at tree roots or fallen trees, etc.

The model results indicate potential erosion to the hard surface in the American River between RMs 6.9-7.5, between RMs 9-10.5, and at RM 20.6. The latter location is uncertain as the hard surface elevations upstream of RM 11.5 were not measured and were assumed to be 10 ft below the 2006 invert (for the purpose of this modeling study).

Overall long-term changes in the American River invert profile simulated by the present updated model are generally consistent with the results from the NHC (2012) system-wide model. Both models show active degradation (on the order of 5-10 ft) in the upper reach between Nimbus Dam and RM 12. However, the present model show less degradation in the lower 8 miles of the study reach compared to the NHC (2012) system-wide model. The difference in the simulated
morphological changes in the lower American River is related to the different bed materials and different hydrology used in the models.

Simulated long-term changes in the Sacramento River invert profile range from about 2-3 ft of degradation to 3-8 ft of aggradation. An overall slight degradational trend is simulated between Verona and the Sacramento Weir and a slight aggradational trend is simulated between the weir and Freeport. In general, however, the study reach of the Sacramento River appears to be stable and most morphological changes are associated with infilling of deep pools and scour of elevated riffles. Long-term changes in the Sacramento River invert profile obtained in this study are generally similar to those simulated for this reach by the NHC (2012) system-wide model.

The computed changes in invert elevations in the study reaches of the American and Sacramento Rivers (Figures 52 and 53) generally follow the bed material deposition/erosion pattern (Figures 46 and 47, respectively). The changes in invert elevations represent in-channel processes, while the bed material deposition/erosion volumes represent overall morphological changes (including both in-channel and overbank areas).

### 8.3. Bed Material Volume

Net changes in bed material volumes computed for different sub-reaches of the American and Sacramento Rivers are summarized in Table 7 and graphically shown in Figure 56. The sub-reach volumes were determined from the bed material deposition data shown in Figures 46 and 47.

For the lower American River, the computed bed volume data show a general degradational trend in the upper 8 miles and aggradational trend in the lower 14 miles of the study reach. A total of about 1,591,000 cubic yards of the bed material is eroded from the upper reach and 1,326,000 cubic yards is deposited in the lower reach. For the entire 22-mile long reach of the American River, the model shows about 265,000 cubic yards of net bed material loss over the 73-years long simulation period, which is equivalent to about 0.20 ft of reach-average depth of bed degradation.

For the Sacramento River between Verona and Freeport, the computed bed volume data demonstrate a predominantly degradational trend upstream of the Sacramento Weir and an aggradational trend downstream of the weir. The total bed material loss between Verona and the weir is about 1,165,000 cubic yards and total bed material deposition between the weir and Freeport is about 2,004,000 cubic yards. For the entire 32-mile long study reach of the Sacramento River, the model shows about 839,000 cubic yards of net bed material deposition, which is equivalent to about 0.22 ft of reach-average bed aggradation.

### 8.4. Bed Surface Gradation

Initial and final surface bed material gradations computed for the American and Sacramento Rivers for the 73-year study period with existing hydrology are shown for selected locations in Figures 57 and 58, respectively. The model generally shows coarsening of the surface bed material in the American River, which is related to overall channel degradation of the river and
gradual removal of finer sediment from bed deposits. For the study reach of the Sacramento River, bed surface composition does not change significantly during the simulations.
9. Project Hydrology Model Results

This chapter discusses HEC-6T model results from long-term movable-bed simulations (WYs 1930-2002) using the project conditions inflow hydrographs. The results include the existing starting channel geometry and widened (by 50 ft and 100 ft) channel of the lower American River. Discussion of the effect of the American River widening is discussed in Chapter 11. The project hydrology results are compared with the existing hydrology results to determine the effect of changing the operation of Folsom Dam with the new auxiliary spillway on long-term geomorphic trends in the lower American River.

9.1. Bed Material Transport

Total bed material yields computed for the project hydrology for WYs 1930-2002 are shown for the American River in Figure 59 and Sacramento River in Figure 60. Computed total bed material deposition in the American and Sacramento Rivers is shown in Figures 61 and 62, respectively. Cumulative (from upstream to downstream) bed material deposition is shown for the American River in Figure 63 and for the Sacramento River in Figure 64.

Similar to the existing hydrology simulation results, computed bed material transport in the lower American River generally increases between Nimbus Dam and RM 14 and reduces downstream of RM 14. As a result, predominant erosion of bed material deposits occurs upstream of RM 14 and predominant deposition downstream of RM 14. Net overall bed material erosion is obtained for the entire study reach of the American River.

Higher flow releases to the lower American River under the project conditions increase bed material loads along most of the study reach except for the reach between RMs 6.5-9.5 where the project conditions loads are slightly less than the existing conditions loads (Figure 59b). The total bed material inflow from the American River to the Sacramento River during the simulation period increases by 15% from 333,000 tons under existing conditions to 382,000 tons under project conditions. The total bed material deposition/erosion pattern is generally similar to the existing conditions, but has greater amplitude (Figure 61b). Project flow releases increase bed material scour between Nimbus Dam and RM 13 and do not affect significantly bed material deposition downstream of RM 14 (Figure 63b).

In the Sacramento River, bed material load and bed material deposition/erosion patterns computed for the project conditions are generally similar to those obtained for the existing conditions. However, project flows in the lower American River result in higher bed material loads in the Sacramento River downstream of about RM 70 (Figure 60b). The increase of bed material loads upstream of the American River confluence is related to the increased negative flows between the American River confluence and the Sacramento Weir and increased outflows over the Sacramento Weir to Yolo Bypass during high floods. The total bed material load at Freeport during the simulation period increases by less than 1% from 43,180,000 tons under existing conditions to 43,280,000 tons under project conditions. Overall bed material deposition in the study reach of the Sacramento River slightly reduces under project conditions compared to existing conditions (Figure 64b).
9.2. Invert Profile

Project conditions invert profiles in the American and Sacramento Rivers are shown in Figures 65 and 66, respectively. Net changes in invert elevations during the simulation period are shown for the American River in Figure 67 and for the Sacramento River in Figure 68. Depths to hard surface below the American River invert computed for the project hydrology are shown in Figure 69. Project and existing conditions timeline progressions of degradation and aggradation trends in the lower American River are compared in Figure 70.

For the American River reach, the project condition model shows maximum invert degradation of about 8-10 ft between RMs 19-22, 6-8 ft between RMs 12-19, and 4-6 ft between RMs 5.5-7. Up to 2-3 ft of invert aggradation is computed between RMs 10.5-11.5, at RM 6.7, and downstream of RM 5.5. The final project conditions invert profile is generally about 1 ft below the existing conditions profile upstream of RM 14 and between RMs 5.5-6.5, and is close to the existing condition profile in the other reaches (Figures 65b and 67b). Higher flow releases to the lower American River under the project conditions increase the rate of channel degradation compared to the existing conditions, particularly during significant flood events (Figure 70).

The project conditions model indicates potential erosion to the hard surface in the American River between RMs 6.9-7.5, between RMs 9-10.5, at RM 20.6, and at RM 22.2 (Figure 69b). The latter two locations are uncertain as the hard surface elevations upstream of RM 11.5 were not measured and were assumed to be 10 ft below the 2006 invert. In general, the project hydrology does not seem to increase overall exposure of the hard materials in the study reach of the American River.

Long-term changes in the Sacramento River invert profile simulated with the project hydrology are practically identical to those simulated with the existing hydrology (Figures 66b and 68b).

9.3. Bed Material Volume

Net changes in bed material volumes in different sub-reaches of the American and Sacramento Rivers computed with the project hydrology are summarized in Table 7 and graphically shown in Figure 71. The sub-reach volumes were determined from the bed material deposition data shown in Figures 61 and 62.

The project conditions model shows overall degradation in the upper 8 miles and aggradation in the lower 14 miles of the study reach of the American River. Similar degradation/aggradation pattern was obtained for existing conditions. However, the total amount of bed material eroded from the upper reach over the 73-years long simulation period increased by about 9% from 1,591,000 cubic yards under existing conditions to 1,727,000 cubic yards under project conditions. The total amount of bed material deposited in the lower reach increased by about 7% from 1,326,000 cubic yards under existing conditions to 1,423,000 cubic yards under project conditions. For the entire study reach of the American River, the project conditions model shows a 15% increase of net bed material erosion from 265,000 cubic yards under existing conditions to 304,000 cubic yards under project conditions. This additional loss of bed material is relatively small and is equivalent to about 0.03 ft of reach-average depth of bed degradation in the study reach of the American River.
For the Sacramento River between Verona and Freeport, the project conditions model demonstrates a predominantly degradational trend upstream of the Sacramento Weir and a predominantly aggradational trend downstream of the weir (similar results were obtained for existing conditions). Bed material erosion between Verona and the Sacramento Weir increased by about 6% from 1,165,000 cubic yards under existing conditions to 1,238,000 cubic yards under project conditions. Bed material deposition between the Sacramento Weir and Freeport increased by about 1% from 2,004,000 cubic yards under existing conditions to 2,030,000 cubic yards under project conditions. For the entire study reach of the Sacramento River, the project conditions model shows a 6% reduction in net bed material deposition from 839,000 cubic yards under existing conditions to 791,000 cubic yards under project conditions. This decrease in net deposition is equivalent to about 0.01 ft of reach-average bed degradation.

9.4. Bed Surface Gradation

Initial and final surface bed material gradations computed for the 73-year study period with project hydrology are shown for the American Rivers in Figures 72 and 73, and for the Sacramento River in Figures 74 and 75. Similar to the existing conditions model, the project conditions model generally shows noticeable coarsening of the surface bed material in the American River (caused by overall channel degradation and removal of fines from bed deposits) and insignificant change in bed material gradations in the Sacramento River.
10. Erosion of Hard Material

According to the Fugro (2012) geophysical data collected in the American River between RM 5.5 and RM 11.5, the hard material is locally exposed at RM 7-7.5 (near Guy West Bridge), RM 8.5 (between Howe Avenue and Watt Avenue), and at several locations between RM 9.3 and RM 10.9 (upstream of Watt Avenue). The one-dimensional HEC-6T model uses section-average hard surface elevations to represent average channel conditions and an initial condition of a minimum of 1 ft of bed material thickness to initiate sediment transport computations.

According to the HEC-6T model results, the hard material beneath the American River channel can become exposed between RMs 6.9-7.5, between RMs 9-10.5, at RM 20.6, and at RM 22.2 (see Figure 69b). The latter two locations are somewhat uncertain as the hard surface elevations upstream of RM 11.5 were not measured and were assumed to be 10 ft below the 2006 invert. Given that the model uses section-average hard material elevations, the hard material can also be locally exposed in the channel at RM 8.7 where the model shows a thin layer (about 2 ft) of alluvial deposits.

The exposed hard material becomes subject to erosion by flowing water. Erosion of the hard material (though relatively slow) may increase channel degradation in the upstream reaches. Wibowo and Robbins (2012) conducted laboratory Jet Erosion Tests (JET) on boring soil samples collected from the lower American River between RM 6 and RM 10. The purpose of their study was to assess the erosion resistance of the river materials. According to their analysis, the erosion resistance of the collected samples varies from very erodible to very resistant, without any clear trends or correlations between erodibility and geographic location. For moderately resistant materials, measured critical shear stress ranges from 0.23 to 0.76 lb/ft². These materials include clay and cemented sand with silt, which can be assumed to represent the hard material mapped by Fugro (2012).

Figures 76-79 shows distribution of bed shear stress along the study reach of the American River as computed by the HEC-6T model for a range of flows measured by the USGS during the 1986 and 1997 flood events. Computations were conducted for the 1997 bathymetry, 2006 bathymetry, and final bathymetries from existing and project conditions long-term simulations. Bed shear stresses were calculated using the smooth wall law which is the preferred method for modeling erosion of cohesive materials (MBH 2009). Also shown on the figures is the minimum critical shear stress for the moderately resistant materials as measured by Wibowo and Robbins (2012). It appears that even the moderately resistant materials can be eroded only during flows exceeding about 100,000 cfs and only in the upper reach between RM 14 and RM 17 (1997 and 2006 bathymetries) and upstream of RM 19 (all bathymetries), which is a location where the depth to the erosion resistant materials was assumed to be 10 ft.

According to the modeling results, the hard material can become exposed at several locations between RMs 6.9-10.5 and upstream of RM 20. Shear stress between RMs 6.9-10.5 is below the critical for erosion of the moderately resistant materials for all the flows modeled in this study. Upstream of RM 20, hard materials can be eroded only during extreme flows exceeding 100,000 cfs. However, exact location of the hard material in this reach is presently unknown.
This analysis does not consider erosion of the hard material by block failure and abrasion due to moving sediment. Block failure may occur but it will unlikely result in mass destruction of the hard surface. Unlike the breach of the Shanghai Rapids on the Feather River, there are no head cut processes in the study reach of the American River as the entire profile is submerged by subcritical flow conditions for all events.

According to available publications (e.g. Sklar and Dietrich 2001, 2004), abrasion of bedrocks (hard materials) by moving sediment is an important erosional mechanism. Therefore, erosion of the hard material can be higher than estimated due to the scouring effects of moving sediment impacting the surface. However, given that the measured thickness of hard material in the American River is several tens of feet (Fugro 2012), such erosion is likely to be a slow process. A separate geophysical investigation may be needed to quantify the hard material susceptibility to fluvial abrasion in the study reach of the American River.
11. Effect of Channel Widening

A series of model sensitivity runs was performed for both the existing and project hydrology to evaluate effects of the potential widening of the American River channel on simulated long-term sediment transport and bed morphological adjustments. The sensitivity analyses were conducted for the channel width increased by 50 ft and by 100 ft. Results of the sensitivity runs are discussed below.

11.1. Bed Material Transport

Total bed material yields in the lower American River computed for the widened channel are shown for the existing hydrology in Figure 44 and project hydrology in Figure 59a. Total bed material deposition in the widened channel is shown in Figures 46 and 61a, respectively. Cumulative (from upstream to downstream) bed material deposition in the widened channel of the American River is shown in Figures 48 and 63a, respectively.

The sensitivity runs indicate that the widening of the American River channel has varying effect on bed material transport in the study reach of the American River. Widening of the channel changes flow hydraulic parameters and active bed width. Combined effect of these changes on bed material load and bed material deposition/erosion is site-specific and depends on local bed material characteristics, channel geometry, bed slope, and water discharge.

For the existing hydrology, widening of the channel generally reduces total bed material loads in the lower American River downstream of RM 7, between RMs 15-16, and between RMs 19-22, and increased bed material loads between RMs 7-14. In general, the wider channel has greater effect (either increase or reduction) on bed material transport. Total existing conditions bed material inflow from the American River to the Sacramento River during the 73-year long simulation period is 333,000 tons for the existing channel width, 338,000 tons (2% increase) for the 50-ft channel widening, and 307,000 tons (8% decrease) for the 100-ft channel widening.

For the project hydrology, widening of the channel reduces total bed material loads in the lower American River downstream of RM 7 and between RMs 13-22, and increased bed material loads between RMs 7-13. Total project conditions bed material inflow from the American River to the Sacramento River is 382,000 tons for the existing channel width, 369,000 tons (3% decrease) for the 50-ft channel widening, and 329,000 tons (14% decrease) for the 100-ft channel widening.

The modeled widening of the American River channel slightly reduces the magnitude of bed material deposition/erosion data for both existing and project conditions. In general, however, the channel widening does not change the overall bed material transport and bed material deposition/erosion patterns in the lower American River.

According to the sensitivity run results, effect of the lower American River widening on bed material loads and bed material deposition/erosion in the Sacramento River is insignificant for both the existing hydrology (Figures 45, 47, and 49) and project hydrology (Figures 60a, 62a, and 64a).
11.2. Invert Profile

Final invert profiles computed for the widened channel of the American River are shown for existing hydrology in Figure 50 and project hydrology in Figure 65a. Net changes in invert elevations in the widened channel during the 73-year long simulation period are shown in Figures 52 and 67a, respectively. Depths to the hard surface at the end of the simulations are shown in Figures 54 and 69a, respectively.

The results of the sensitivity runs clearly show less significant invert degradation in the widened channel of the American River, particularly upstream of about RM 13. Invert profiles in the widened channel are up to about 1-3 ft higher than the invert profile simulated for the existing channel width. The wider the channel, the less invert degradation in the study reach of the American River. As a result, depth to the hard surface at the end of the long-term simulations in the widened channel upstream of RM 13 increases by up to about 1-3 ft. At the same time, the channel widening does not change the potential exposure of the hard materials between RMs 6.9-7.5 and between RMs 9-10.5.

The modeled widening of the lower American River does not appear to have any effect on invert elevations in the Sacramento River for both the existing (Figures 51 and 53) and project (Figures 66a and 68a) hydrology.

11.3. Bed Material Volume

Net changes in bed material volumes in different sub-reaches of the American and Sacramento Rivers computed for the widened channel of the lower American River are summarized in Table 7 and graphically shown for existing hydrology in Figure 56 and project hydrology in Figure 71a.

The sensitivity run results indicate that the widening of the American River channel reduces bed degradation immediately downstream of Nimbus Dam, has varying effect on bed degradation/aggradation in the middle part of the study reach, and does not affect significantly deposition in the lower 5 miles of the river. For the existing hydrology, net bed material erosion from the entire study reach is about 265,000 cubic yards for the existing channel width, 269,000 cubic yards (2% increase) for the 50-ft channel widening, and 245,000 cubic yards (8% decrease) for the 100-ft channel widening. For the project hydrology, corresponding bed material erosion volumes are 304,000 cubic yards, 294,000 cubic yards (3% decrease), and 262,000 cubic yards (14% decrease). In general, changes in bed volumes caused by the channel widening are relatively small and do not increase exposure of the hard materials in the study reach of the American River.

Effect of the American River widening on bed volume changes in the Sacramento River is insignificant.

11.4. Bed Surface Gradation

Bed material gradations in the widened channel of the American River are shown for existing hydrology in Figure 57 and project hydrology in Figure 72. The results from the sensitivity tests indicate that the modeled channel widening does not cause systematic coarsening or fining of the
bed material in the study reach of the American River. Changes in bed material gradations (relative to the existing channel width) are relatively small and appear to be site-specific.

The widening of the lower American River has insignificant effect on bed material gradation in the Sacramento River (Figures 58 and 74).
12. Summary

The main objective of this modeling study was to investigate long-term sediment transport processes and geomorphic trends along the lower American River under existing and project hydrologic conditions using the updated Ayres HEC-6T model. The study area includes 22 miles of the American River below Nimbus Dam and 32 miles of the Sacramento River between Verona and Freeport. Following is a summary of the main results from this modeling study.

12.1. Model Update

NHC extended the Ayres HEC-6T model of the lower American River to include the Sacramento River between Verona and Freeport (in order to assess downstream changes in the American River); converted the model to vertical datum NAVD88, and updated it with the most recent surface and sub-surface bed material data and results from geotechnical investigations of hard (erosion-resistant) materials. The model’s hydraulic performance was verified with high water mark data collected after the 1997 flood event. The updated model was calibrated to reproduce measured sediment loads and observed bed changes in the American River (between 1997 and 2006) and Sacramento River (between 1997 and 2008). The calibrated model was then used to simulate long-term morphological changes in the lower American River under existing and project hydrologic conditions. The existing and project hydrographs were developed by the USACE for WYs 1930-2002 (73 years). The existing conditions hydrology assume regulated flow for the entire simulation period with post-Oroville Dam and Central Valley Project flow conditions in effect and reflect the existing operation of the river system. The with-project hydrology is based on simulated operation of Folsom Dam with the new auxiliary spillway.

12.2. American River

The model results indicate active degradation of the American River channel between Nimbus Dam and RM 14 and predominant aggradation downstream of RM 14. This is in agreement with measurements of channel change for the calibration time period of 1997 through 2006. The upstream sediment supply to the lower American River is interrupted by Folsom and Nimbus Dam, which results in ongoing channel degradation below the dams. Bed material eroded from the upstream reach is transported to and partially deposit in the downstream reach.

Project condition flows (with modified Folsom Dam spillway and operation) generally increase bed material transport through the study reach of the American River. The total bed material inflow from the American River to the Sacramento River during the 73-year long simulation period is 333,000 tons for the existing hydrology and 382,000 tons (15% increase) for the project condition hydrology.

Simulated changes in invert elevations vary significantly along the study reach of the American River. This variability is attributed to complex channel adjustments in the model caused by a variety of factors including local channel geometry, successive wetting and drying of different parts of the river channel during high and low flow periods, varying sediment transport capacity at different flows, and alternating aggradation and degradation processes in different parts of the channel during different flow periods. Maximum channel invert degradation computed with the
existing hydrology is about 8-10 ft upstream of RM 19, 6-7 ft between RMs 12-19, and 4-6 ft between RMs 5.5-7. Up to 2-3 ft of localized invert aggradation is computed in between RMs 10.5-11.5, at RM 6.7, and at RM 5. The lower 4 miles of the American River are in a slight aggradational state, with 1-3 ft of localized invert aggradation. Project flows increase (by about 1 ft) invert degradation upstream of RM 14 and between RMs 5.5-6.5, and do not affect significantly invert profile in the other reaches.

A potential implication of the simulated long-term changes in the American River bed profile can be increased stress along the toe of the project levees in the degradational reaches, which may result in increased scour along unrevetted channel sections. In the aggradational reaches, increases in bed elevations may result in higher flood stages and reduced flood conveyance capacity of the leved system.

The total amount of bed material eroded between Nimbus Dam and RM 14 over the 73-years long simulation period is 1,591,000 cubic yards for the existing hydrology and 1,727,000 cubic yards (9% increase) for the project hydrology. The total amount of bed material deposited downstream of RM 14 is 1,326,000 cubic yards for the existing hydrology and 1,423,000 cubic yards (7% increase) for the project hydrology. Net bed material erosion in the 22-mile long study reach of the American River is about 265,000 cubic yards for the existing hydrology and 304,000 cubic yards (15% increase) for the project hydrology. The additional erosion of bed material under project conditions is relatively small and is equivalent to about 0.03 ft of reach-average depth of bed degradation.

According to the HEC-6T model results, the hard material beneath the American River channel can become exposed over the simulation time period at several locations between RMs 6.9-10.5 and upstream of RM 20. The latter location is somewhat uncertain as the hard surface elevations upstream of RM 11.5 were not measured and were assumed to be 10 ft below the 2006 invert. In general, the project condition hydrology does not seem to increase overall exposure of the hard materials in the study reach of the American River.

The exposed hard material becomes subject to erosion by flowing water. However, modeling results indicate that the shear stress computed using the smooth wall law between RMs 6.9-10.5 is below the critical for erosion of the moderately resistant materials (clay and cemented sand with silt) for all the flows modeled in this study. Upstream of RM 20, hard materials can be eroded only during extreme flows exceeding 100,000 cfs. However, the exact location of the hard material in this reach is presently unknown. The elevation of the hard surface needs to be determined in this reach to better evaluate the risk of hard material exposure. Erosion of the hard material can be higher than simulated due to the scouring effects of moving sediment impacting the surface.

The model generally shows coarsening of the surface bed material in the American River, which is consistent with the overall channel degradation of the river and gradual removal of finer sediment from bed deposits.

Given that the Laursen-Copeland sediment transport method used in the model provided reasonably conservative predictions of sediment loads and bed degradation in the American River in the calibration exercise, the overall results obtained in this modeling study are likely to be
conservative. The actual long-term rates of degradation and deposition are likely to be somewhat lower than that predicted by the model.

12.3. Sacramento River

For the Sacramento River between Verona and Freeport, the model results indicate an overall slight degradational trend upstream of the Sacramento Weir and a slight aggradational trend downstream of the weir. In general, however, the study reach of the Sacramento River appears to be stable. Project condition flows in the lower American River increase bed material loads in the Sacramento River downstream of about RM 70. The total bed material load at Freeport during the simulation period is 43,180,000 tons under existing conditions and 43,280,000 tons (less than 1% increase) under project conditions.

Long-term changes in the Sacramento River invert profile simulated with the existing hydrology range from about 2-3 ft of degradation to 3-8 ft of aggradation. The project condition hydrology does not have a significant effect on long-term changes in the Sacramento River profile.

Net deposition of bed material in the 32-mile long study reach of the Sacramento River is about 839,000 cubic yards for the existing condition hydrology and 791,000 cubic yards (6% reduction) for the project condition hydrology. This decrease in net deposition is equivalent to about 0.01 ft of reach-averaged bed degradation.

Bed surface composition in the study reach of the Sacramento River does not change significantly during the simulations for both the existing and project condition hydrology.

12.4. Effect of American River Widening

A series of model sensitivity runs was performed for both the existing and project condition hydrology to evaluate the effects of potential widening of the American River channel on sediment transport processes and geomorphic trends in the lower American River. The sensitivity analyses were conducted for the channel width increased by 50 ft and by 100 ft. The results of the sensitivity runs generally show less significant bed degradation in the widened channel of the American River, particularly upstream of about RM 13. Invert profiles in the widened channel are up to about 1-3 ft higher than the invert profile simulated for the existing channel width. The wider the channel, the less bed degradation in the study reach of the American River. As a result, the depth to the hard surface below the invert in the widened channel upstream of RM 13 is about 1-3 ft greater compared to the existing channel width. At the same time, the channel widening does not change the potential exposure of the hard materials between RMs 6.9-10.5. In general, the modeled channel widening does not change the overall bed material transport and bed material deposition/erosion patterns in the lower American River and has insignificant effects on the Sacramento River.
References


Table 1. Hard surface elevations in American River in HEC-6T model (based on Fugro 2012 geophysical data).

<table>
<thead>
<tr>
<th>HEC-6T River Mile</th>
<th>Section-average hard surface elevation (ft NAVD88)</th>
<th>Fugro (2012) data</th>
<th>Adopted in HEC-6T model</th>
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Note: * Assumed 1 ft below 1997 invert; ** Assumed 1 ft below 2006 invert.
Table 2. Sediment concentration diversion ratios at Sacramento Weir in HEC-6T model (calculated using Rouse equation; from NHC 2012).

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<thead>
<tr>
<th>Flow (cfs)</th>
<th>Very fine sand (0.062-0.0125 mm)</th>
<th>Fine sand (0.125-0.25 mm)</th>
<th>Medium sand (0.25-0.5 mm)</th>
<th>Coarse sand (0.5-1 mm)</th>
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Table 3. Stage-discharge rating curve for Sacramento River at Freeport (from USACE 2014).

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<thead>
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<th>Median stage (ft NAVD88)</th>
<th>Flow (cfs)</th>
<th>Median stage (ft NAVD88)</th>
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<td>100,000</td>
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Table 4. Roughness coefficients in HEC-6T model.

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<th>HEC-6T River Mile</th>
<th>Manning roughness coefficient</th>
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<td>Main channel</td>
<td>Right overbank</td>
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</tr>
<tr>
<td>American River</td>
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<td></td>
</tr>
<tr>
<td>10.221-22.330</td>
<td>0.07</td>
<td>0.04</td>
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<tr>
<td>6.023-9.960</td>
<td>0.07</td>
<td>0.035</td>
<td>0.07</td>
<td></td>
</tr>
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<td>0.302-5.510</td>
<td>0.07</td>
<td>0.04</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>Sacramento River</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>61.00-78.75</td>
<td>0.045</td>
<td>0.025-0.035*</td>
<td>0.045</td>
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</tr>
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<td>60.60-60.75</td>
<td>0.04</td>
<td>0.025-0.035*</td>
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<td>0.025-0.033*</td>
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<tr>
<td>59.29-59.50</td>
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<td>0.025-0.033*</td>
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<td>58.52-59.00</td>
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<td>0.025-0.033*</td>
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<td>46.42-58.25</td>
<td>0.05</td>
<td>0.025-0.033*</td>
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Note: * Roughness varies with discharge.

Table 5. Measured and computed bed material yields in Sacramento River at Freeport (movable-bed model calibration).

<table>
<thead>
<tr>
<th>Method</th>
<th>Bed material yield (mln tons)</th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total (1997-2008)</td>
<td>Average annual</td>
<td>Error** (%)</td>
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</tr>
<tr>
<td>Measured*</td>
<td>5.6</td>
<td>0.51</td>
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<td></td>
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<tr>
<td>Yang</td>
<td>3.5</td>
<td>0.32</td>
<td>-37</td>
<td></td>
</tr>
<tr>
<td>Toffaleti-MPM</td>
<td>5.7</td>
<td>0.52</td>
<td>+2</td>
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</tr>
<tr>
<td>Laursen-Copeland</td>
<td>6.6</td>
<td>0.60</td>
<td>+18</td>
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</tr>
<tr>
<td>Wilcock</td>
<td>0.6</td>
<td>0.05</td>
<td>-89</td>
<td></td>
</tr>
</tbody>
</table>

Note: * Based on measured USGS suspended load data and NHC’s bed load estimates (from NHC 2012); ** Error = (computed - measured) / measured.
### Table 6. Measured and computed bed volume changes (movable-bed model calibration).

<table>
<thead>
<tr>
<th>HEC-6T River Mile</th>
<th>Bed volume changes (thousand cubic yards)*</th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Measured</td>
<td>Yang</td>
<td>Toffaleti-MPM</td>
<td>Laursen-Copeland</td>
<td>Wilcock</td>
</tr>
<tr>
<td><strong>American River</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>20-22</td>
<td>-129</td>
<td>-26</td>
<td>-43</td>
<td>-76</td>
<td>-16</td>
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<tr>
<td>15-20</td>
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<td>-44</td>
<td>-64</td>
<td>-145</td>
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</tr>
<tr>
<td>5-10</td>
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<td>+82</td>
<td>+50</td>
<td>+120</td>
<td>+1</td>
</tr>
<tr>
<td>0-5</td>
<td>+183</td>
<td>+28</td>
<td>+65</td>
<td>+97</td>
<td>0</td>
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<td><strong>Total</strong></td>
<td>-10</td>
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<td>-64</td>
<td>-3</td>
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<tr>
<td><strong>Sacramento River</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75-79</td>
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<td>+140</td>
<td>-70</td>
<td>-400</td>
<td>+2,830</td>
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<tr>
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<td>+180</td>
<td>-50</td>
<td>-210</td>
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<td>+1,010</td>
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<td>+1,150</td>
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<td>50-55</td>
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<td>+840</td>
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<td>-90</td>
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<td>+1,540</td>
<td>+870</td>
<td>+5,590</td>
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</tbody>
</table>

Note: * Positive = aggradation; negative = degradation; ** Measured data are from NHC (2012).
Table 7. Computed bed volume changes (long-term simulations).

<table>
<thead>
<tr>
<th>HEC-6T River Mile</th>
<th>Bed volume changes (thousand cubic yards)*</th>
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<th></th>
<th></th>
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<tr>
<td></td>
<td>Existing hydrology</td>
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<td></td>
</tr>
<tr>
<td></td>
<td>100-ft LAR widening</td>
<td>10-15</td>
<td>+251</td>
<td>+134</td>
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<td>+344</td>
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<tr>
<td></td>
<td></td>
<td>5-10</td>
<td>+154</td>
<td>+253</td>
<td>+316</td>
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<td></td>
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<td>+499</td>
<td>+514</td>
<td>+501</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>Existing channel</td>
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<td>-463</td>
<td>-464</td>
<td>-477</td>
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<td>50-ft LAR widening</td>
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<td>-288</td>
<td>-289</td>
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<tr>
<td></td>
<td>100-ft LAR widening</td>
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<td>-190</td>
<td>-192</td>
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<td>+55</td>
<td>+54</td>
<td>+54</td>
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<td></td>
<td>55-60</td>
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<td>+947</td>
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<td>Total</td>
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<td>+839</td>
<td>+832</td>
<td>+814</td>
<td>+791</td>
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</tbody>
</table>

Note: * Positive = aggradation; negative = degradation.
Figure 1. Study area and vicinity map.
Figure 2. Schematic of HEC-6T model stream network.
Figure 3. Conversion factors from vertical datum NGVD29 to vertical datum NAVD88 (provided by USACE).
**Figure 4.** Relationship between USACE stationing and HEC-6T stationing for American River.
Figure 5. Conversion factor from USACE stationing to HEC-6T stationing for American River.
Figure 6. Measured and modeled sub-surface bed material gradations (American River; NHC data).
Figure 7a. Measured surface bed material gradations (American River; NHC and Ayres data).
Figure 7b. Measured surface bed material gradations (American River; NHC and Ayres data).
Figure 8a. Surface bed material gradations adjusted for sand content (American River; NHC and Ayres data).
Figure 8b. Surface bed material gradations adjusted for sand content (American River; NHC and Ayres data).
Figure 9. Measured bed material gradations (Sacramento River; NHC data).
**Figure 10.** Invert and hard surface elevations in American River in HEC-6T model.
Figure 11. Daily flow hydrographs used for model calibration against observed bed changes.
Figure 12a. Existing conditions hydrographs developed by USACE for long-term simulations.
Figure 12b. Existing conditions hydrographs developed by USACE for long-term simulations.
Figure 13a. Project conditions hydrographs (preliminary) developed by USACE for long-term simulations.
Figure 13b. Project conditions hydrographs (preliminary) developed by USACE for long-term simulations.
Figure 14. Downstream stage-discharge rating curve for Sacramento River at Freeport used for test runs based on 1997 geometry.
Figure 15. Downstream stage-discharge rating curve for Sacramento River at Freeport used for long-term with-project simulations (from USACE 2014).
**Figure 16.** Upstream total bed material inflows in Sacramento River at Verona computed by NHC (2012) model for 1997-2008.
Figure 17. Total bed material load gradations in Sacramento River at Verona computed by NHC (2012) model for 1997-2008.
Figure 18. Comparison of measured and computed stage-discharge relationships (fixed-bed model test).
Figure 19. Computed and observed water surface elevations for January 2-3, 1997 flood event (fixed-bed model test).
**Figure 20.** Water surface profiles computed for American River (fixed-bed model test). Total flows are shown for Fair Oaks gage.
Figure 21. Water surface profiles computed for Sacramento River (fixed-bed model test). Total flows are shown for Verona gage.
Figure 22. Channel discharge profiles computed for American River (fixed-bed model test). Total flows are shown for Fair Oaks gage.
Figure 23. Channel discharge profiles computed for Sacramento River (fixed-bed model test). Total flows are shown for Verona gage.
Figure 24. Channel velocity profiles computed for American River (fixed-bed model test). Total flows are shown for Fair Oaks gage.
Figure 25. Channel velocity profiles computed for Sacramento River (fixed-bed model test). Total flows are shown for Verona gage.
Figure 26. Comparison of measured and computed suspended bed material loads for American River at Sacramento (RM 6.6). Measured zero loads are shown on the bottom of the graph.
Figure 27a. Comparison of bed loads (gravel and cobble) computed for American River at Sacramento (RM 6.6).
Figure 27b. Comparison of bed loads by size class (very fine gravel) computed for American River at Sacramento (RM 6.6).
Figure 27c. Comparison of bed loads by size class (fine gravel) computed for American River at Sacramento (RM 6.6).
Figure 27d. Comparison of bed loads by size class (medium gravel) computed for American River at Sacramento (RM 6.6).
**Figure 27e.** Comparison of bed loads by size class (coarse gravel) computed for American River at Sacramento (RM 6.6).
**Figure 27f.** Comparison of bed loads by size class (very coarse gravel) computed for American River at Sacramento (RM 6.6).
Figure 27g. Comparison of bed loads by size class (small cobbles) computed for American River at Sacramento (RM 6.6).
Figure 28a. Comparison of measured and computed suspended bed material loads for Sacramento River at Verona (RM 78.8).
Figure 28b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Verona (RM 78.8).
Figure 28c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Verona (RM 78.8).
Figure 28d. Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Verona (RM 78.8).
Figure 29a. Comparison of measured and computed suspended bed material loads for Sacramento River at Sacramento (RM 59.7).
Figure 29b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Sacramento (RM 59.7).
Figure 29c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Sacramento (RM 59.7).
**Figure 29d.** Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Sacramento (RM 59.7).
Figure 30a. Comparison of measured and computed suspended bed material loads for Sacramento River at Freeport (RM 46.4).
Figure 30b. Comparison of measured and computed suspended bed material loads by size class (very fine sand) for Sacramento River at Freeport (RM 46.4).
Figure 30c. Comparison of measured and computed suspended bed material loads by size class (fine sand) for Sacramento River at Freeport (RM 46.4).
Figure 30d. Comparison of measured and computed suspended bed material loads by size class (medium sand) for Sacramento River at Freeport (RM 46.4).
Figure 31. Computed total bed material load in American River (movable-bed model calibration). Includes sand, gravel, and cobbles.
Figure 32. Computed total bed material load in Sacramento River (movable-bed model calibration). Includes sand, gravel, and cobbles.
Figure 33. Computed total bed material deposition in American River (movable-bed model calibration). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 34. Computed total bed material deposition in Sacramento River (movable-bed model calibration). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 35. Computed cumulative bed material deposition in American River from upstream to downstream (movable-bed model calibration). Includes sand, gravel, and cobbles.
Figure 36. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (movable-bed model calibration). Includes sand, gravel, and cobbles.
Figure 37a. Measured and computed invert profiles in American River (movable-bed model calibration).
Figure 37b. Measured and computed invert profiles in American River (movable-bed model calibration).
Figure 38a. Measured and computed invert profiles in Sacramento River (movable-bed model calibration).
Figure 38b. Measured and computed invert profiles in Sacramento River (movable-bed model calibration).
Figure 39a. Measured and computed net changes in invert elevations in American River (movable-bed model calibration).
Figure 39b. Measured and computed net changes in invert elevations in American River (movable-bed model calibration).
Figure 40a. Measured and computed net changes in invert elevations in Sacramento River (movable-bed model calibration).
Figure 40b. Measured and computed net changes in invert elevations in Sacramento River (movable-bed model calibration).
Figure 41. Measured and computed bed volume changes in American and Sacramento Rivers (movable-bed model calibration). Positive = aggradation; negative = degradation.
Figure 42a. Measured and computed initial and final surface bed material gradations in American River (movable-bed model calibration).
Figure 42b. Measured and computed initial and final surface bed material gradations in American River (movable-bed model calibration).
Figure 42c. Measured and computed initial and final surface bed material gradations in American River (movable-bed model calibration).
Figure 43a. Measured and computed initial and final surface bed material gradations in Sacramento River (movable-bed model calibration).
Figure 43b. Measured and computed initial and final surface bed material gradations in Sacramento River (movable-bed model calibration).
Figure 44. Computed total bed material load in American River (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles.
Figure 45. Computed total bed material load in Sacramento River (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles.
Figure 46. Computed total bed material deposition in American River (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 47. Computed total bed material deposition in Sacramento River (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 48. Computed cumulative bed material deposition in American River from upstream to downstream (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles.
Figure 49. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (long-term simulations, existing hydrology). Includes sand, gravel, and cobbles.
Figure 50. Computed invert profiles in American River (long-term simulations, existing hydrology).
Figure 51. Computed invert profiles in Sacramento River (long-term simulations, existing hydrology).
Figure 52. Computed net changes in invert elevations in American River (long-term simulations, existing hydrology).
Figure 53. Computed net changes in invert elevations in Sacramento River (long-term simulations, existing hydrology).
Figure 54. Computed depth to hard surface below invert in American River (long-term simulations, existing hydrology).
Figure 55. Timeline progression of degradation and aggradation trends at selected cross sections in American River (long-term simulations, existing hydrology).
Figure 56. Computed bed volume changes in American and Sacramento Rivers (long-term simulations, existing hydrology). Positive = aggradation; negative = degradation.
Figure 57a. Computed surface bed material gradations in American River (long-term simulations, existing hydrology).
Figure 57b. Computed surface bed material gradations in American River (long-term simulations, existing hydrology).
Figure 57c. Computed surface bed material gradations in American River (long-term simulations, existing hydrology).
Figure 58a. Computed surface bed material gradations in Sacramento River (long-term simulations, existing hydrology).
Figure 58b. Computed surface bed material gradations in Sacramento River (long-term simulations, existing hydrology).
Figure 59a. Computed total bed material load in American River (long-term simulations, project hydrology). Includes sand, gravel, and cobbles.
**Figure 59b.** Comparison of total bed material loads in American River computed for existing and project hydrology.
Figure 60a. Computed total bed material load in Sacramento River (long-term simulations, project hydrology). Includes sand, gravel, and cobbles.
Figure 60b. Comparison of total bed material loads in Sacramento River computed for existing and project hydrology.
**Figure 61a.** Computed total bed material deposition in American River (long-term simulations, project hydrology). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 61b. Comparison of total bed material depositions in American River computed for existing and project hydrology.
Figure 62a. Computed total bed material deposition in Sacramento River (long-term simulations, project hydrology). Includes sand, gravel, and cobbles. Positive = deposition; negative = erosion.
Figure 62b. Comparison of total bed material depositions in Sacramento River computed for existing and project hydrology.
Figure 63a. Computed cumulative bed material deposition in American River from upstream to downstream (long-term simulations, project hydrology). Includes sand, gravel, and cobbles.
Figure 63b. Comparison of cumulative bed material depositions in American River (from upstream to downstream) computed for existing and project hydrology.
Figure 64a. Computed cumulative bed material deposition in Sacramento River from upstream to downstream (long-term simulations, project hydrology). Includes sand, gravel, and cobbles.
Figure 64b. Comparison of cumulative bed material depositions in Sacramento River (from upstream to downstream) computed for existing and project hydrology.
Figure 65a. Computed invert profiles in American River (long-term simulations, project hydrology).
Figure 65b. Comparison of invert profiles in American River computed for existing and project hydrology.
Figure 66a. Computed invert profiles in Sacramento River (long-term simulations, project hydrology).
Figure 66b. Comparison of invert profiles in Sacramento River computed for existing and project hydrology.
Figure 67a. Computed net changes in invert elevations in American River (long-term simulations, project hydrology).
Figure 67b. Comparison of net changes in invert elevations in American River computed for existing and project hydrology.
Figure 68a. Computed net changes in invert elevations in Sacramento River (long-term simulations, project hydrology).
Figure 68b. Comparison of net changes in invert elevations in Sacramento River computed for existing and project hydrology.
Figure 69a. Computed depth to hard surface below invert in American River (long-term simulations, project hydrology).
Figure 69b. Comparison of depths to hard surface in American River computed for existing and project hydrology.
Figure 70. Comparison of timeline progression of degradation and aggradation trends in American River computed for existing and project hydrology.
Figure 71a. Computed bed volume changes in American and Sacramento Rivers (long-term simulations, project hydrology). Positive = aggradation; negative = degradation.
Figure 71b. Comparison of bed volume changes in American and Sacramento Rivers computed for existing and project hydrology. Positive = aggradation; negative = degradation.
Figure 72a. Computed surface bed material gradations in American River (long-term simulations, project hydrology).
Figure 72b. Computed surface bed material gradations in American River (long-term simulations, project hydrology).
Figure 72c. Computed surface bed material gradations in American River (long-term simulations, project hydrology).
Figure 73a. Comparison of surface bed material gradations in American River computed for existing and project hydrology.
Figure 73b. Comparison of surface bed material gradations in American River computed for existing and project hydrology.
Figure 73c. Comparison of surface bed material gradations in American River computed for existing and project hydrology.
Figure 74a. Computed surface bed material gradations in Sacramento River (long-term simulations, project hydrology).
Figure 74b. Computed surface bed material gradations in Sacramento River (long-term simulations, project hydrology).
Figure 75a. Comparison of surface bed material gradations in Sacramento River computed for existing and project hydrology.
Figure 75b. Comparison of surface bed material gradations in Sacramento River computed for existing and project hydrology.
Figure 76. Bed shear stress for cohesive materials computed for American River (1997 bathymetry).
Figure 77. Bed shear stress for cohesive materials computed for American River (2006 bathymetry).
Figure 78. Bed shear stress for cohesive materials computed for American River (long-term simulations, existing hydrology, final bathymetry).
Figure 79. Bed shear stress for cohesive materials computed for American River (long-term simulations, project hydrology, final bathymetry).
Appendix A

Study Reach of American River
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Legend
HEC-6T Model Stationing
HEC-6T Cross Sections

Sacramento Sediment - Phase 2
American River Study Reach
Appendix A
Sheet 4

Job: 50571
Date: DECEMBER 2014
DATA SOURCES:
- NAIP Color Orthoimagery, 5/22-7/5 2012
- ESRI Roads, 2012

LEGEND:
- HEC-6T Model Stationing
- HEC-6T Cross Sections

SCALE - 1:12,000

Sacramento Sediment - Phase 2

American River Study Reach
Sheet 7

Appendix A

Job: 50571
Date: DECEMBER 2014

US Army Corps of Engineers
northwest hydraulic consultants

ABC, P:\50571 Sac Sediment Phase 2\GIS\Workmaps\Figures\Cross_Section_Location_Maps\American_River_Study_Reach.mxd

US Army Corps of Engineers
Appendix B

Study Reach of Sacramento River
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Sacramento River Study Reach
Appendix B
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Sacramento River Study Reach

Legend
- HEC-6T Model Stationing
- HEC-6T Cross Sections

California State Plane, Zone 6
Units: Feet

Job: 50571
Date: DECEMBER 2014
Appendix B
Sheet 5
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Job: 50571
Date: DECEMBER 2014
Sacramento Sediment - Phase 2
Study Reach
Sheet 6

Appendix B
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Job: 50571
Date: DECEMBER 2014
Sacramento Sediment - Phase 2
Sacramento River Study Reach
Sheet 7

Appendix B
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Date: DECEMBER 2014

Appendix B
Sacramento River Study Reach
Sheet 8
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

US Army Corps
of Engineers

Legend
- HEC-6T Model Stationing
- HEC-6T Cross Sections

Sacramento Sediment - Phase 2

California State Plane, Zone 6
Units: Feet

Appendix B
Sacramento River
Study Reach
Sheet 9
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

California State Plane, Zone 6
Units: Feet
DATA SOURCES:
NAIP Color Orthoimagery, 5/22-7/5 2012.

SCALE - 1:12,000

Job: 50571
Date: DECEMBER 2014
Appendix B
Appendix C

1997 and 2006 Cross Sections in HEC-6T Model of American River
American River   RM 22.33

American River   RM 22.164

Lower American River HEC-6T Model
Lower American River HEC-6T Model
American River  RM 20.391

American River  RM 20.117

Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
American River  RM 11.633

American River  RM 11.462
Lower American River HEC-6T Model
American River  RM 9.0074

American River  RM 8.7423

Lower American River HEC-6T Model
American River  RM 8.4999

American River  RM 8.2695

Lower American River HEC-6T Model
American River  RM 8.1062

American River  RM 7.9992

Lower American River HEC-6T Model
American River RM 7.5449

American River RM 7.4169

Lower American River HEC-6T Model
Lower American River HEC-6T Model
American River RM 6.5823

American River RM 6.3643

Lower American River HEC-6T Model
American River  RM 6.0234

American River  RM 5.5096

Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
American River  RM 3.6833

American River  RM 3.5657

Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
Appendix D

Modified 2006 Cross Sections
(for Sensitivity Analyses)
Lower American River HEC-6T Model
American River  RM 21.548

American River  RM 21.32
American River RM 20.391

American River RM 20.117

Lower American River HEC-6T Model
Lower American River HEC-6T Model

American River  RM 19.548

American River  RM 19.384
American River  RM 19.165

American River  RM 18.862

Lower American River HEC-6T Model
American River  RM 18.422

American River  RM 17.027

Lower American River HEC-6T Model
American River  RM 14.746

American River  RM 14.505

Lower American River HEC-6T Model
Lower American River HEC-6T Model
Lower American River HEC-6T Model
American River  RM 12.921

American River  RM 12.73
American River RM 12.016

American River RM 11.921

Lower American River HEC-6T Model
American River  RM 11.633

American River  RM 11.462

Lower American River HEC-6T Model
American River   RM 9.4569

American River   RM 9.3642

Lower American River HEC-6T Model
American River   RM 9.0074

American River   RM 8.7423
American River  RM 8.4999

American River  RM 8.2695
Lower American River HEC-6T Model
American River  RM 7.7967

American River  RM 7.7179

Lower American River HEC-6T Model
American River  RM 7.5449

American River  RM 7.4169
American River  RM 7.0788

American River  RM 6.9193
Lower American River HEC-6T Model
American River  RM 4.4133

American River  RM 4.1148

Lower American River HEC-6T Model
American River  RM 3.948

American River  RM 3.893
Lower American River HEC-6T Model
American River  RM 1.644

American River  RM 1.2895

Lower American River HEC-6T Model
American River   RM 1.0031

American River   RM 0.3016