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COTTONWOOD CREEK SEDIMENT BUDGET: 2010-2014

FINAL REPORT

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1. Introduction

1.1 Background

This project was conducted by Graham Matthews and Associates (GMA) under US Fish and Wildlife Service (USFWS) Funding Opportunity Number AFRP-08-N05 through the Cottonwood Creek Watershed Group (Cooperative Agreement No. 81330-9-G734). The Anadromous Fish Restoration Program (AFRP) and this project are funded under the legislative authority of the Central Valley Project Improvement Act (CVPIA). The objectives of AFRP are to:

1. Improve habitat for all life stages of anadromous fish through provision of flows of suitable quality, quantity, and timing, and improved physical habitat;
2. Improve survival rates by reducing or eliminating entrainment of juveniles at diversions;
3. Improve the opportunity for adult fish to reach their spawning habitats in a timely manner;
4. Collect fish population, health, and habitat data to facilitate evaluation of restoration actions;
5. Integrate habitat restoration efforts with harvest and hatchery management; and
6. Involve partners in the implementation and evaluation of restoration actions.

Excerpted from the USFWS 2008 Request for Proposals (RFP): Cottonwood Creek Sediment Budget

The USFWS and AFRP, recognized that:

1. Cottonwood Creek provides habitat for three runs of Chinook salmon (fall run, late fall run and spring run, *Oncorhynchus tshwaytscha*) and Central Valley steelhead (*Oncorhynchus mykiss*);
2. Cottonwood Creek is the largest undammed tributary on the west side of the Sacramento River;
3. Well-developed montane, foothill and valley riparian forests abound within the Cottonwood Creek Ecological Management Zone and provide continuity with the Sacramento River Ecological Management Zone;
4. Cottonwood Creek is a critical producer of spawning gravel for the Sacramento river (second only to Cache Creek, supplying ~85 percent of the gravel between Redding and Red Bluff); and
5. Severe streambank erosion in the lower watershed has prompted landowners to implement "piecemeal" responses to reduce property loss (which may include armoring) and that these measures may cause new or exacerbate existing problems elsewhere along the channel.

This created the need for:

1. A coordinated restoration/management effort that emphasizes watershed-scale processes and is supported by up-to-date geomorphic analyses; and
2. A report that is understandable and accessible to individual landowners and the watershed group is a necessity.

Adapted from the USFWS 2008 RFP: Cottonwood Creek Sediment Budget

Key questions presented in the 2008 RFP included:

1. How "stable" is the stream channel?
2. What roles do in-channel islands play and how might the practice of removal of these islands affect the upstream and downstream channel and habitat conditions?
3. Is current channel configuration a limiting factor to aquatic or terrestrial organisms of concern?

4. Is the channel instability due to the amount of aggregate being removed by gravel mining?
5. Are current land use practices affecting the sediment budget in such a way as to create channel instability and if so, why?
6. The main concern is channel instability of the lower watershed, so how the does the bed material budget affect channel response to differing flow events?

This project attempts to develop the priority components of a sediment budget for the Cottonwood Creek watershed. Instream gravel mining as well as other human induced watershed impacts are generally considered to have had significant deleterious impacts on the channel integrity and the supply of spawning sized sediments, thus affecting habitat for a variety of salmonid and other sensitive aquatic species. Recent channel instability in the lower alluvial reaches of Cottonwood Creek may also be related to these impacts. Developing a sediment budget and conducting additional geomorphic analyses will assist stakeholders, land managers, and resource agencies with determining the best strategies in dealing with a variety of sediment related issues within the watershed. Sediment budgets are a useful tool to identify the major source areas for sediment generation, storage, and movement in a riverine system as well as system response to changes in the supply of sediment that often occur as a result of various land use changes. The sediment budget as proposed for the context of this study is intended to identify transport balance and/or imbalance between upstream reaches (e.g. the South Fork Cottonwood Creek) and the lower mainstem.

Alluvial valley reaches in river systems often act as “response reaches,” since they are areas of temporary (in a time frame of tens to hundreds of years) sediment storage that adjust their geometry in response to changes in streamflow and sediment discharge. Thus, episodic events such as large floods may cause the channel location to change, sometimes dramatically, in response to the energy of high flows which exceed the resisting forces of the stream channel banks and riparian vegetation. In a similar manner, large influxes of sediment, whether derived in a single large storm event or delivered chronically over a longer time period, may cause changes in channel form in these response reaches as sediment deposition locally overwhelms the capacity of the channel to transport it. Braided and rapidly laterally migrating channels are often the result. Human occupation of alluvial valley floors may then provide a situation where channel adjustments are seen negatively and attempts to control these adjustments are often made, frequently in a piecemeal manner.

Piecemeal restoration may take the form of bank armoring, high flow deflection structures, or channel straightening. Each of these practices tends to redistribute stream energy in an unbalanced manner which can result in effects such as: increased erosion rates (laterally or vertically), knickpoint migration and decreased alluvial function (e.g. bed and bar scour to claypan, reduced floodplain function resulting from increases in channel capacity and rapid channel migration) (Harvey 2006). In a system exhibiting sediment transport imbalances (such as might be identified in a sediment budget), piecemeal restoration may exhibit even more pronounced, negative effects. Since piecemeal restoration often occurs in response to such imbalances (such as when a dam cuts off upstream sediment supply and “hungry water” rapidly erodes stream banks ([Kondolf 1998]), a rapidly deteriorating feedback loop ensues in which a degraded stream becomes further degraded through short sighted actions, thus exacerbating the problem. Cottonwood Creek may be headed into such a downward spiral (GMA 2003). The goal of this project is to provide the background data to support a reversal of this phenomenon.

1.2 Previous Work

This 2009 project builds directly upon data collected and analyses performed in 2003 by GMA under the *Hydrology, Geomorphology, and Historic Channel Changes of Lower Cottonwood Creek, Shasta and Tehama Counties* project (GMA 2003). The 2003 report focused on the lower mainstem and consisted primarily of:

1. A literature review of relevant geomorphic studies in lower Cottonwood Creek;
2. Conducting a suite of hydrologic analyses for Cottonwood Creek to place geomorphic change within a hydrologic context;
3. Examining sediment transport relations developed from USGS data collected at various points within the watershed;
4. Surveying long profiles and cross sections, many of which had been previously surveyed by others;
5. Constructing historic planform alignments from maps and aerial photographs to compare with contemporary alignments;
6. Collecting and analyzing bed surface and bulk sample grain size information within selected sub-reaches.

1.3 Approach and Objectives

The GMA proposal to the 2008 RFP included a strategy to address most of the USFWS/AFRP key questions (see Section 1.1) with a sediment budget-based approach. The study design entailed three primary elements: (1) Geomorphic Mapping, (2) Sediment Transport Monitoring, and (3) Data Analysis. The goals of this approach were to develop a sediment budget, describe the geomorphic trajectory of lower Cottonwood Creek and provide recommendations to guide potential management actions.

The project scope was expanded by a modification in 2011 to include: (1) detailed study site assessments to investigate the effects of island removal using hydraulic models to predict habitat changes, (2) a greater sediment transport monitoring effort; and (3) an expansion of the data analysis task to include comparisons with historic data sets. The three original primary project elements were then reorganized and expanded into the following objectives (arranged by category):

1. Hydrology
    - Update the 2003 long-term hydrologic analyses through Water Year (WY) 2014;
    - Re-occupy two historic USGS streamflow stations along the South Fork and upper mainstem of Cottonwood Creek;
    - Compute 15 minute discharge for each of the five years in the study period to support sediment discharge calculations.
2. Sediment Transport Monitoring
    - Establish continuous turbidity monitors at the stations described above and at the USGS Cottonwood Creek near Cottonwood site (#11576000);

- Collect suspended sediment samples for the purpose of computing annual suspended sediment loads from turbidity; and
- Collect a limited number of bedload samples to facilitate estimation of total sediment load.

3. Geomorphic Mapping
    - Re-survey 2002 GMA cross sections and profile;
    - Survey cross sections at each gaging location for potential modeling support;
    - Map topography at selected focused study sites to support hydraulic model development;
    - Using 2011 orthophotos:
        - Develop centerline alignment to compare with previous years;
        - Examine sequential claypan exposure.
4. Hydraulic/Habitat Modeling at one or more focused study sites
    - Using the data collected under “Geomorphic Mapping – topography,” develop a 2D hydraulic model;
    - Model hydraulics and habitat attributes for anadromous salmonids under existing conditions and as modified by potential management actions such as island removal; and
5. Data Analysis and Evaluation
    - Calculation of hydrologic analyses
    - Field survey data processing and analysis
    - 2-d hydraulic modeling and habitat-attribute interpretation of selected study sites Streamflow, turbidity, and sediment transport data reduction and analysis
    - Sediment data (laboratory) processing and analysis
    - Develop the Sediment Budget
    - Synthesize analyses into a description of lower Cottonwood
    - Prepare final reports
    - Attend public meeting to discuss findings

The original proposal also included facies mapping, examination of other sites documented in the 2003 report, and selected volumetric computations which were not implemented.

We understood from the outset that no single line of inquiry (e.g. sediment transport monitoring) would likely explain the geomorphic trajectory of Cottonwood Creek. We hoped instead that the results of sediment transport monitoring, geomorphic assessments and hydraulic/habitat modeling could be synthesized to illuminate the sediment-related geomorphic trajectory of lower Cottonwood Creek, thus informing management strategies.

1.4 Report Organization

Due to the data intensive nature of this project and acknowledging USFWS/AFRP’s desire to generate an easily understood document, most of the data is relegated to the Appendix. The Methods and Results sections are fairly technical and the reader wishing to “get to the point” may wish to only examine the Synthesis and Recommendations sections, which are relatively short and are less technical in nature.

Definitions useful for this report:

"Sediment discharge" is often used to describe both the instantaneous rate of sediment transport and/or the cumulated load over time. While others' definitions may vary, in this report we attempt to distinguish between sediment discharge and sediment load as follows.

(1) Sediment discharge: an instantaneous sediment transport rate, expressed in mass or volume per unit time (tons/day). For example, "a bedload discharge of 105 tons/day was measured on the Trinity River below Limekiln Gulch sample measurement #7 on 5/6/12 at 13:15;" and
(2) Sediment load: a mass or volume of sediment transported over a pre-defined unit of time (tons). This is the rate (sediment discharge) integrated over a period of time. For example, "674 tons of bedload were transported past the Trinity River below Limekiln Gulch monitoring station during the WY 2013 Spring Flow Release".

In this report, *sediment discharge* describes sediment in transport, and *sediment load* describes the amount that was accumulated over a longer time period. A useful comparison is with streamflow: discharge is the instantaneous rate (cfs, analogous to sediment discharge) and yield is the volume of water cumulated over time (acre feet, analogous to sediment load).

We use the term "sediment budget" in this study to describe relative rates of sediment production between the entire watershed and selected sub-watersheds. Other components of a sediment budget (such as upslope delivery and quantification of storage) are beyond the scope of this particular study.

2. METHODS

2.1 HYDROLOGY

The purpose of this section is to provide a succinct overview of office methodologies employed for collection and analysis of precipitation and streamflow data.

2.1.1 Precipitation Data

Long-term precipitation data for the project vicinity were obtained and annual totals and cumulative departure were plotted to evaluate trends over time.

2.1.2 Streamflow Data

Presently, one USGS streamflow gaging station is operated in the Cottonwood Creek watershed: the USGS gage near Cottonwood (no. 11376000). Historically, a number of USGS gages have been maintained in the basin (Table 1, Figure 1) on the mainstem and on the North, Middle, and South Forks. Only the Cottonwood Creek near Cottonwood (CCNC) gage is still in operation (period of record 1941-present), and all other gages were discontinued by 1986. For this report, only the following gages are used for analysis:

1. USGS 11376000, Cottonwood Creek near Cottonwood (CCNC) with its 73 years of record is used for historical and statistical analyses;
2. USGS 11375810 – Cottonwood Creek near Olinda (CCNO), reoccupied for this study; and
3. USGS 11375900 -- SF Cottonwood at Evergreen Road (SFCC), reoccupied for this study.

A variety of streamflow data were obtained from the USGS for the CCNC station, including station descriptions, the 9-207 listing of all discharge measurements since operation of the gage began, mean daily flows for the period of record, annual runoff for the period of record, and instantaneous peak discharges. These data were analyzed for magnitude, duration, and frequency and were used for historical and statistical analyses.

Table 1. USGS gaging stations within the Cottonwood Creek, California watershed.

Station Number	Station Name	Drainage Area (mi2)	Period of Record
11374400	Middle Fork Cottonwood Creek near Ono	244	1957-75
11375500	North Fork Cottonwood Creek at Ono	58.8	1908-13
11375700	North Fork Cottonwood Creek near Igo	88.7	1957-80
11375810	Cottonwood Creek near Olinda	395	1971-86
11375815	Cottonwood Creek above South Fork, near Cottonwood	478	1982-85
11375820	South Fork Cottonwood Creek near Cottonwood	217	1963-78
11375870	South Fork Cottonwood Creek near Olinda	371	1977-86
11375900	South Fork Cottonwood Creek at Evergreen Rd near Cottonwood	397	1982-85
11376000	Cottonwood Creek near Cottonwood	927	1941-present

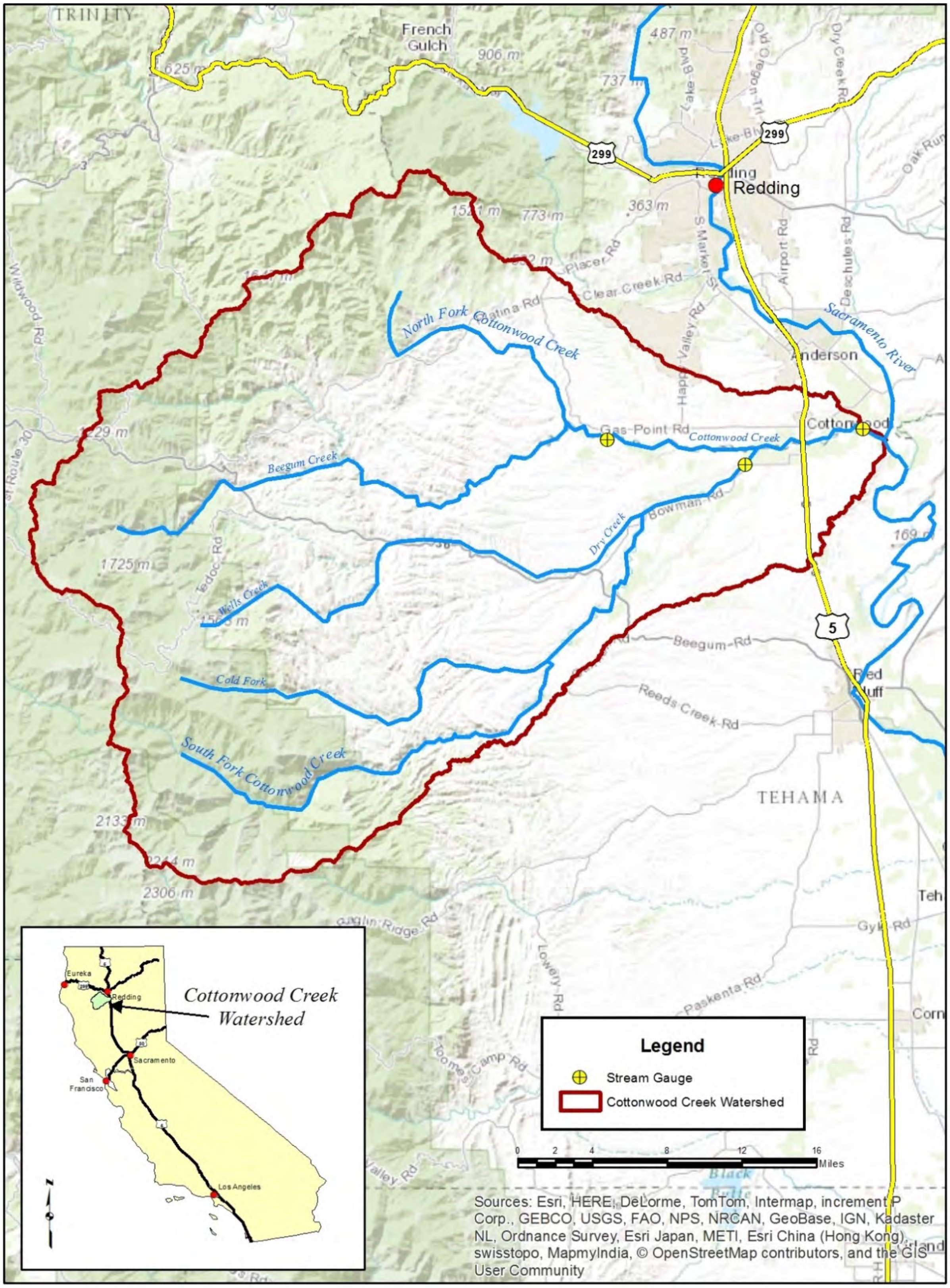

Figure 1. The Cottonwood Creek watershed showing the locations of two historic and current USGS gaging stations. From left to right: CCNO 11375810, SFCC 11375900 and CCNC 11376000.

2.1.3 Flood Frequency

Flood frequency analysis is a statistical examination of the hydrologic record. Using annual peak discharges, the likelihood that a peak flow (equaling or exceeding a certain magnitude) will occur in a given year as the annual peak, can be computed. The method assigns probabilities to flood magnitudes, expressed as recurrence interval (the average period in years between peaks of a given size or larger), or exceedance probability (the percent chance a peak will be equaled or exceeded in any year, expressed as the inverse of recurrence interval). A variety of plotting position formulae and probability distributions can be applied to flood peak data: the Weibull plotting position formula and the log-Pearson Type III distribution have been selected as the standards by federal agencies (Gordon et al, 1992).

Annual maximum peaks were obtained from the USGS for the Cottonwood Creek near Cottonwood gage for WY1941 to WY2014 (WY2014 data are provisional). Using the USGS PeakFQ program, standard techniques (USGS 1982) were applied to generate the log-Pearson III flood frequency curve.

2.1.4 Flow Duration

Flow Duration analysis relates mean daily discharge to its frequency of occurrence based on the complete historic record of mean daily flows. All mean daily flows are ranked by magnitude and the exceedance probability of each discharge is computed.

2.1.5 Water Year 2010-2014 Stream Gaging

During the five year study period, GMA operated two gages within the watershed: one on the mainstem near Olinda (CCNO) just below the confluence with the North Fork (reoccupation of USGS 11375810) and one along the South Fork of Cottonwood Creek (SFCC) at Evergreen Road (reoccupation of USGS 11375900, Figure 1). For descriptive purposes, the GMA gage at South Fork Cottonwood Creek at Evergreen Road (SFCC) is included here. The purpose of gaging at this location is to quantify streamflow and sediment exiting the South Fork Cottonwood sub-basin.

A Campbell Scientific CR850 data collection platform (DCP), Design Analysis, Inc. (H-310) pressure transducer and a Forest Technology System, Inc. (DTS-12) turbidimeter were installed at the site. H-310 pressure transducer accuracy is to 0.01 ft. DTS-12 turbidimeter accuracy at 25 C: 0-499.99 NTU is ± 2 percent and 500 to 1600 NTU ± 4 percent. The DCP is housed in a locked steel box that is installed on the left bank approximately 40 feet downstream of Evergreen Road. The DTS-12 is attached to a fixed mount that is located 12 feet from the left bank and approximately 40 feet from the DCP enclosure. The pressure transducer is located on the riverbed approximately 10 feet from the left bank. Three USGS style A staff gages mounted on redwood were attached to channel iron that has been driven into the streambed, adjacent to the turbidity probe on the left bank: limits 0.0 ft. to 10.12 ft.

Streamflow measurements were generally collected according to standard USGS protocols using wading or boat techniques and Price AA current meters. High flow measurements were collected from either a cataraft on a cableway or from a jetboat (Figure 2). Some high flow measurements utilized an ADCP (Acoustic Doppler Current Profiler) paired with a GPS receiver to provide spatial orientation. The gage was downloaded monthly and checked for drift periodically.

All discharge measurements were entered and catalogued using a modified USGS-type 9-207 discharge measurement summary form. Stage/discharge relationships (rating curves) were developed and applied to the adjusted continuous-stage records to generate 10 or 15 minute discharge records within the WISKI hydrologic software database, a comprehensive hydrologic time-series database management system developed by Kisters AG. The WISKI Suite incorporates complete USGS standards for surface water streamflow computations which utilize methods according to *WSP 2175, Measurement and Computation of Streamflow vols.1 and 2* (Rantz 1982). The USGS Cottonwood Creek near Cottonwood gaging station data (USGS 11376000) was used to provide supporting data for the project -- for hydrographic comparison and statistical examination of the computed hydrologic records (USGS 1982, Gordon et al, 1992).

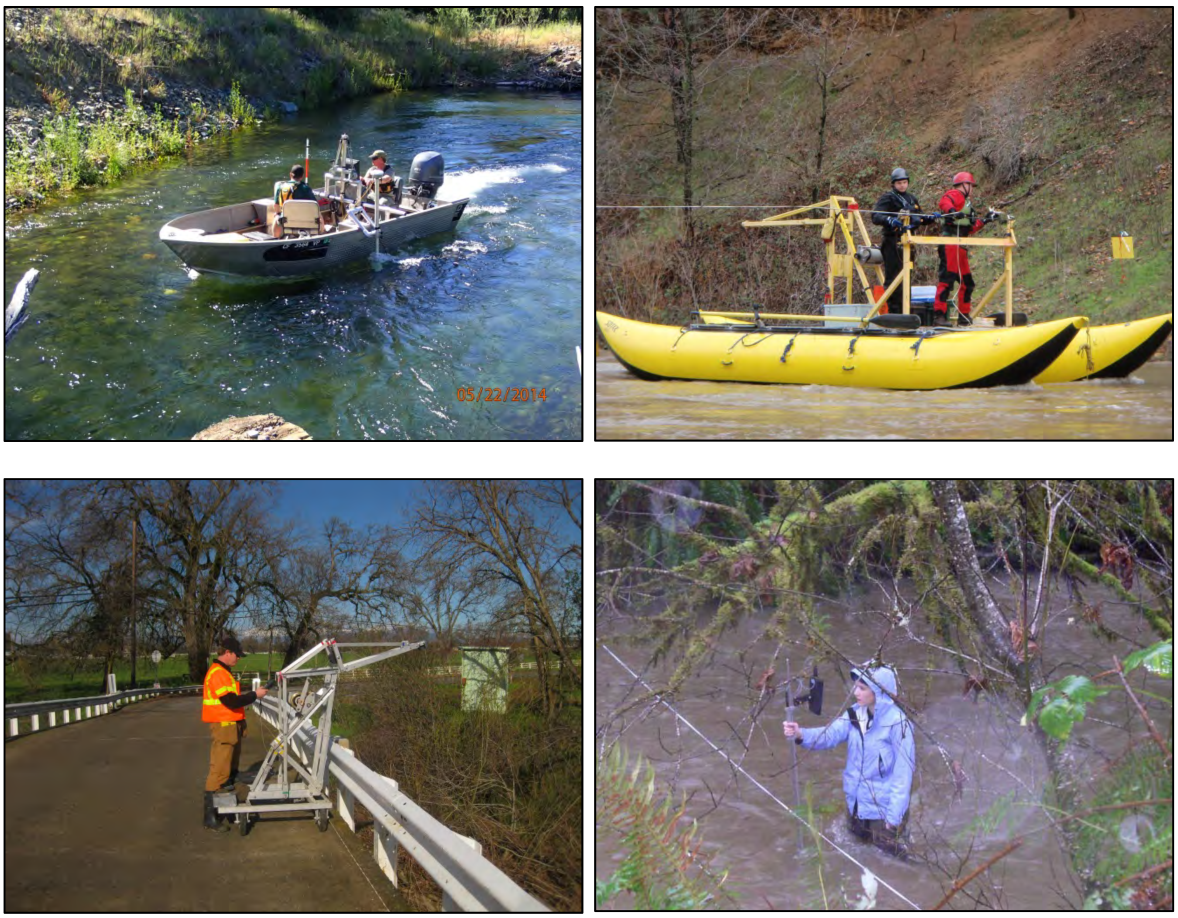

Figure 2. Discharge measurement using two different boat-based platforms, a bridge based platform and wading. Clockwise from top left: a jetboat outfitted with GPS/RTK and an ADCP, a cataraft on a cableway utilizing standard reel-meter-sounding weight, a bridge crane at South Fork Evergreen Road and a wading measurement utilizing a current meter and a topset rod.

2.2 Sediment Transport

2.2.1 Continuous Turbidity

Continuous turbidity (collected as described in Section 2.1.5) was utilized as a surrogate for continuous suspended sediment concentration (SSC), once a relationship between turbidity and suspended sediment concentration had been established.

2.2.2 Suspended Sediment Sampling

Depth-integrated turbidity and suspended sediment sampling was performed at three locations within the watershed (CCNO, SFCC and CCNC). Sampling was performed using either a US DH-48 Depth-Integrating Suspended Sediment Sampler (for wade-able flows), a US DH-59 Depth-Integrating Suspended Sediment Sampler (rope-deployed from the cataraft at un-wade-able flows), or a D-74 Depth-Integrating Suspended Sediment Sampler (cable-deployed from a bridge, cataraft or jetboat at un-wade-able flows). A temporary cableway was suspended near the CCNO gage for deployment of the cataraft (Figure 2). Standard methods, as developed by the USGS and described in Edwards and Glysson (1998) and in the GMA QAPP (GMA 2002), were generally used for sampling. Suspended sediment concentrations were computed in the GMA sediment lab following USGS and ASTM D-3977 protocols. A laboratory QAPP is available to interested parties.

2.2.3 Bedload Sampling

A 6x12 inch TR-2 bedload sampler (Figure 3) was lowered from the same cataraft crane assembly described in the methods for discharge. A two-thirds scale TR2 (Elwha sampler) was used from a bridge crane and from the jet boat. Wading measurements utilized an aluminum Elwha sampler with a rod attached. Sampler bags utilized 0.5mm mesh fabric. The fraction <0.5mm which escaped the sampler was not accounted for. Standard methods, as developed by the USGS and described in Edwards and Glysson (1998), were used.

Beginning and end stations, sample interval, sample duration, start time and end time, beginning and end gage height, and pass number were recorded. All bedload sample data are stored together in Excel workbooks. Bedload samples were processed at the GMA coarse sediment lab in Placerville, California. Processing involves sieving and computing the percent retained in each sieve class as determined by weight. These data are entered into Excel spreadsheets for subsequent conversion to the cumulative percentage finer (by weight) than the corresponding sieve size.

Figure 3. Bedload sampling from a cataraft using the 6x12 inch TR2 and from a bridge crane utilizing the 2/3 scale Elwha bedload sampler with a 4x8 inch aperture.

2.2.4 Sediment Load Computation

Utilizing the annual streamflow and turbidity records, and the sample data, annual loads were computed for suspended sediment using continuous turbidity as an index of continuous suspended sediment concentration (SSC). Equations were developed utilizing turbidity as the independent variable, and concentration as the dependent variable. For some periods of missing turbidity record, a relation between discharge and concentration was used. Continuous SSC (mg/l) was computed using the gaging record (Q, cfs) and the appropriate equation for each 15 minute period in the gaging record. The corresponding discharge for each period was used to compute the continuous loads (SSC (mg/l) x Q (in cfs) x 0.002697, in tons/day) which were then summed for the entire period of record. Bedload discharge was computed using the observed fraction of bedload in the total load. Total load (the sum of suspended and bedload) is considered estimated.

2.3 Geomorphic Mapping

2.3.1 Surveys

<u>Longitudinal Profile Data Collection</u>

In July of 2011 GMA re-surveyed the longitudinal profile from 2,500 ft above Little Dry Creek (approximately 5 miles upstream of the South Fork, see yellow trace in Appendix 4-1) to the confluence of the Sacramento River. For the most part, the survey follows the thalweg (deepest portion), though in some deep areas it is impossible to discern the thalweg, thus we refer to this as a longitudinal profile. The profile survey was conducted using a single-beam sonar system that was deployed from a 19-ft Sotar Cataraft (Figure 4). Geodetic control was provided using a shore-based Trimble R8 Model 3 GNSS receiver broadcasting RTK corrections to the survey vessel by UHF radio link. The survey vessel was equipped with an Ohmex Sonarmite MilSpec portable single-beam sonar and a Trimble R8 Model 3 GNSS receiver. The sonar data and RTK GNSS data were combined in a ruggedized laptop computer running Hypack hydrographic surveying software.

Figure 4. Terrestrial topographic surveying with GPS/RTK and bathymetric surveying with a cataraft equipped with a depth sounder coupled with GPS/RTK.

Longitudinal Profile Data Processing and Analysis:
The longitudinal profile data was processed in the Hypack hydrographic surveying software package. Processing included removing spikes and drop-outs in the data as well as removing small localized features (wood and boulders) that would adversely affect the profile. Once processing was complete the data was exported to ArcMap for further analysis.

Using ArcMap, planform alignments were created for each of the long profiles. Analysis indicated a channel length difference of 2,300 feet, with the 2011 longitudinal profile being longer than the 2002 profile. In order to make the profiles comparable a mean profile alignment was developed. The mean alignment was developed as a generalization of the two surveyed alignments when viewed in planform. Once the mean alignment was developed, the survey points collected during each of the longitudinal profile efforts were located along the mean alignment and prepared for plotting in Excel.

Topography

LiDAR Data Collection and Processing:
GMA contracted Watershed Sciences (Now Quantum Spatial) to acquire and process high resolution LiDAR and well as color orthophotography from the North/Middle Fork confluence of Cottonwood Creek to the confluence of the Sacramento River. The LiDAR and photos were collected in July of 2011. Details on data acquisition and processing can be found in Appendix 3-26. GMA obtained this proprietary LiDAR dataset independently, under the assumption that it would prove immensely valuable for a variety of Cottonwood Sediment Budget analyses (e.g. verification of cross section shots, valley profile analysis, topographic map development and supplemental cross section data).

Baker Ranch Data Collection:
Detailed channel topography, conventional and sonar, were collected at the Baker Ranch (see Appendix 3-6, cross section 104) to support a Hydraulic Modeling effort to assess hypothetical channel modifications and their impact on channel hydraulics and subsequently, fish habitat. Sonar data were collected using a single-beam sonar system as described for the long profile but traverses and profiles

were collected in order to provide approximately a 4 foot grid. In general, sonar data were collected in areas with water depths exceeding 1.5 feet.

Conventional survey data collection in wade-able areas included GPS and Total Station surveying equipment. The GPS equipment included Trimble R8 Model 3 GNSS receivers and additional survey data was collected with a Leica 1201+ robotic Total Station. Conventional surveys were conducted both as breakline and grid based surveys depending on the type of topography encountered by the survey technician. All conventional survey data were stored in Trimble TSC3 data collectors running Trimble Access survey software. In general conventional survey data was collected in dry areas and in areas were water depths were less than 1.5 feet.

Baker Ranch Data Processing and Analysis:

Sonar data was processed using Hypack hydrographic surveying software package. Processing included removing spikes and drop-outs in the data. Once processing was complete the sonar data was exported to ArcMap for integration with the conventional and LiDAR data sets. Conventional survey data was processed in Trimble Business Center Software. Processing Included: verifying values for geodetic control, verifying and modifying rod heights, verifying and modifying point codes, and sorting the data to various layers. Once processed, the conventional survey data were exported to ArcMap for integration with the sonar and LiDAR data sets.

Once initial processing of the various data sets was complete all data were integrated in ArcMap to form a single digital terrain model (DTM). A Triangulated Irregular Network (TIN) was used as a basis for integrating the various data sets. Integration included developing and applying breaklines, hydro flattening of the LiDAR data set, and developing DTM extents. The final TIN was converted to a Raster and exported for hydraulic model development.

Cross Section Data Collection

In July 2011, during the longitudinal profile data collection effort, GMA re-surveyed a subset of the cross sections that were surveyed in 1999 and 2002 (GMA 2003). Cross section data were collected using conventional and sonar surveying equipment. Conventional survey data was collected using a Trimble R8 Model 3 GNSS receiver mounted to a survey rod and the sonar data was collected using the same equipment and techniques as described the longitudinal profile. Collection of conventional survey data was limited to areas with water depths less than 1.5 feet and included a limited number of dry terrestrial shots. The assumption during cross section data collection was that the LiDAR could be relied upon for all dry surfaces and the focus should be on mapping the wetted channel.

Cross Section Data Processing and Analysis

Sonar data was processed using Hypack hydrographic surveying software package. Processing included removing spikes and drop-outs in the data. Once processing was complete the data was exported to ArcMap for integration with the conventional and LiDAR data sets.

Conventional survey data was processed in Trimble Business Center Software. Processing included: verifying values for geodetic control, verifying and modifying rod heights, verifying and modifying point codes, and sorting the data to various layers. Once processed, the conventional survey data were exported to ArcMap for integration with the sonar and LiDAR data sets.

Once initial processing of the various data sets was completed the data was compiled in ArcMap so that integrated cross sections could be developed. In general the cross section alignments surveyed in 1999 through 2002 were maintained. However in some instances it was necessary to modify the alignments to accommodate channel planform changes. Once final alignments were developed, the LiDAR DTM (3-ft Raster) was sampled along the alignment at the raster resolution. Water return data in the LiDAR data set was removed and the bathymetric data was inserted. Bathymetry data were inserted as points using a spacing of roughly 3 feet.

After developing the 2011 cross section data it was plotted in Excel for comparison with the cross section data collected during the 1999-2002 period. Comparison of fixed surfaces (i.e. terraces) indicated that there were some elevation issues in the 1999-2002 dataset. In order to make cross sections comparable, the 1999-2002 data were adjusted using the LiDAR as a reference. Only cross sections with common alignments were compared.

Valley Profile Departure

A valley profile (generalized valley slope) was developed using the LiDAR DTM and the orthophotos. Using ArcMap, points were generated along the valley floor at locations that seemed to represent the general slope of the valley. Once the points were located the LiDAR DTM was used to assign elevations to the points. Finally, points were located along the mean alignment used for the long profile comparison. The data was exported to Excel for analysis.

2.3.2 Aerial Photo Analysis

Claypan Exposure

Commonly referred to as “claypan” or “hardpan,” clay-like structures occur along Cottonwood Creek in the form of adjacent, crumbling cliffs and as sheets or ribs exposed along the riverbed following scouring events (Figure 5). The material is likely composed of Tehama Formation materials, gray or tan or yellow in color and consisting of clay, silt, sand and in some cases fine gravel (DWR 1992, USGS 1999). The grain size distribution within the formation can vary (California Division of Mines and Geology, 1969) as does presumably its resistance to erosion. Claypan often scours in the form of deep slots, leaving ribs exposed as a “fluted” appearance. These slots often capture the low flow stream channel and are generally considered deleterious to salmonid rearing and spawning habitat (McBain and Trush, 2000).

Using Google Earth © historical imagery we examined five locations along Cottonwood Creek where claypan has become increasingly more exposed since 1998. We did not conduct a basin-wide assessment of claypan exposure, rather we chose what we felt were representative areas within distinct geomorphic sub-reaches. Selection criteria are further explained in Section 3.3.2.


Figure 5. Two types of claypan (Tehama Formation) along lower Cottonwood Creek: adjacent cliffs, slowly retreating due to undercutting along the toe, and substrate exposure along the streambed.

GMA conducted two low elevation aerial-photography reconnaissance flights (courtesy CDFW) in April 2010 and April 2012. Using Google Earth © historical imagery, we examined five locations along Cottonwood Creek where claypan has increased since 1998 (we use 1998 as the benchmark because the earliest photos in the Google Earth © historical imagery showing adequate resolution to identify claypan are from 1998). During the course of the study, GMA conducted numerous field campaigns (e.g. mapping longitudinal profile, hiking the stream channel) and we were able to ground-truth our interpretations. Claypan is readily apparent in photographs with adequate resolution. It stands out as a tan block against a field of white gravel or against the green water in the channel. Some (but not all) exposures are readily identified underwater. Note that we do not quantify claypan exposures (e.g. area or thickness); rather we qualitatively describe the progressive exposure over time relative to high flow events and consequent changes in planform geometry. Historical imagery from the following years was utilized: 1998, 1999, 2003-2007, 2009-2013. Not all photos were available for all sites.

<u>Channel Planform Alignment</u>

Channel planform alignments were generated for 2003, 2006, and 2011. The 2003 and 2006 alignments were developed using the National Agriculture Imagery Program (NAIP) imagery whereas the 2011 alignment was developed using the 2011 orthophotograhy collected by Watershed Sciences. Alignments were developed by delineating the channel centerline. In cases where split channels were encountered the alignment follows the apparent predominant flow path.

2.4 Habitat and Hydraulic Modeling

GMA Hydrology contracted with McBain Associates to conduct a comparative analysis to evaluate potential impacts to salmonid habitat and river hydraulics associated with management actions (e.g. island removal) intended to reduce active bank erosion. We modeled one site using the 2-D hydraulic model System for Transport and River Modeling (SToRM). The comparative analysis assessed changes in instream hydraulics (depth, velocity, and bed shear stress) and salmonid habitat (fall-run Chinook fry, juvenile, and spawning – and steelhead juvenile rearing) for three flows (1,800 cfs, 4,800 cfs, and 7,800 cfs).

Tasks included:

1. Import existing topographic and bathymetric data provided GMA Hydrology into AutoCAD Civil 3D to prepare baseline topography for 1-D and 2-D hydraulic models;
2. Prepare 1-D hydraulic model from existing topography to establish upstream and downstream boundary conditions;
3. Prepare roughness polygons for open channel and vegetated areas for use in 2-D hydraulic model;
4. Assess 2-D hydraulic model stability (change in outflow between iterations), and model convergence (inflow vs. outflow);
5. Prepare two alternative grading plans based on GMA Hydrology recommendations with the objective to reduce bank erosion;
6. Compare instream hydraulics (depth, velocity, and bed shear stress); and
7. Compare changes in salmonid habitat (fall-run chinook fry, juvenile, and spawning– and steelhead juvenile rearing) at three flows (1,800 cfs, 4,800 cfs, and 7,800 cfs) for existing site conditions and grading alternatives.

Modeling results from SToRM are output and post processed in Arc GIS to allow comparison between existing conditions and proposed alternatives, including: shear stress, velocity, depth, and up to four life stages of salmonid habitat.

Methods used to evaluate changes in habitat were chosen based upon consultation with USFWS' Mark Gard (see Appendix 5):

- Weighted Usable Area (WUA) habitat values calculated from depth and velocity habitat suitability index developed by USFWS on Clear Creek in Northern California; and
- Binary criterial established from the upper 60% of the same depth and velocity habitat suitability index used to calculate Weighted Usable Areas.

3. RESULTS

A summary of data collected and analyses performed as part of this five year study is provided in Table 2. Due to the data-intensive nature of this project, most of the data is relegated to the Appendix. Only the most relevant figures and tables are presented in the text. Please refer to the Appendix for more detail.

Table 2. GMA work summary: data acquisition and analyses completed for WY2010-2014 Cottonwood Creek Sediment Budget project.

Geomorphic Mapping	#	Hydrology	#
Field Efforts		**Field Efforts**	
Longitudinal profile	1	Gaging stations constructed	2
Cross sections reoccupied	24	Gaging stations operated (years)	8
Topography/bathymetry	2	Discharge measurements	52
Analyses		**Analyses**	
Topographic/bathymetric surfaces	1	Hydrologic analyses using historic data	10
Longitudinal profile comparions	6	Discharge ratings developed	4
Cross section width change analysis	19	Annual discharge records computed	8
Cross section elevation change analysis	19	**GIS or Aerial Imagery Analyses**	**#**
Sediment Transport	**#**	Aerial photo planform anlayses	3
Field Efforts		Progressive claypan exposure investigations	5
Suspended sediment samples collected	55	Mean alignments developed	1
Box Samples (Correlation Samples)	50	Maps developed	8
Bedload samples collected (passes)	26	Valley Profile Departure Anaylsis	2
Continuous Turbidimeter - Years Operated	8	**Hydraulic Modeling**	**#**
Analyses		Sites modeled	1
Annual turbidity records corrected	8	Flows modeled	3
SSC vs Turbidity relations developed	2	**Other Analyses, Investigations, Data Acquisitions**	**#**
SSC vs Discharge relations developed	3	Lab Analysis: Bottles analyzed for SSC (aprox)	600
Continuous SS discharge computed	13	Lab Analysis: Bedload samples analyzed	26
Annual bedload discharge calculations	13	Field reconnaissance trips	3
Annual total sediment load calculations	13	CDFW sponsored fly-overs	2
Historical sediment load calculations	3	LiDAR Data Acquisition	1
Sediment yield calculations	4	Orthorectified Aerial Imagery	1
Individual storm load calculations	9	Photographs collected (aprox)	500

3.1 HYDROLOGY

Supporting data for this section are provided in Appendix 1 – Hydrologic Data. The purpose of this section is to (1) provide an update to the GMA (2003) longer-term hydrologic analyses (e.g. flood frequency); and (2) to describe the setting for this WY2010-2014 study based upon GMA and USGS stream gaging efforts.

3.1.1 Hydrologic Setting

Cottonwood Creek drains a basin of about 927 square miles (mi^2) upstream from the USGS gaging station near Cottonwood (USGS 11376000), located at river mile 2.8 (with virtually no change in drainage area) above the confluence with the Sacramento River. This gage, with its record dating back to 1940, provides the dataset with which most of the 2014 hydrologic analyses were conducted. The Cottonwood Creek watershed rises to over 8,000 feet at the crest of the Coast Ranges, which separates

Shasta and Tehama Counties to the east from Trinity County on the west. The entire watershed is essentially unregulated, although a small reservoir, Rainbow Lake (capacity 4,800 acre-feet), is located on North Fork Cottonwood Creek. Normal annual precipitation for the entire Cottonwood Creek watershed has been estimated by the U.S. Army Corps of Engineers (1977) at 36.3 inches.

3.1.2 Previous Work

Previous hydrologic analyses of various types have been conducted by U.S. Army Corps of Engineers (1977), the USGS (McCaffrey et al., 1988), Water Engineering & Technology, Inc. (1991), and GMA (2003).

3.1.3 Precipitation

Precipitation in the Cottonwood Creek Watershed, as is typical of California, is highly seasonal, with about 90 percent falling between October and April. A small portion of the annual precipitation falls as snow at the higher elevations in the upper watershed, but snowmelt runoff is typically not a major component of the streamflow in the Cottonwood Creek Watershed. Occasionally though, rain-on-snow events can produce large floods. Normal annual precipitation for the watershed is about 36 inches (U.S Army Corps of Engineers 1977). The isohyetal maps for the watershed for the 1911-1960 period indicate that annual precipitation generally increases toward the higher elevations along the western portion of the watershed, increasing from about 25 inches per year in the lower reaches to over 70 inches in the high elevations along the watershed divide.

There are relatively few long-term precipitation stations near the basin and none located high in the watershed. The longest record is that of the National Weather Service Red Bluff gage roughly ten miles to the south of the mouth (elevation 353 feet, with a period of record of 1905-present). The Red Bluff gage was used in this 2014 analysis. Rainfall data are generally presented by calendar year (Jan-Dec), which means little in a hydrologic context when streamflow phenomena are examined by Water Year (WY). Therefore, we cumulated rainfall totals within Water Years so that the data represent discreet wet seasons (October 1 – September 30). Figure 6 shows the WY precipitation totals at Red Bluff along with the computed cumulative departure from the mean for WY1906-2014. The wettest Water Year is 1995, when precipitation totals reached 47.83 inches, slightly wetter than 1941, 1983 or 1998, the next three highest, when 45.03, 44.86, and 45.82 inches respectively, were recorded. The driest year at Red Bluff was 1924, when only 9.0 inches of precipitation were recorded and the second lowest is WY2014, with only 10.04 inches. *Note: conducting this analysis using calendar years lends quite different results than cumulating by water year (e.g. the driest year is 1976 and the wettest is 1998, GMA 2003).*

The mean for the 108-year record for Red Bluff is 22.55 inches, considerably less than the Army Corps watershed-average estimate (1977). This difference is likely due to the basin-averaging effect, which includes areas with much higher rainfall than measured at Red Bluff only. Cumulative departure from the mean is a measure of the consecutive and cumulative relationship of each year's rainfall to the long-term mean. The cumulative departure line descending (left to right), indicates a relatively drier period, while an ascending line denotes a relatively wetter period (Figure 6). Some researchers argue that the technique is more appropriate for describing short term trends than long term (multiple decades) trends

(Weber and Stewart, 2004), thus we present this analysis to describe apparent short term patterns in the 109 year record.

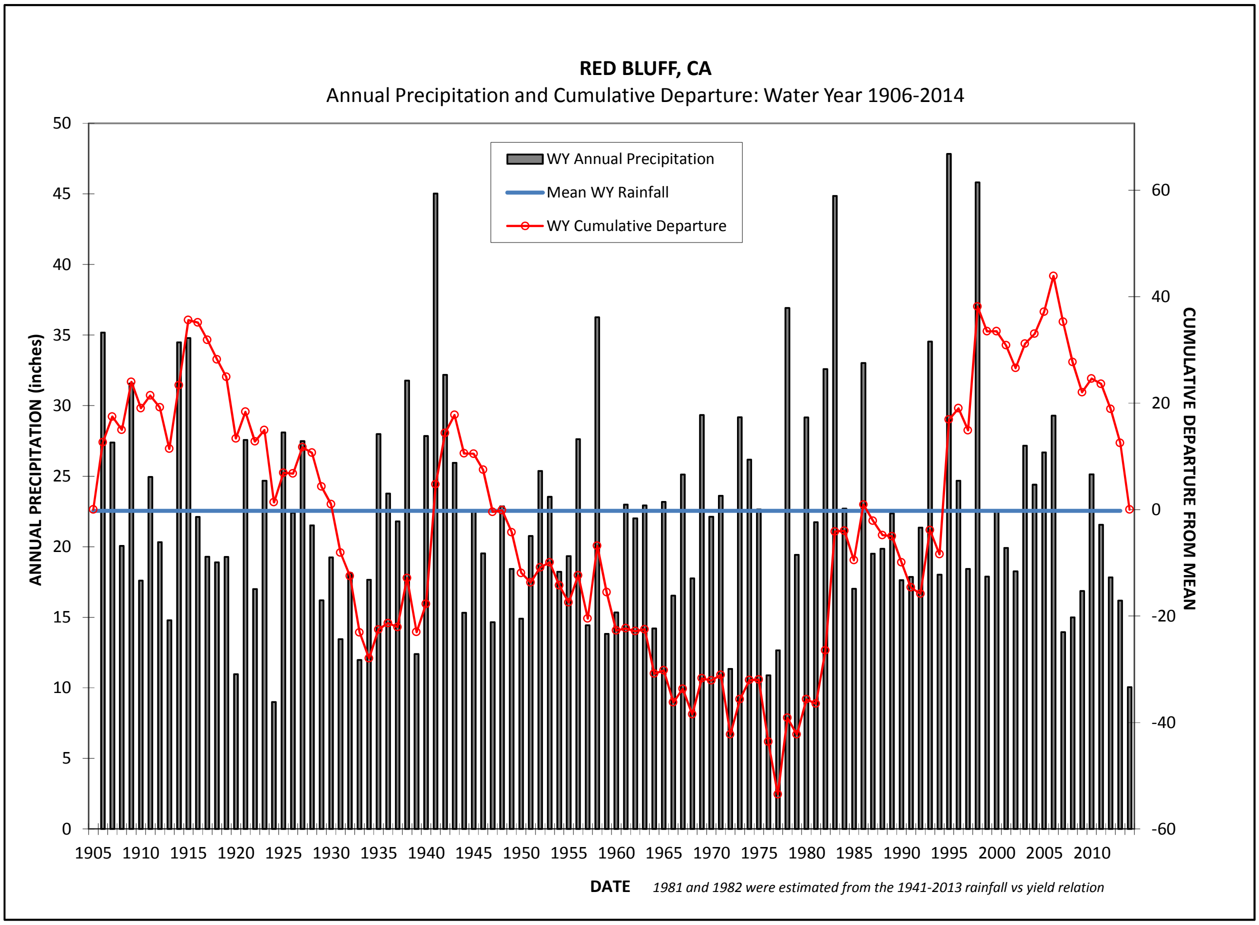

Figure 6. Annual precipitation by water year for Red Bluff, California, 1906-2014.

In the Red Bluff data (Figure 6), a slightly wetter than normal period appears from 1906 through 1915, followed by a prolonged drought period from 1916-1934. 1935-1943 was a wet period, followed by a prolonged dry period that lasted essentially from 1944 to 1977. 1978-1986 was a wet period followed by the 1987-1992 dry period. 1992 through 2006 was essentially a wet period but since 2006, Red Bluff has shown a steady decline into the recent drought. 2014 (10.04 inches) was even drier than the historic 1976 (10.89 inches) drought but wetter than the driest Water Year, which was 1924 with only 9.0 inches.

3.1.4 Streamflow

Most of the following analyses were computed through WY2014 using USGS provisional data for 2014. When provisional data were not available, analyses were conducted through WY2013.

Daily Flows

A flow duration analysis was performed using the historic mean daily discharge records for the USGS gage Cottonwood Creek near Cottonwood (Appendix 1-2). The analysis indicates that Cottonwood Creek only exceeds 2,000 cfs (as the daily mean) 10 percent of the time, or 36 days per year on average. Instantaneous discharges of 2,000 cfs occur far more frequently, though are of much shorter duration and are thus obscured in the daily mean analysis of flow duration. Fifty percent of the time flows are below 224 cfs.

Monthly Flows

As Appendix 1-3 shows, the distribution of streamflow for Cottonwood Creek is dominated by rain runoff during the months of January through March. Significantly lower monthly average totals occur in December and April. Although large rainstorms have occurred in November-December and April-May, they are infrequent enough not to have a large effect on the mean monthly flows for the 73 year period of record.

Annual Flows

Annual precipitation is not a robust indicator of flood magnitude, as substantial flood peaks often occur in years with only normal or slightly higher than normal precipitation. However, annual rainfall (by Water Year) is a reasonable predictor of annual runoff or yield (Figure 7, Appendix 1-5). 1941, 1958, 1983 etc. all show very high rainfall and very high annual yields. Monthly (and thus annual) runoff has been measured in the Cottonwood Creek watershed at the USGS streamflow gage since October 1940 (WY1941). The mean annual runoff for the 1941-2014 period is 626,000 acre-feet. The range of annual runoff totals is large, with only 68,000 acre-feet in 1977, while 1983 had almost 2 million acre-feet. Large volumes of runoff are often (but not always) associated with large flood years and always with years of high annual precipitation. The two largest annual runoff years were 1983 and 1998, followed by 1941, 1958, and 1995. Only one of the five largest volumes of runoff is associated with a large peak-flood year (1983). The other years had very high annual precipitation but no unusually large individual flows were generated. Four particular dry periods stand out in a cumulative departure analysis of annual runoff, 1942-1951, 1958-1968, 1986-1994 and 2006 to present (Figure 7). The other dry period of note, though shorter than those mentioned, was 1976-1977, which was marked by extraordinarily low yields (158,000 and 68,000 acre feet). As was the case with annual rainfall, WY2014 with 121,000 acre feet of runoff, is the second lowest on record.

In order to consider a single year in the context of the entire flow record, these annual yields were ranked, plotted as an exceedance probability and divided into five equal classes ranging from “extremely wet” to “critically dry” (Figure 8). This method (after McBain & Trush 2001) accounts for the range in variability between water years and provides an equal opportunity for each class that a given year will fall within that class. Within our study, only the yields from WY2010 and 2011 trended toward the wet end of the spectrum, with exceedance probabilities of 44 and 40 percent respectively. The remaining three years were quite dry, with 2012 and 2014 falling into the “critically dry” category and 2014 producing the second lowest yield on record and 96 percent of annual yields exceeding that for 2014 (Figure 8).

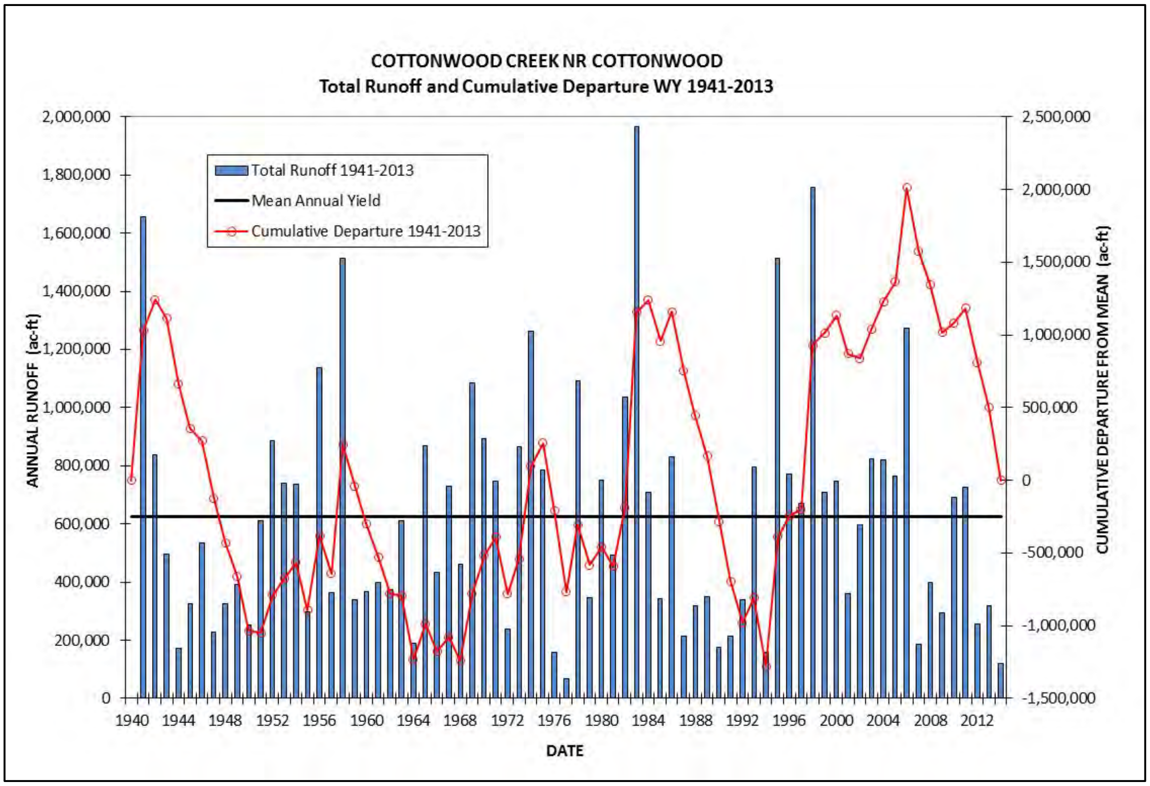

Figure 7. Annual runoff (yield) and cumulative departure by water year for USGS 11376000.

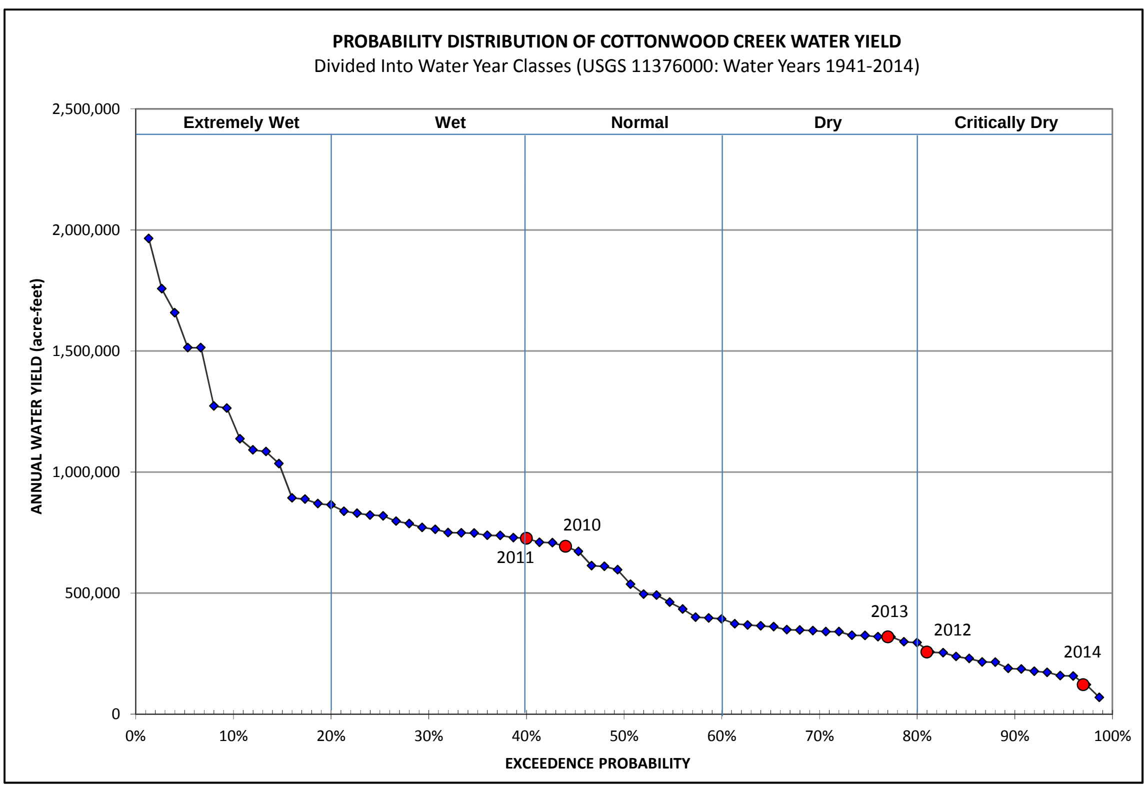

Figure 8. Water year classes for Cottonwood Creek, 1941-2014.

3.1.5 Flood History, Peak Flows, Flood Frequency

Historic Regional Floods

The various historic storm events prior to the earliest (1941) peak discharge records on Cottonwood Creek were evaluated through historical accounts and other regional streamflow records in GMA 2003. The extensive period of streamflow records for the Sacramento River provides considerable insight into for the 1880-1943 period, which was prior to the construction of Shasta Dam and also prior to the first streamflow gage on Cottonwood Creek (Appendix 1-8).

There have been a number of significant floods in the historic streamflow record in the Sacramento basin. Accounts from early settlers describe particularly unusual floods in January 1862, which is well-known to have been a very large, basically state-wide flood (GMA 2003). USGS records at Sacramento River near Bend Bridge near Red Bluff gage for the period 1880 to 1943 indicate that large floods occurred in: February 1881, January 1890 (missing), February 1909, February 1915, December 1937, and February 1940.

When the two sources of gaging records (Cottonwood Creek and the Sacramento River) are combined with other regional and historic data, a reasonable evaluation of significant floods from 1862 to present can be developed. Known large flood events in the region, many or most of which would also have occurred in the Cottonwood Creek watershed, are known to have taken place in Water Years 1862, 1890, 1937, 1940, and 1983. The available evidence suggests that the events in 1862, 1940, and 1983 were the largest floods in the historic record. The largest of these is likely to have been the 1862 event, followed by the 1983, 1940, 1937 and 1890 events.

Cottonwood Creek Peak Discharge

Long-term records of annual maximum peak discharges in the study area were obtained for the USGS gage Cottonwood Creek near Cottonwood gage (11376000, Figure 9). The largest flood in the watershed, during the 1941-2014 period, occurred in January 1983, when discharge reached 86,000 cfs (Appendix 1-6, 1-7). This was probably the largest flood event in the watershed in the 20th century, although December 1937 and February 1940 were also very large events and were larger on some streams in the area (Battle Creek [December 1937], Sacramento River above Bend Bridge [February 1940], for example) (GMA 2003). The 1937, 1940 or 1983 events were probably the largest since 1862 (GMA 2003). January 1974, January 1982, December 1964 (WY1965), and January 1970 round out the top five peak flows in the period of record. January 1997, although very significant in areas with substantial snow, was only about a 5-year event in Cottonwood Creek. The five largest floods during the 74-year period of record occurred in an 18 year period from 1964-1983. The only significant flood since the 2003 GMA study was in 2006, with a peak of 46,700 cfs.

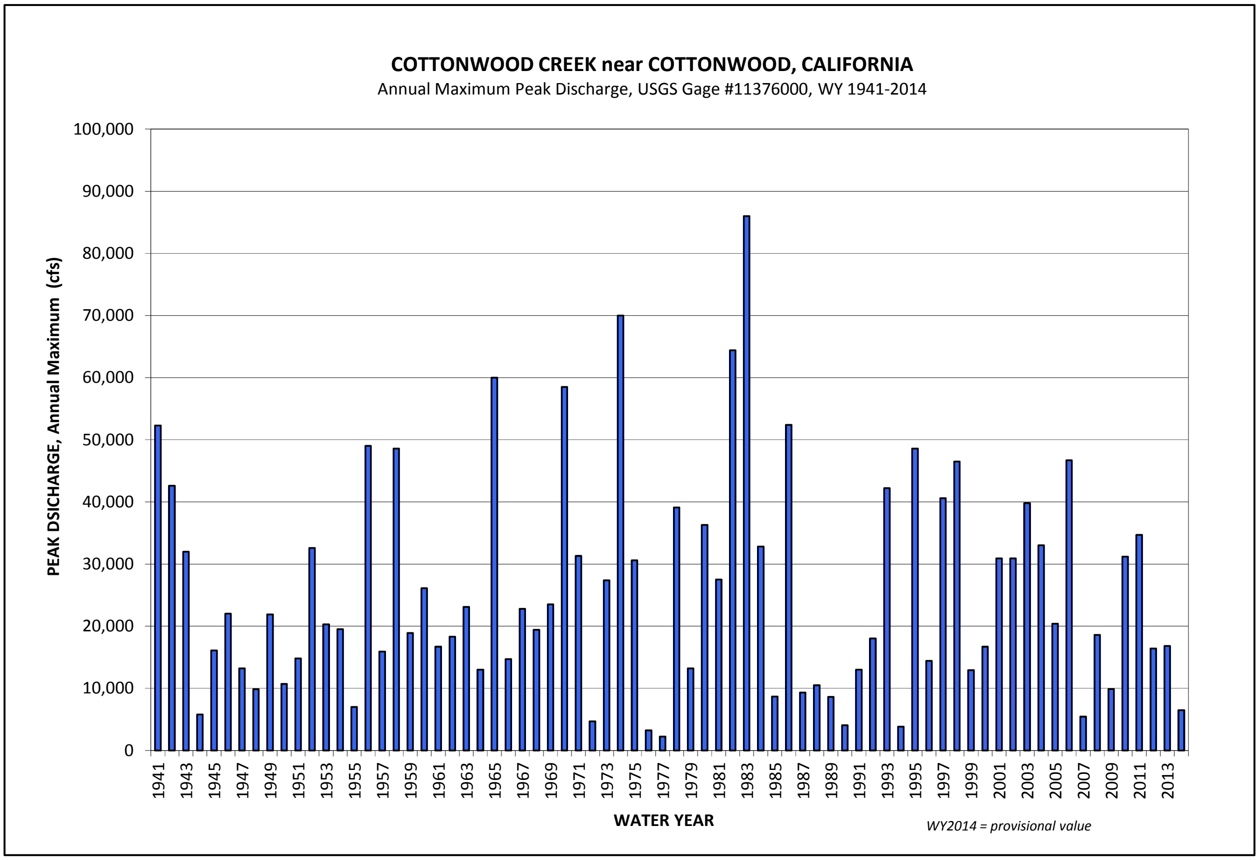

Figure 9. Annual peak flows for USGS 11376000, 1941-2014.

Flood Frequency Analysis

Flood frequency analysis for the Cottonwood Creek annual maximum peak discharges was computed for the 1941-2013 period (2014 is a provisional value). Computed recurrence interval values (RI) are shown in Table 3 and Figure 9. This analysis indicates that the 1983 flood would be about a 74-year event, while flows similar to January 1974 would be about a 37-year event (Table 4). The 2-year event is about 21,400 cfs, while the 1.5-year event is about 15,100 cfs. Flows occurring during the study period, corresponded to a maximum 3.9 year peak (March 2011 at 34,700 cfs) and a minimum 1.1 year recurrence (March 2014 at 6,460 cfs) (Figure 10). Drainage area-scaled relations for selected sub basins (the two GMA gaging stations occupied for this study, and the focused study reach) are presented in Table 5.

Table 3. Recurrence interval values for USGS 1137600, 1941-2013.

Recurrence Interval (years)	Bull 17B Estimate Annual Maximum (cfs)*
2	21,350
5	39,170
10	52,100
25	69,010
50	81,740
100	94,420

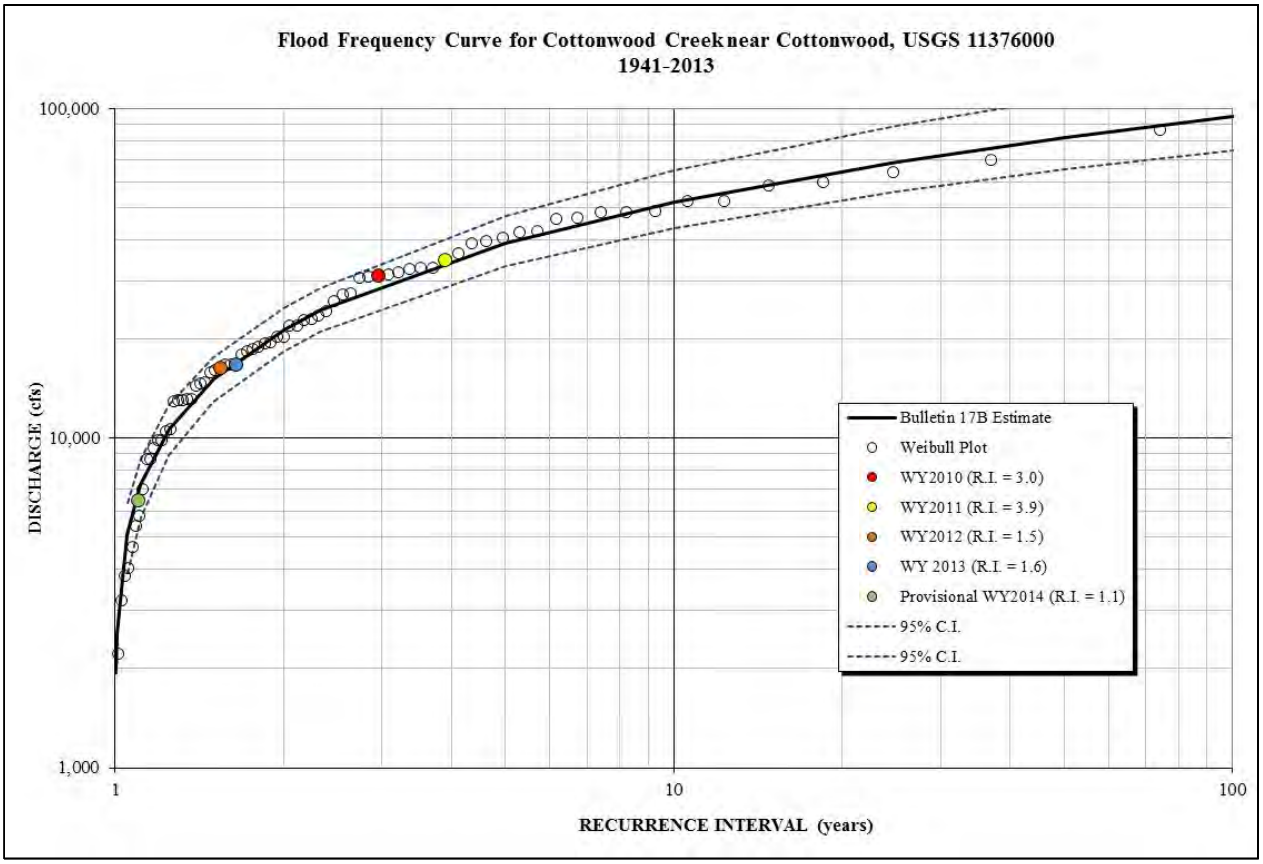

Figure 10. The flood frequency analysis for USGS 11376000, 1941-2013.

Table 4. Annual maximum peak discharges for USGS 1137600, 1941-2014.

Water Year	Recurrence Interval (yrs)	Peak Discharge, Annual Maximum (cfs)	Unit Peak Discharge (cfs/mi^2)
1941	10.6	52,300	56
1942	5.7	42,600	46
1943	3.2	32,000	35
1944	1.1	5,800	6
1945	1.5	16,100	17
1946	2.1	22,000	24
1947	1.4	13,200	14
1948	1.2	9,870	11
1949	2.1	21,900	24
1950	1.3	10,700	12
1951	1.5	14,800	16
1952	3.4	32,600	35
1953	1.9	20,300	22
1954	1.9	19,500	21
1955	1.1	7,020	8
1956	9.3	49,000	53
1957	1.5	15,900	17
1958	8.2	48,600	52
1959	1.8	18,900	20
1960	2.5	26,100	28
1961	1.6	16,700	18
1962	1.7	18,300	20
1963	2.2	23,100	25
1964	1.3	13,000	14
1965	18.5	60,000	65
1966	1.4	14,700	16
1967	2.2	22,800	25
1968	1.9	19,400	21
1969	2.3	23,500	25
1970	14.8	58,500	63
1971	3.1	31,300	34
1972	1.1	4,670	5
1973	2.6	27,400	30
1974	37.0	70,000	76
1975	2.7	30,600	33
1976	1.0	3,220	3
1977	1.0	2,210	2
1978	4.4	39,100	42
1979	1.3	13,200	14
1980	4.1	36,300	39
1981	2.6	27,500	30
1982	24.7	64,400	69
1983	74.1	86,000	93
1984	3.5	32,800	35
1985	1.2	8,660	9
1986	12.3	52,400	57
1987	1.2	9,310	10
1988	1.2	10,500	11
1989	1.1	8,620	9
1990	1.1	4,050	4
1991	1.3	13,000	14
1992	1.7	18,000	19
1993	5.3	42,200	46
1994	1.0	3,820	4
1995	7.4	48,600	52
1996	1.4	14,400	16
1997	4.9	40,600	44
1998	6.2	46,500	50
1999	1.3	12,900	14
2000	1.6	16,700	18
2001	2.8	30,900	33
2002	2.4	30,900	33
2003	4.6	39,800	43
2004	3.7	33,000	36
2005	2.0	20,400	22
2006	6.7	46,700	50
2007	1.1	5,430	6
2008	1.8	18,600	20
2009	1.2	9,900	11
2010	3.0	31,200	34
2011	3.9	34,700	37
2012	1.5	16,400	18
2013	1.6	16,800	18
2014	(provisional value)	6,460	7
Mean		**25,802**	**28**
Max		**86,000**	**93**
Min		**2,210**	**2**

Table 5. Sub-basin drainage area and scaled flow duration and flood frequencies for relevant gaging locations within Cottonwood Creek.

		Drainage Area		Flow Duration (cfs)		Computed Recurrence Interval (yrs, cfs)			
USGS Gage	#	(sq mi)	% of basin	10%	5%	1.5	5	10	25
Cottonwood nr Cottonwood	11376000	927	100%	2,000	3,550	15,150	39,200	51,070	65,690
Cottonwood abv SFCW	11375815	478	52%	1,031	1,831	7,812	20,213	26,334	33,873
Cottonwood near Ono	11375810	395	43%	852	1,513	6,456	16,703	21,761	27,991
South Fork @ Evergreen	11375900	397	43%	857	1,520	6,488	16,788	21,871	28,133

WY2010-2014 Streamflow

USGS 11376000, Cottonwood Creek near Cottonwood

The hydrograph for the USGS lower mainstem gage for this 5 year study is presented in Figure 11. Individual annual hydrographs are presented in Appendix 1. WY2010 and WY2011 were by far the strongest hydrologic years in the study. WY2010 peaked at 31,200 cfs (RI = 3.0) and produced five storms that peaked at over 10,000 cfs. Most storms occurred in January and February 2010 though one large storm occurred in late April. WY2010 produced an annual yield of 693,000 acre feet (Figure 7), above the mean of 626,000 acre feet. WY2011 showed the highest peak during the study period at 34,700 during March 2011 (RI = 3.9). Aside from the December 29, 2010 peak, virtually all of the WY2011 storm flows occurred from mid-March to mid-April. WY2011 also contained five peaks over 10,000 cfs and produced a higher yield than WY2010 at 726,000 acre feet.

Following WY2011, a dry period ensued with WY2012 and WY2013 each peaking slightly higher than 16,000 cfs. Annual yield for WY2012 and 2013 was 256,000 and 319,000 acre feet. WY2014 presented a provisional annual peak of 6,460 cfs, the 8th lowest on record and an annual yield of 121,000 acre feet, the second lowest on record.

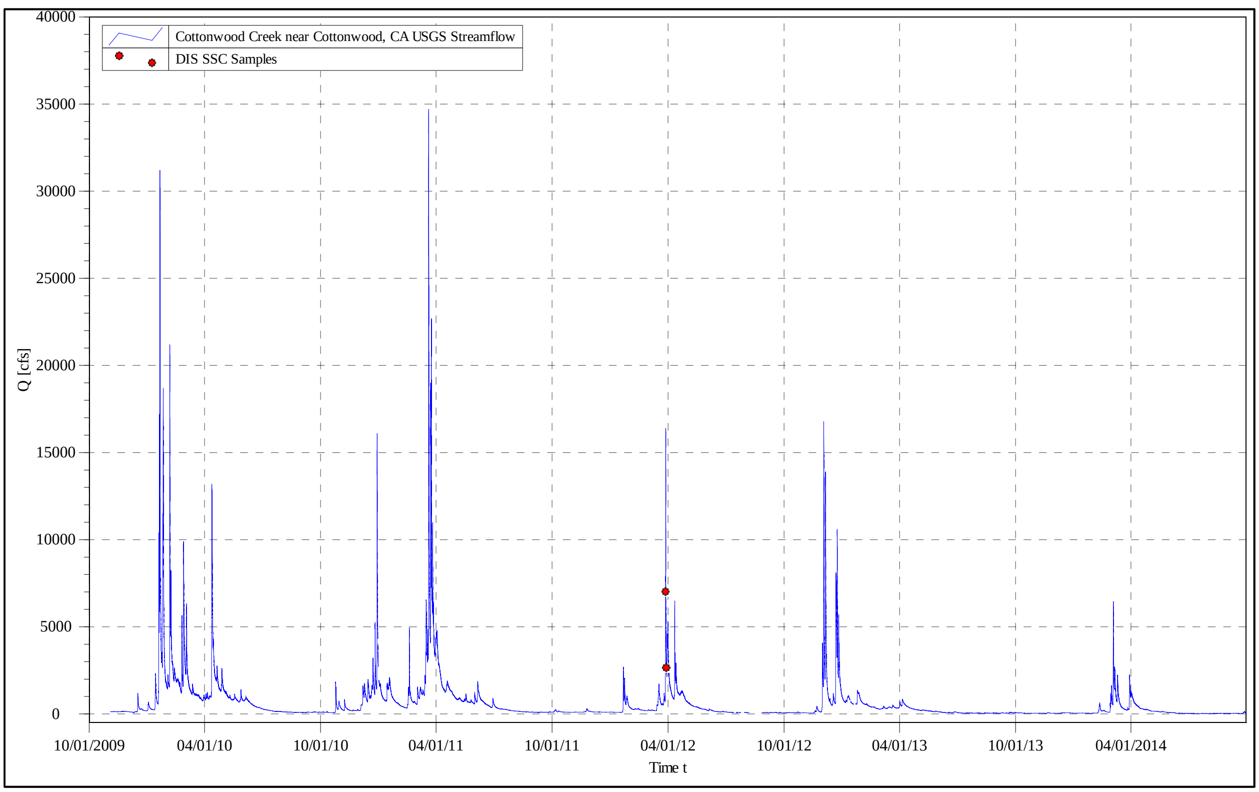

Figure 11. WY2010-WY2014 hydrograph for USGS 11376000, Cottonwood Creek near Cottonwood.

GMA South Fork Cottonwood at Evergreen Road (Reoccupation of USGS 11375900)

GMA reoccupied the USGS South Fork at Evergreen road location on January 18, 2010 for the purpose of collecting hydrologic data to support sediment load calculations. Over the five year period, GMA collected 32 discharge measurements ranging from 0.49 to 10,800 cfs (Appendix 1-16). Two ratings were developed in the period; one for January 18, 2010 – March 20, 2011 and one for March 20, 2011 – April 28, 2014 (Figure 12 and Appendix 1-16).

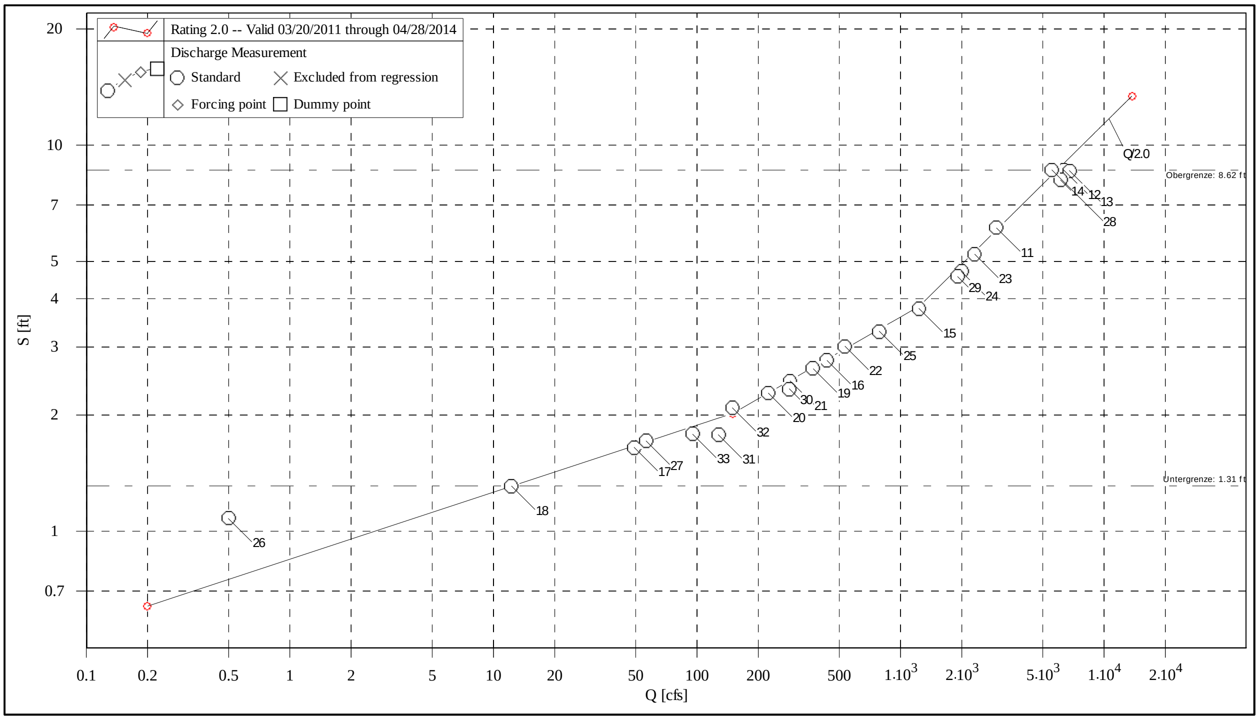

Figure 12. Stage - discharge Rating #2 for South Fork Cottonwood at Evergreen Road.

The South Fork hydrograph for WY2010-2014 is presented in Figure 13. Individual annual hydrographs are presented in Appendix 1-17 to 1-21. The South Fork gage was installed two days before the WY2010 annual peak on January 20, 2010 and in general, its computed hydrograph tracks with the mainstem (USGS 11376000) hydrograph, though relative peak flow magnitude varies; for example, in WY2010 the South Fork peaked at 13,500 cfs, compared to 31,200 cfs at USGS 11376000, representing 43 percent of the total discharge of the mainstem, which also happens to be the ratio of drainage areas between the South Fork and the mainstem. The South Fork produced as little as 23 percent of the total discharge, such as in WY2012 when the South Fork peaked at 3,760 cfs and the mainstem peaked at 16,400 cfs. The range in flow proportion is likely due to differences in storm and runoff characteristics within the basin. The flat line sections of the hydrograph represent zero discharge (but a wet channel) while the gaps represent periods when the channel completely dry. The summers of 2013 and 2014 appear as much drier than the rest.

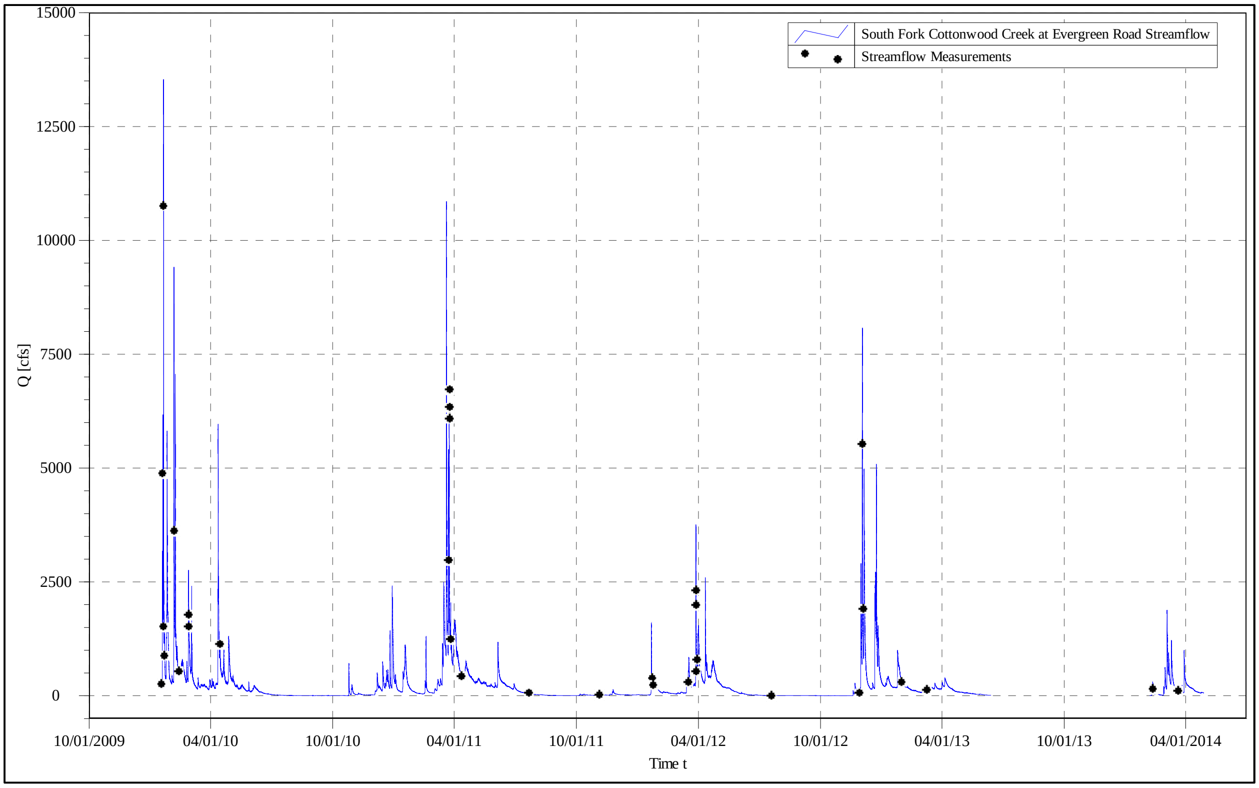

Figure 13. WY2010-2014 hydrograph and discharge measurements for GMA SF Cottonwood at Evergreen Road.

GMA Cottonwood Creek near Olinda (Reoccupation of USGS 11375810)

GMA reoccupied the USGS Cottonwood Creek near Olinda location on December 24, 2011 for the purpose of collecting hydrologic data to support sediment load calculations. Over the three year period, GMA collected 15 discharge measurements ranging from 42.1 to 6,270 cfs (Appendix 1-22). A single rating was developed for use during the period (Figure 14). Hydrograph shape for WY2012-2014 is similar to the other two sites (Figure 15) but relative peak flow magnitudes range from 52 to 77 percent of CCNC (Table 6). In WY2013, the sum of the two peak flows would have been over 21,000 cfs while the USGS gage (11376000) indicated 16,800 cfs. Such discrepancies likely occur due to differences in flood-wave shape, timing and attenuation characteristics (i.e., tributary maxima are not always entirely additive).

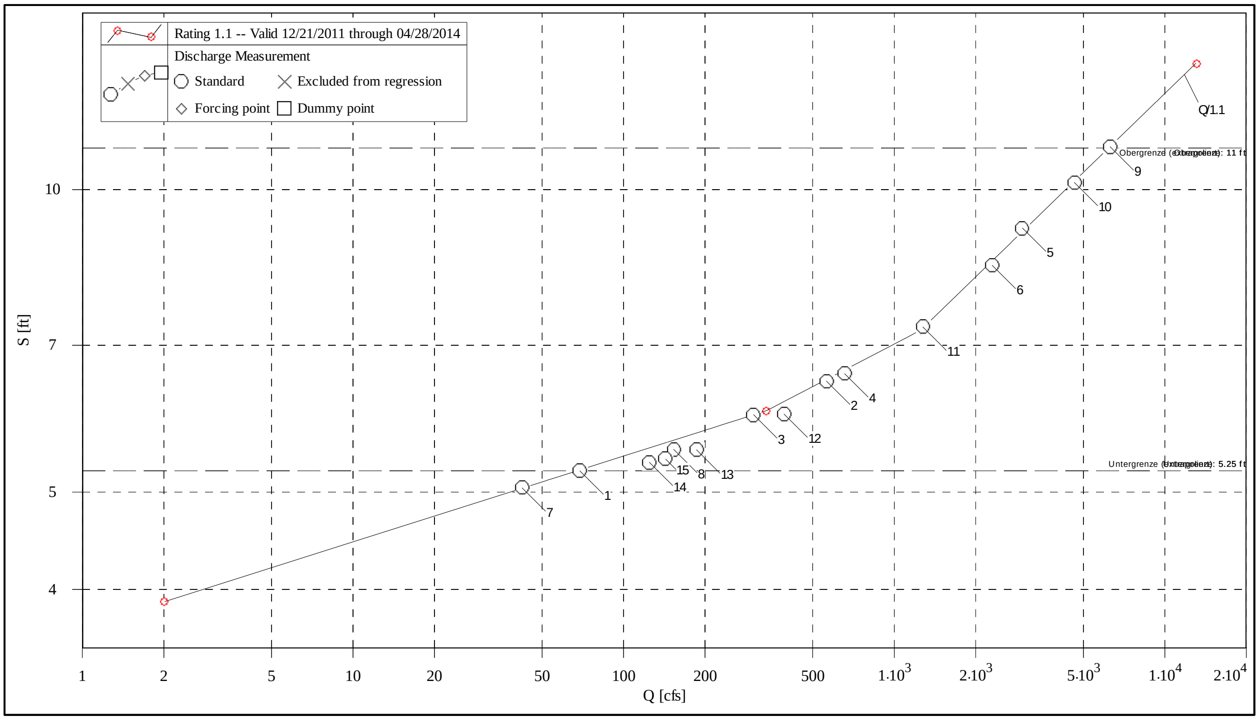

Figure 14. Stage - discharge rating for GMA Cottonwood Creek near Olinda.

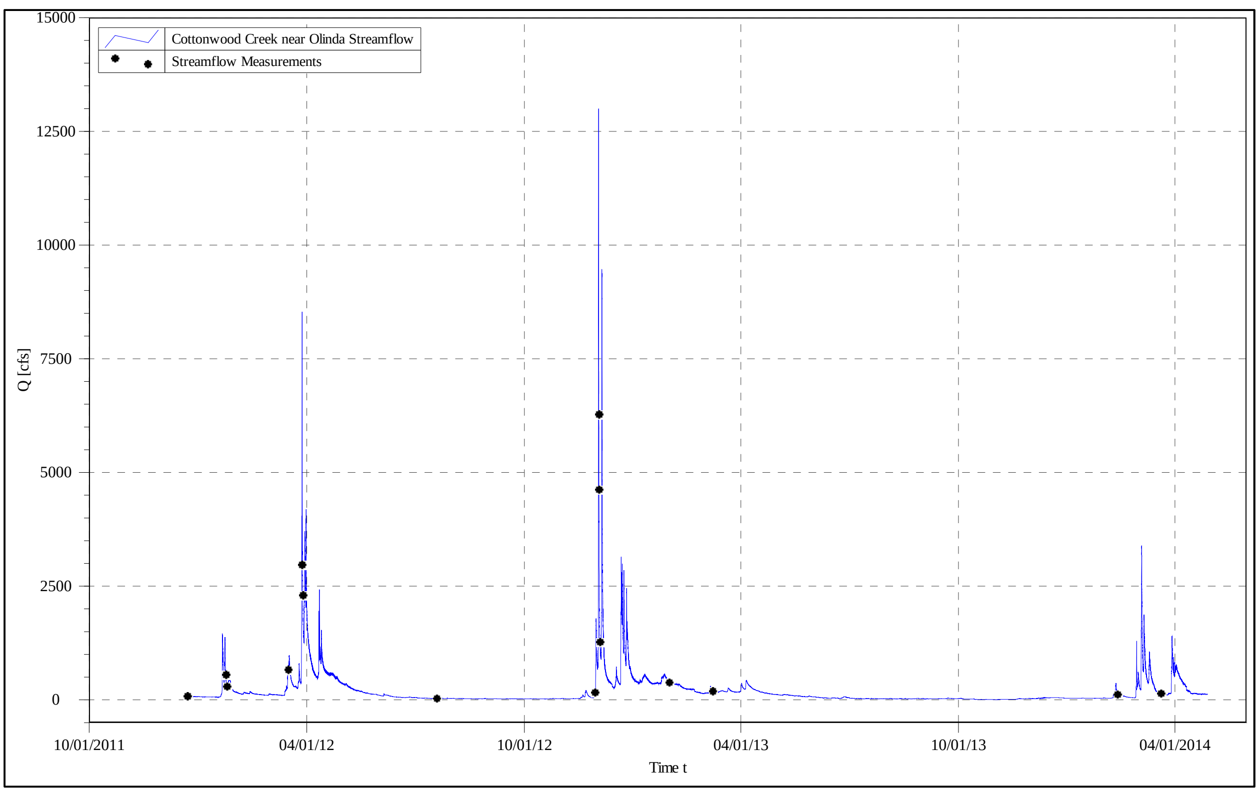

Figure 15. WY2012-WY2014 hydrographs and discharge measurements for GMA Cottonwood Creek near Olinda.

Table 6. Relative contributions to total mainstem discharge at USGS 11376000.

Water Year	USGS CC nr CW 11376000 (cfs)	GMA SFCCER 11375900 (cfs)	% Total	GMA CCNO 11375810 (cfs)	% Total
2010	31,200	13,500	43%	--	--
2011	37,600	10,900	29%	--	--
2012	16,400	3,760	23%	8,530	52%
2013	16,800	8,080	48%	13,000	77%
2014	6,460	1,860	29%	3,390	52%

3.2 Sediment Transport

Supporting data for this section are provided in Appendix 2 – Sediment Data. Only the most relevant figures and tables are presented in the text. The purpose of this section is to (1) to summarize the results of GMA's WY2010-2014 sediment transport monitoring; and (2) to compare data collected during our study period to data collected by others during different time periods. The objective is to examine sediment transport at different points in the drainage network and to assess sediment transport attributes over time. We will accomplish this objective by reviewing/describing data collected at SF Cottonwood (SFCC), Cottonwood Creek near Olinda (CCNO), and at USGS Cottonwood Creek near Cottonwood (CCNC) (Sections 3.2.1, 3.2.2, and 3.2.3, respectively). We then summarize these data to develop a conceptual sediment budget (Section 3.2.8). The goal of this task is to present the data required to develop (at least a partial) sediment budget for Cottonwood Creek and (in the Synthesis section) to describe its sediment-related geomorphic trajectory (Section 4).

Unless indicated otherwise, sediment concentration, discharge and load values are rounded as per Porterfield (1972).

3.2.1 South Fork Cottonwood Creek at Evergreen Road (SFCC)

Turbidity

The streamgage was launched on January 18, 2010 and the DTS-12 turbidimeter was launched on January 29, 2010. Measured turbidity ranged from zero to the instrument maximum reliable threshold of 1,600 NTU. The maximum turbidity threshold was exceeded seven times during the study. For three of these brief periods, turbidity was estimated from the particular storm event's discharge- turbidity relation. On the other four occasions, when the turbidimeter reached its maximum detection limit and the discharge-SSC relation predicted minimal increase above the maximum, the maximum value was held. The turbidimeter successfully captured variations in sediment concentration which would not have been described by discharge alone. For example, during the weak WY2014 storms, very high turbidities occurred (Figure 16). Each Water Year's turbidity graph and hydrograph are provided in Appendix 2. Numerous examples of disproportionately-high turbidity increases appear in Appendix 2, notably in WY2012, when very modest storms produced turbidity up to (or near) the reliable maximum of 1,600 NTU.

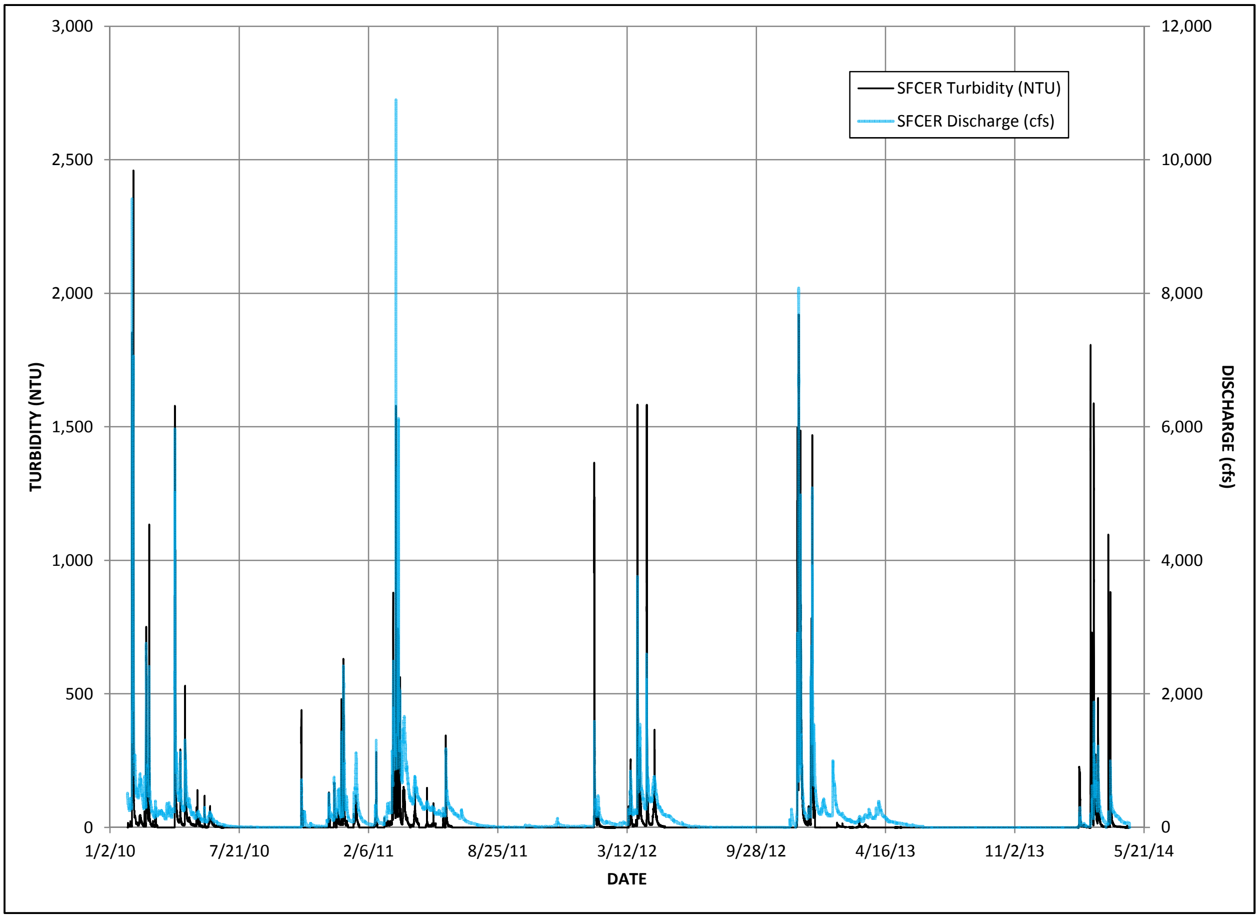

Figure 16. Continuous turbidity and discharge for South Fork Cottonwood at Evergreen Road, WY2010-2014.

Suspended Sediment

Full cross section depth integrated samples (DIS) and single point correlation samples (box) were collected from WY2010 through WY2014. Every significant storm during the 5 year study period was sampled, with the following exceptions: February 7, 2010. April 12, 2010 and December 23, 2011; however the turbidity-SSC relation (Figure 17) and the quality of the turbidity record (Figure 16) lend a high degree of confidence to sediment load computations for these un-sampled events. For the 11 day period prior to tubidimeter launch, suspended sediment data collection was sufficiently comprehensive (44 samples, box and DIS, Appendix 2-6) to cover the period without turbidity (Appendix 2-9).

During the study, GMA collected 40 full cross section, two-pass, depth integrated samples and 49 box samples (Appendix 2-6). Sampled suspended sediment concentrations ranged from 3 to 8,020 mg/l, and the maximum (instantaneous) suspended sediment discharge was 225,000 tons/day. Figure 18 describes the sampling effort for WY2010-2014 at SFCC. Individual water year sedigraphs are presented along with their respective hydrographs in Appendix 2. A brief overview of each water year is described below.

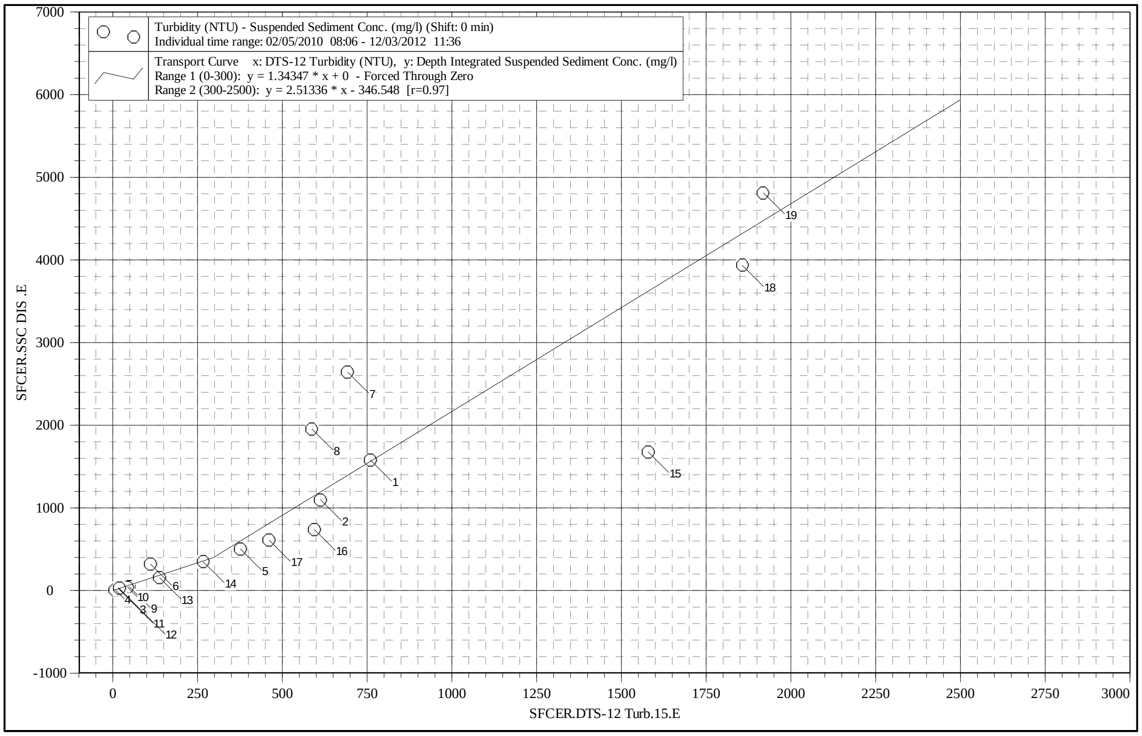

Figure 17. Turbidity versus suspended sediment concentration, South Fork Cottonwood at Evergreen Road, WY2010-2014

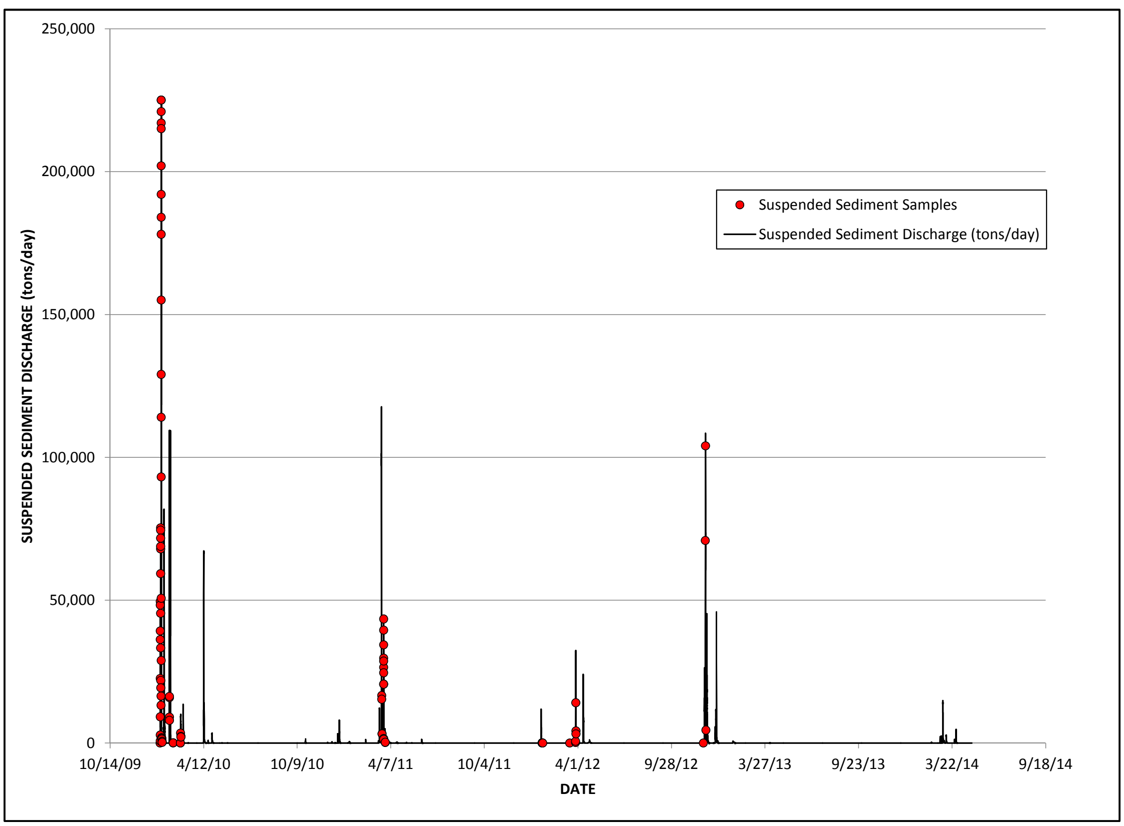

Figure 18. Suspended sediment discharge and samples for GMA South Fork Cottonwood Creek at Evergreen Road (11375900), WY2010-2014

WY2010 is a partial Water Year, as the gage was constructed on January 18, 2010. Hydrographic comparison with the USGS gage near Cottonwood reveals that no significant storms occurred prior to gage installation on the South Fork, so we consider the effect of the partial year to be negligible for annual sediment load computation. The very first storm (January 18-22, 2010 -- Figure 19) produced by far the highest suspended sediment concentrations and with the very high streamflows (over 13,000 cfs), and resulted in the highest suspended sediment load computed for any storm in the study; 41 percent (93,400 tons) of the WY2010 annual load was produced during the January 18-22 storm. The January 24-28 and February 4-8 storms produced 21 and 23 percent of the annual total respectively. WY2010 was the largest sediment producer during the period, with 228,000 tons for the year (Table 7).

Figure 19. South Fork Cottonwood at Evergreen Road, January 20, 2010. Downstream view at approximately 10,000 cfs.

Table 7. Suspended sediment load totals for South Fork Cottonwood at Evergreen Road, WY2010-2014.

WY2010	WY2011	WY2012	WY2013	WY2014
228,000	80,000	26,800	123,000	11,300

Bedload and Total Load

GMA collected five bedload samples at the Evergreen Road Bridge in WY2012 (Table 8). Bedload data were collected to estimate bedload as a percentage of the total (bedload + suspended) sediment load, with the objective of estimating of annual total sediment load as a function of suspended sediment load. The mean bedload/total load fraction of the five samples is 20.8 percent. Using this relation (bedload as 20.8 percent percent of total load), we estimated the total sediment load for each Water Year in Table 9.

Table 8. Bedload sampling summary for SF Cottonwood Creek at Evergreen Road, WY2011-2012.

Sample Number	Date & Mean Time	Discharge (cfs)	Bedload Discharge (tons/day)	Suspended Sediment Discharge (tons/day)	Total Load (tons/day)	Bedload as Percent of Total Load
SFCER-BLM2012-01	01/23/2012 14:17	372	17.8	63	81	22%
SFCER-BLM2012-02	03/27/2012 18:16	683	36.7	702	738	5%
SFCER-BLM2012-03	03/28/2012 09:25	2,360	1,685	7,028	8,710	19%
SFCER-BLM2012-04	03/28/2012 10:40	2,140	1,770	4,690	6,460	27%
SFCER-BLM2012-05	03/28/2012 12:45	1,940	1,303	2,995	4,300	30%

Table 9. Suspended, Bedload and Total Sediment Loads for South Fork Cottonwood Creek, WY2010-2014 (tons).

Component	WY2010	WY2011	WY2012	WY2013	WY2014
Suspended Load	228,000	80,000	26,800	123,000	11,300
Bedload	59,700	21,000	7,000	32,200	3,000
Total Sediment Load	287,700	101,000	33,800	155,200	14,300

3.2.2 Cottonwood Creek near Olinda (CCNO)

Turbidity

A gaging and turbidity monitoring station was established below the Middle Fork confluence on December 21, 2012 (access was not available until 2012.). No storms of any significance occurred in WY2013 prior to installation, as evidenced by the USGS gage near Cottonwood (Appendix 1). Figure 20 describes the three year turbidity record for the Olinda gage. Individual years are provided in Appendix 2. Although turbidity exceeds the range of the DTS-12 (1,600 NTU) three times during the period, each occasion is of such short duration that the record was not corrected (the effect on the load computation would be negligible). Even more evident than South Fork at Evergreen Road, steep increases in turbidity occur at rates different than the rate of increase in discharge indicating hysteresis, which in the case of sediment transport, generally refers to variation in the sediment load as a function of discharge relation (e.g. more sediment may be available for transport of the rising limb than on the falling limb). In WY 2012, the April 11 storm produced nearly 1,600 NTU with a peak discharge of 2,430 cfs, the same as the March 27 event with a peak discharge of 8,530 cfs. In WY2013, the December 2 storm produced the highest turbidity (>1,600 NTU) with its peak discharge of 13,000 cfs, while the December 21, 2012 storm generated nearly 1,300 NTU with a peak of only 3,100 cfs. WY2014, with no peaks exceeding 3,380 cfs, produced turbidity exceeding 1,200 NTU on three separate occasions (Figure 20, Appendix 2).

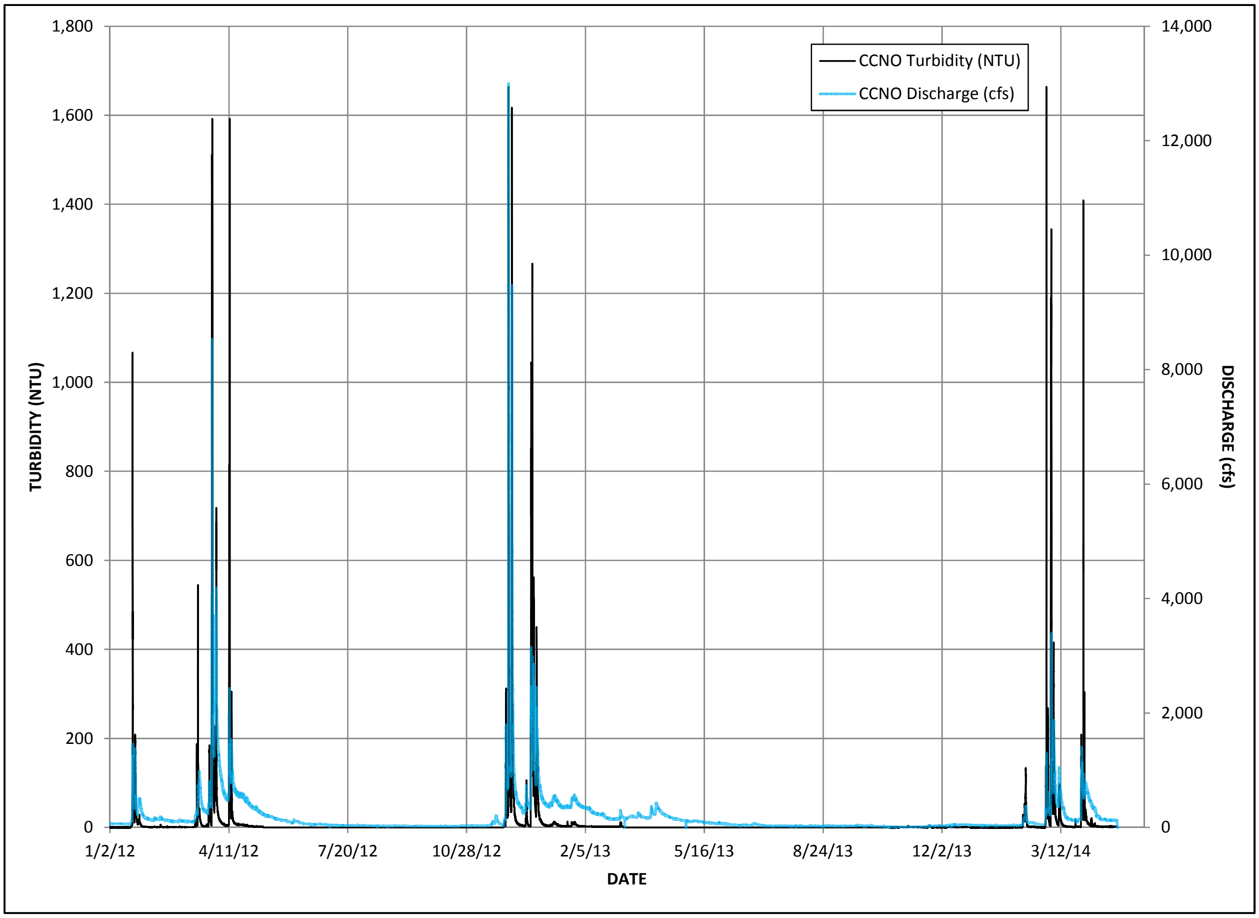

Figure 20. Continuous turbidity and discharge for Cottonwood Creek near Olinda, WY2012-2014.

<u>Suspended Sediment</u>

GMA collected 13 two-pass suspended sediment samples (Appendix 2) at the CCNO site over the three year period during which the monitoring station was operated. High flow sampling at this site requires either a jetboat or a cataraft-on-cableway to conduct sampling and discharge measurements, thus the site is considerably more difficult to sample than SFCC and fewer samples were collected (Figure 21). GMA sampled two of the three largest sediment-transport events (March 27, 2012 and December 2, 2012) (Figure 22). Measured concentrations during these high flow events ranged from 873 to 2,580 mg/l (Appendix 2), in contrast, somewade-able sampling events during lower flows showed concentrations as low as 3.2 mg/l (96 cfs on November 28, 2012).

As on the South Fork, individual short term events were the primary contributors to annual loads. In WY2012, the March 24 to April 10, 2012 storm period transported 18,400 tons (77 percent) of the 24,000 ton annual load (Table 10). In WY2013, the December 2-3, 2012 storm generated 38,000 tons (76 percent of the annual total of 49,900 tons) while the December 21-24, 2012 storm generated 10,000 tons, another 20 percent of the annual load. All of WY2014 produced roughly the same load as one storm did in WY2012 (the December 21 storm); most (62 percent) of the WY2014 10,500 ton total was produced in the March 3-5, 2014 storm (6,460 tons).

Figure 21. Cataraft sampling at 8,000 cfs at Cottonwood Creek near Olinda during the December 2-3, 2012 peak flow event.

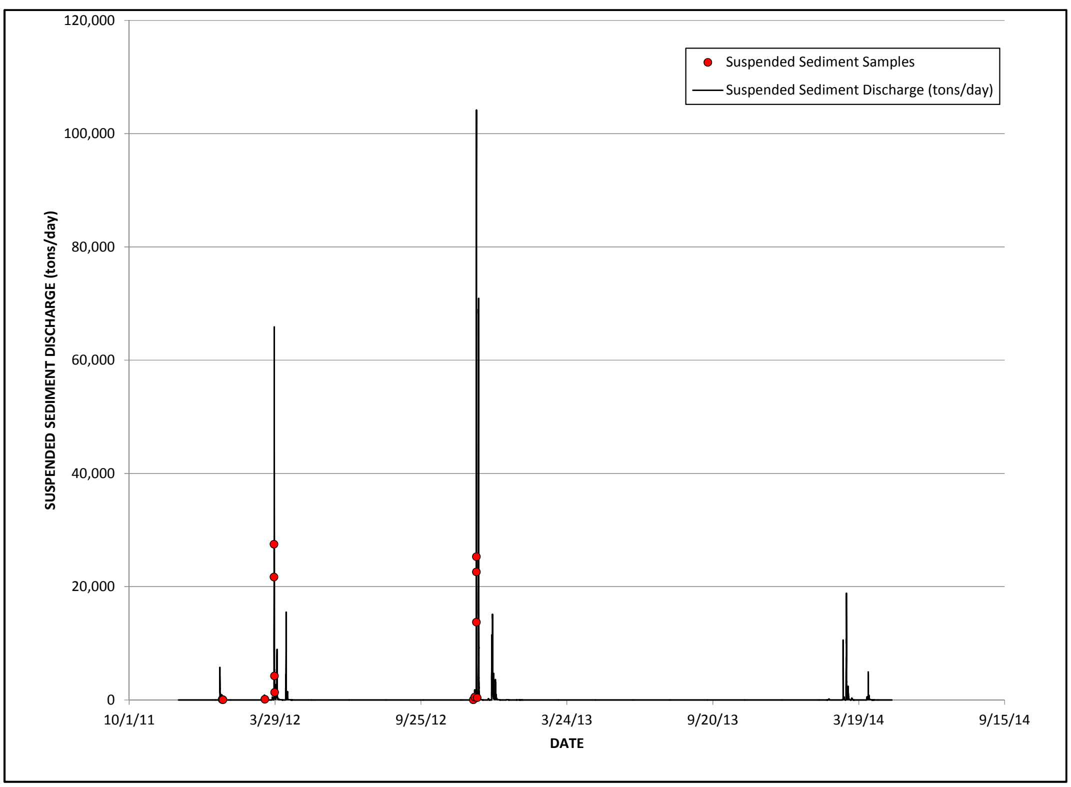

Figure 22. Suspended sediment load for GMA South Fork Cottonwood Creek near Olinda (11375810), WY2010-2014.

Over the two years for which we had no data at Cottonwood near Olinda (WY2010-2011), we scaled the USGS Cottonwood near Cottonwood (11376000) 15 minute discharge hydrograph by the ratio of drainage areas between the two stations (43 percent, Table 5) to create a synthetic hydrograph. Then, using the discharge - suspended sediment discharge regression developed from WY2012-2014 sample data (Figure 23), we computed the estimated annual suspended sediment loads for WY2010-2011 (Table 10) which, as at the other stations, are much larger than the loads for the other three years.

Table 10. Suspended sediment loads for Cottonwood Creek near Olinda, WY2010-2014.

WY2010	WY2011	WY2012	WY2013	WY2014
183,000	237,000	24,000	49,900	10,500

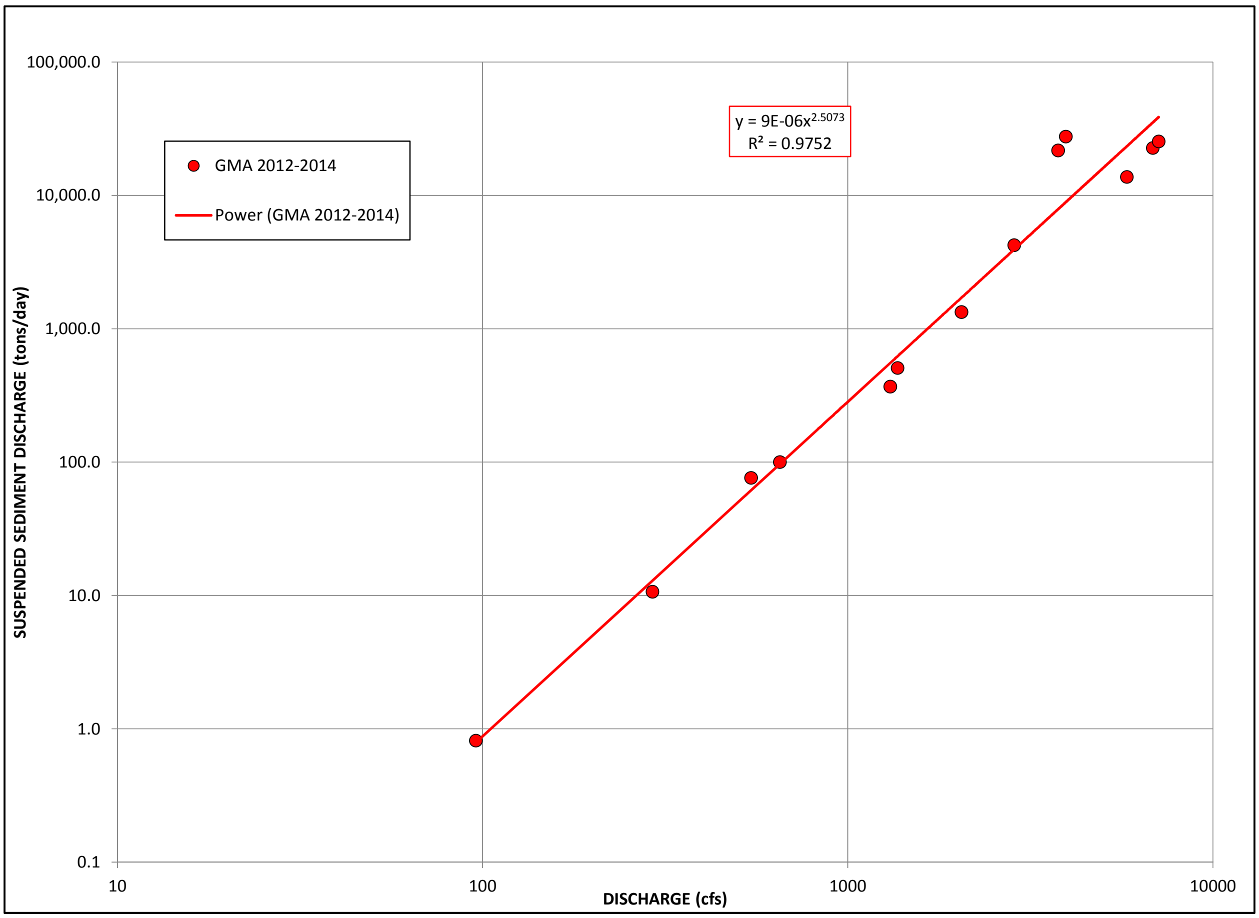

Figure 23. Cottonwood Creek near Olinda, suspended sediment discharge versus discharge WY2012-2014.

Bedload and Total Load

GMA collected five bedload samples at the Cottonwood near Olinda site in WY2012 and 2013 (Table 11). Total measured bedload discharge ranged from 591 to 1,800 tons/day. The data show a wide range in the bedload as percent of total load (3-28 percent). The mean bedload fraction of the five samples in Table 11 is 12.7 percent (bedload as fraction of total load), somewhat less than what was estimated at South Fork at Evergreen. Using this relation (bedload as 12.7 percent of total load), we estimated the total sediment load for each Water Year in Table 12.

Table 11. Bedload sampling summary for Cottonwood Creek near Olinda, WY2012-2013

Sample Number	Date & Mean Time	Discharge (cfs)	Bedload Discharge (tons/day)	Suspended Sediment Discharge (tons/day)	Total Sediment Discharge (tons/day)	Bedload as Percent of Total
CCNO-BLM2012-01	03/27/2012 17:31	3,750	735	19,200	20,000	3.7%
CCNO-BLM2012-02	03/27/2012 18:38	3,990	785	27,700	28,500	2.8%
CCNO-BLM2012-03	03/28/2012 09:52	2,890	785	4,300	5,080	15.5%
CCNO-BLM2012-04	03/28/2012 16:30	2,050	591	1,540	2,130	27.7%
CCNO-BLM2013-01	12/02/2012 15:16	5,180	1,800	11,000	12,800	14.1%

Table 12. Suspended, Bedload and Total Sediment Loads for Cottonwood Creek near Olinda, WY2010-2014 (tons).

Component	WY2010	WY2011	WY2012	WY2013	WY2014
Suspended Load	183,000	237,000	24,000	49,900	10,500
Bedload	26,500	34,400	3,500	7,200	1,500
Total Sediment Load	209,500	271,400	27,500	57,100	12,000

3.2.3 USGS Cottonwood Creek near Cottonwood (11376000, CCNC)

Turbidity

We were unable to secure permission to establish a turbidimeter in the vicinity of the USGS station along the lower mainstem. Continuous turbidity paired with SSC samples would have facilitated direct computation of the suspended sediment load during the 2010-2014 study period. Without turbidity, we fall back upon discharge relations using historic data and data collected during this study period, detailed in the following sections.

Suspended Sediment

The GMA 2003 report on channel change in Cottonwood Creek examined a variety of sediment-discharge relations using historic data collected by the USGS. The estimated 1941-2000 total suspended sediment load based on mean daily values was 52,200,000 tons, resulting in an annual average of 871,000 tons (GMA 2003). We updated this analysis to include the 2001-2014 period which resulted in 60,200,000 tons over 74 years yielding an average of 814,000 tons per year for the 1941-2014 period. Because turbidity data were not available, we scaled historic mean daily discharge-SS load relations by collecting a few measurements at the mainstem during the study period and using USGS discharge at 11376000 to compute suspended sediment discharge.

In WY2012, GMA collected two two-pass suspended sediment samples from a jetboat during the March 28-29, 2012 storm, approximately 1,000 feet downstream of the USGS gaging station. Discharge during sampling was 7,030 and 2,690 cfs (Figure 24, Appendix 2). In order to compare our instantaneous measurements with the USGS historic daily average values, we used the simple discharge - SSC regression developed from our samples (Figure 25) to compute (the two-days) 15 minute suspended sediment load using the standard equation:

SS Load (tons/day) = Discharge (cfs) x SSC (mg/l) x 0.002697 (Edwards and Glysson, 1982)

We then averaged suspended sediment load and discharge for the 24 hour periods corresponding to March 28-29, 2012 to develop estimated mean daily values (Table 13). *Note, our computed mean daily discharge varied slightly (<4 percent) from the USGS published values.*

Figure 24. Sediment sampling from a jet boat on the mainstem Cottonwood Creek during the March 28-29, 2012 storm, downstream of the USGS (11376000) gaging station.

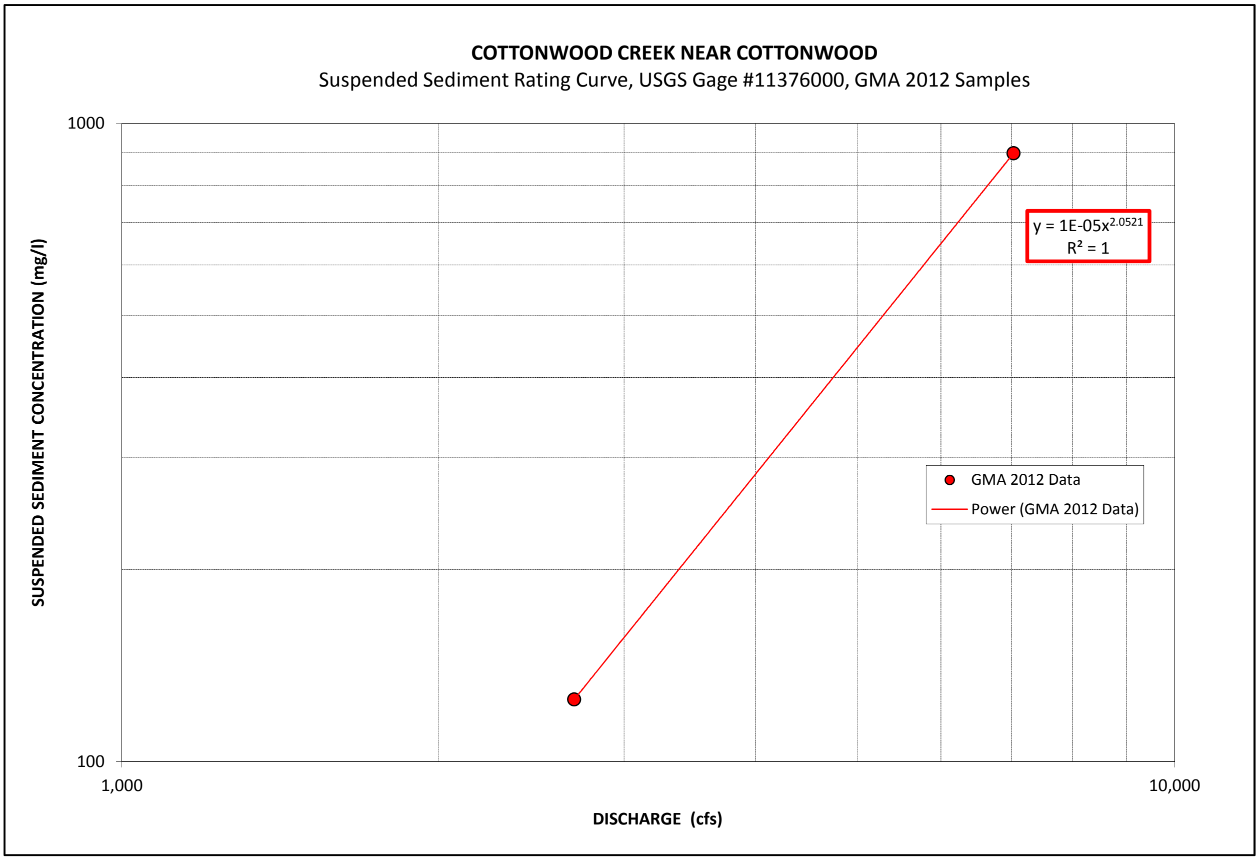

Figure 25. Discharge versus suspended sediment concentration for USGS 11376000, WY2012.

Table 13. Sample data and estimated mean daily values for WY2012 suspended sediment samples collected near USGS 11376000.

Sample Number	Date & Mean Time	Type	Average Discharge (cfs)	Average SSC (mg/l)	Average SSD (tons/day)	Type	Mean Daily Discharge (cfs)	Mean Daily SSD (tons/day)
CCNC-SSC2012-01	03/28/2012 12:45	DIS	7,030	898	17,000	MD Value	8,150	40,600
CCNC-SSC2012-02	03/29/2012 11:59	DIS	2,690	125	907	MD Value	2,880	963

We plotted these 2012 values with the 1963-1980 USGS data (used to compute the 2001-2014 average annual loads) and they fit well inside the cloud of historic measurements (Figure 26). The March 29, 2012 sample was collected on the falling limb and likely describes hysteresis in suspended sediment transport (reduced supply during the wane of a flood hydrograph), thus suggesting why it sits below the regression. We conclude that the 2012 data do not describe a significant departure from the 1963-1980 relation. Assuming the general shape of the regressions remains constant (an assumption we cannot test without additional data), we then applied the transport equations in Figure 26 (GMA 2003) to the WY2010-2014 mean daily discharge records (USGS 11376000) to estimate annual loads. Computed loads during the study period vary widely (Table 14). WY2010 and 2011 produced very similar loads. Each load was over 600,000 tons and roughly 50 times the annual load of WY2014; however, all water years fell below the long term average of 814,000 tons.

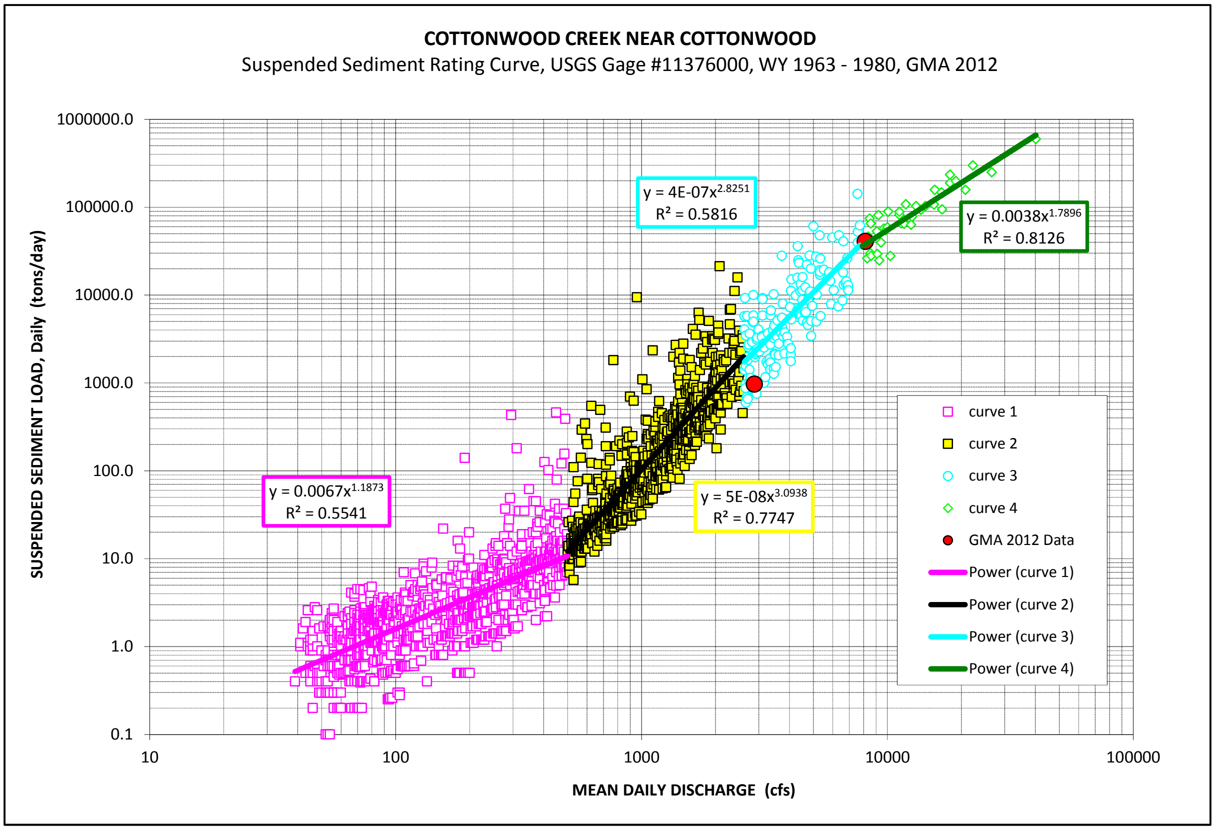

Figure 26. USGS suspended sediment data (1963-1980) and GMA data (2012) for #11376000.

Table 14. Estimated annual suspended sediment loads for Cottonwood Creek near Cottonwood, USGS 11376000. The long-term average for this gage is 814,000 tons.

WY2010	WY2011	WY2012	WY2013	WY2014
622,000	665,000	70,000	184,000	13,000

<u>Bedload and Total load</u>

GMA collected two bedload samples in March 2012, paired with the suspended sediment samples mentioned in the previous section. Sample data are provided in Figure 27 and in Table 15. The GMA samples plot higher than the trendline computed from the USGS 1977-1979 relation which may suggest an increase in bedload as a function of discharge since 1979 though with only two data points, this is not a strong inference. Bedload as a percentage of total load is again fairly variable (47 and 24 percent, Table 15), likely as a function of hysteresis in the suspended sediment load as described earlier. The mean bedload percentage is 35.4 percent. Using this relation to estimate total load from suspended load yields the data in Table 16. Similar to the other sites, WY2010 and 2011 appear to be much larger than the other years, roughly 10 times larger than WY2012 and 50 times larger than WY2014.

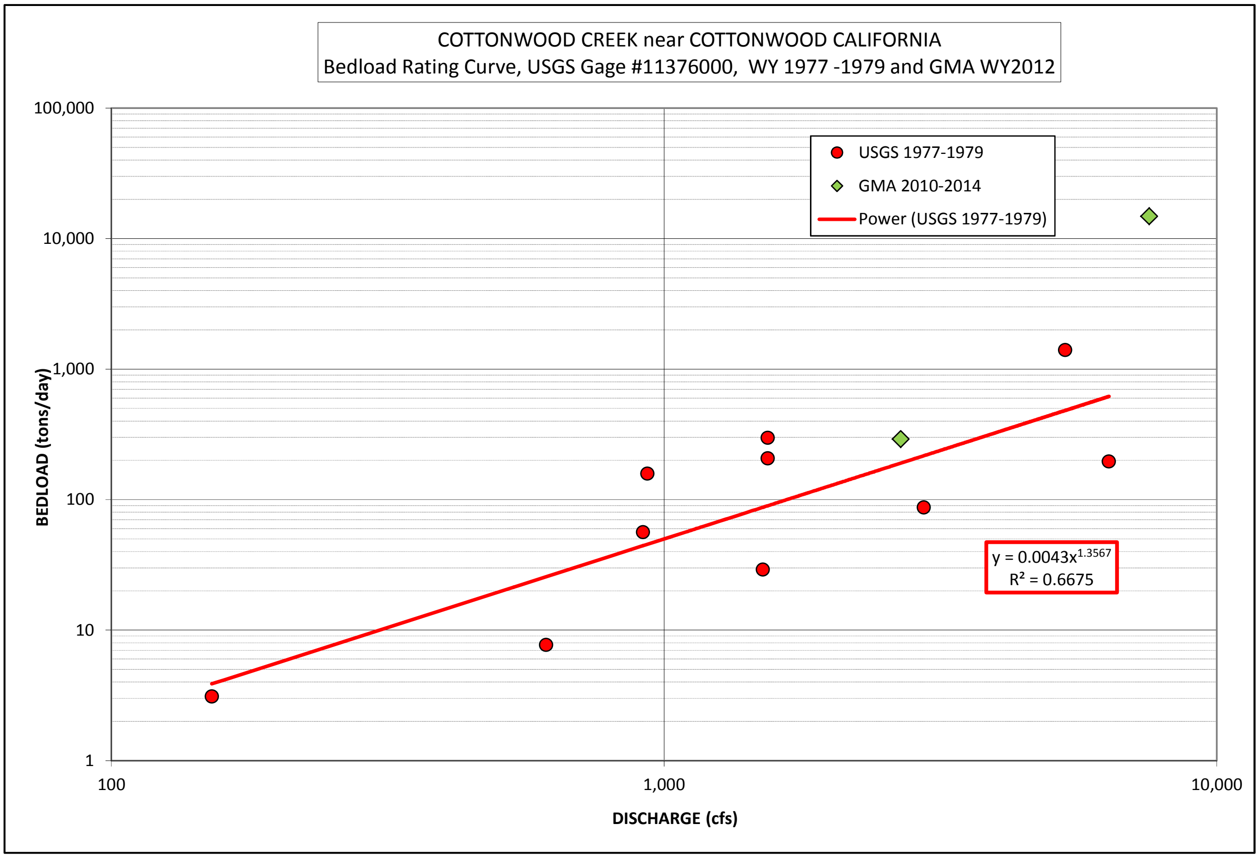

Figure 27. Bedload discharge at USGS 11376000: USGS 1977-1979 and GMA WY2012.

Table 15. Bedload sampling summary for Cottonwood Creek near Cottonwood, WY2012.

Sample Number	Date & Mean Time	Discharge (cfs)	Bedload Discharge (tons/day)	Suspended Sediment Discharge (tons/day)	Total Sediment Discharge (tons/day)	Bedload as Percent of Total
CCNC-BLM2012-01	03/28/2012 12:15	7,290	14,800	17,000	31,800	47%
CCNC-BLM2012-02	03/29/2012 11:51	2,690	290	907	1,197	24%

Table 16. Suspended Load, Bedload and Total Load for Cottonwood Creek near Cottonwood, WY2010-2014.

Component	WY2010	WY2011	WY2012	WY2013	WY2014
Suspended Load	622,000	665,000	70,000	184,000	13,000
Bedload	340,900	364,400	38,400	100,800	7,100
Total Sediment Load	962,900	1,029,400	108,400	284,800	20,100

3.2.4 Annual Sediment Loads

To facilitate sediment load comparisons between the three stations over the five year study period, we tabulated suspended sediment loads for each year (Table 17). Assuming complete routing of suspended sediment (i.e., no loss between gages), the USGS gage should show a suspended load as high as or higher than the sum of the two upstream stations. WY2014 was critically dry and the negative difference in the sum of the tributary stations versus the lower mainstem station may well be due to uncertainty in the SSC - discharge relation at lower flows at USGS 11376000. The remaining four Water Years show increases of 6-52 percent with wetter years generally showing a greater increase (Table 17). An examination of total sediment load reveals the same anomaly in WY2014 (a negative difference), with the other years showing an increase of 25-64 percent between the upstream stations to the USGS site (Table 18).

Table 17. Suspended sediment loads for all three Cottonwood Creek stations, WY2010-2014.

Site	WY2010	WY2011	WY2012	WY2013	WY2014
South Fork at Evergreen	228,000	80,000	26,800	123,000	11,300
Cottonwood near Olinda	183,000	237,000	24,000	49,900	10,500
Sum	**411,000**	**317,000**	**50,800**	**172,900**	**21,800**
USGS 11376000	622,000	665,000	70,000	184,000	13,000
difference	211,000	348,000	19,200	11,100	-8,800
percent difference	34%	52%	27%	6%	-68%

Table 18. Total sediment loads for all three Cottonwood Stations, WY2010-2014.

Site	WY2010	WY2011	WY2012	WY2013	WY2014
South Fork at Evergreen	287,700	101,000	33,800	155,200	14,300
Cottonwood near Olinda	209,500	271,400	27,500	57,100	12,000
Sum	**497,200**	**372,400**	**61,300**	**212,300**	**26,300**
USGS 11376000	962,900	1,029,400	108,400	284,800	20,100
difference	465,700	657,000	47,100	72,500	-6,200
percent difference	48%	64%	43%	25%	-31%

3.2.5 Sediment Yield

Water Years 2010-2013 show an increasing sediment load in the downstream direction but WY2014 does not, as described above. To help better understand these results (i.e., the broad range of differences as well as the negative difference for WY2014), we considered sediment production at the sub-watershed level. In order to examine the relative rate of sediment production for sub-watersheds, we must examine their annual unit sediment yields (tons/mi^2). The suspended sediment relations expressed as unit sediment loads (yield, tons/mi^2) are provided in Table 19. Excluding the anomalous WY2014, the mean data suggest that (on average), the lower mainstem generates 25-31 percent more sediment per square mile than either of the upstream gages. Some discrepancies exist which contradict the apparent increase, such as in WY2013, where the South Fork produced a sediment yield roughly a third *higher* than the lower mainstem. An examination of total load sediment yield provides similar results (since the totals are computed as a function of suspended load), yet since the relative proportion of bedload varies, the total sediment yield appears to increase by roughly 44 percent between the upstream sub-watersheds and the entire watershed as described by CCNC (mean values column, Table 20).

Table 19. Suspended sediment yield for all three Cottonwood sub-basins, WY2010-2013 (tons/mi²).

Site	Drainage Area (mi²)	WY2010 (tons/mi²)	WY2011 (tons/mi²)	WY2012 (tons/mi²)	WY2013 (tons/mi²)	WY2014 (tons/mi²)	2010-2013 Mean
South Fork at Evergreen	397	574	202	68	310	*28*	288
Cottonwood near Olinda	395	463	600	61	126	*27*	313
USGS 11376000	927	671	717	76	198	*14*	416
The record drought year WY2014 is omitted from the mean							

Table 20. Total sediment yield for all three Cottonwood sub-basins, WY2010-2013.

Site	Drainage Area (mi²)	WY2010 (tons/mi²)	WY2011 (tons/mi²)	WY2012 (tons/mi²)	WY2013 (tons/mi²)	WY2014 (tons/mi²)	2010-2013 Mean
South Fork at Evergreen	397	725	254	85	391	*36*	364
Cottonwood near Olinda	395	530	687	70	145	*30*	358
USGS 11376000	927	1,039	1,110	117	307	*22*	643
The record drought year WY2014 is omitted from the mean							

3.2.6 Intra-annual Variation in Sediment Transport

The results in the previous two sections tend to homogenize intra-annual differences in storm types (by summing into annual loads), perhaps exacerbating the relative difference between upstream and downstream stations as presented above. A comparison of individual storms from within the Water Years in which we have the most data confidence (i.e., WY2012 and WY2013, years with turbidity and discharge data at the upstream sites) may provide a better examination of relative suspended sediment yield. Loads were summed for the periods during which they exceeded their background transport rates ("flatline" periods in the sedigraphs in Appendix 2) for the storms which peaked on the dates presented in Table 21.

These peak transport events (lasting up to 10 days) represent the three largest storms during the period in which we have the best data. With the exception of the December 2, 2012 storm, the South Fork and the mainstem site near Olinda produce similar yields. The December 2, 2012 event produced very high flows at both sites (~8,000 cfs at South Fork and ~13,000 cfs at CCNO), but the South Fork remained more turbid for longer (Appendix 2), thus transporting a higher load. For this particular event it seems that the mainstem diluted the South Fork load, which appears to be out of the ordinary and may represent a unique erosional event in the South Fork sub-basin or the disparity may be a function of difference in methods used to compute loads at the different sites[1]. This is also suggested by the anomalous yield ratios observed in WY2013 in Table 19 and Table 20 above. For the other two storm events, the yield increases between the upstream sites and the lower mainstem site, suggesting more sediment is available for transport (per unit area) below the upstream stations than above (Table 21).

[1]*Note: a turbidimeter at CCNC would have eliminated the dilution question.*

Table 21.Total sediment yield for all three Cottonwood stations for the three largest storms during WY2012-2013.

Site	Drainage Area (mi^2)	March 28, 2012		December 2, 2012		December 23, 2012	
		(tons)	(tons/mi^2)	(tons)	(tons/mi^2)	(tons)	(tons/mi^2)
South Fork at Evergreen	397	20,354	51	132,298	333	24,806	62
Cottonwood near Olinda	395	21,160	54	43,700	111	11,500	29
USGS 11376000	927	91,605	99	175,150	189	104,780	113

3.2.7 Unit Transport Rates

Instantaneous suspended sediment loads, computed from individual sediment samples, with discharge normalized by drainage area, are presented in Figure 28. The rates of increase for South Fork and the mainstem near Olinda are virtually the same, with power function exponents of 2.56 and 2.51 respectively. The South Fork equation sits above (and essentially parallel to) the Olinda equation, meaning that the South Fork begins to produce suspended sediment at a lower unit discharge. Since the two stations' drainage areas are virtually the same, according to this transport rate analysis based on unit discharge, the South Fork generates more suspended sediment than the mainstem near Olinda. While the data set collected at the lower mainstem site (11376000), consisting of only two data points, is too small to make a strong inference, the steeper slope in the equation may suggest that the entire 927 mi^2 watershed above the USGS (11376000) site (and thus the 135 mi^2 sub-watershed which lies downstream of the upstream stations) produces more sediment per unit discharge than does the watershed above each of the other two stations.

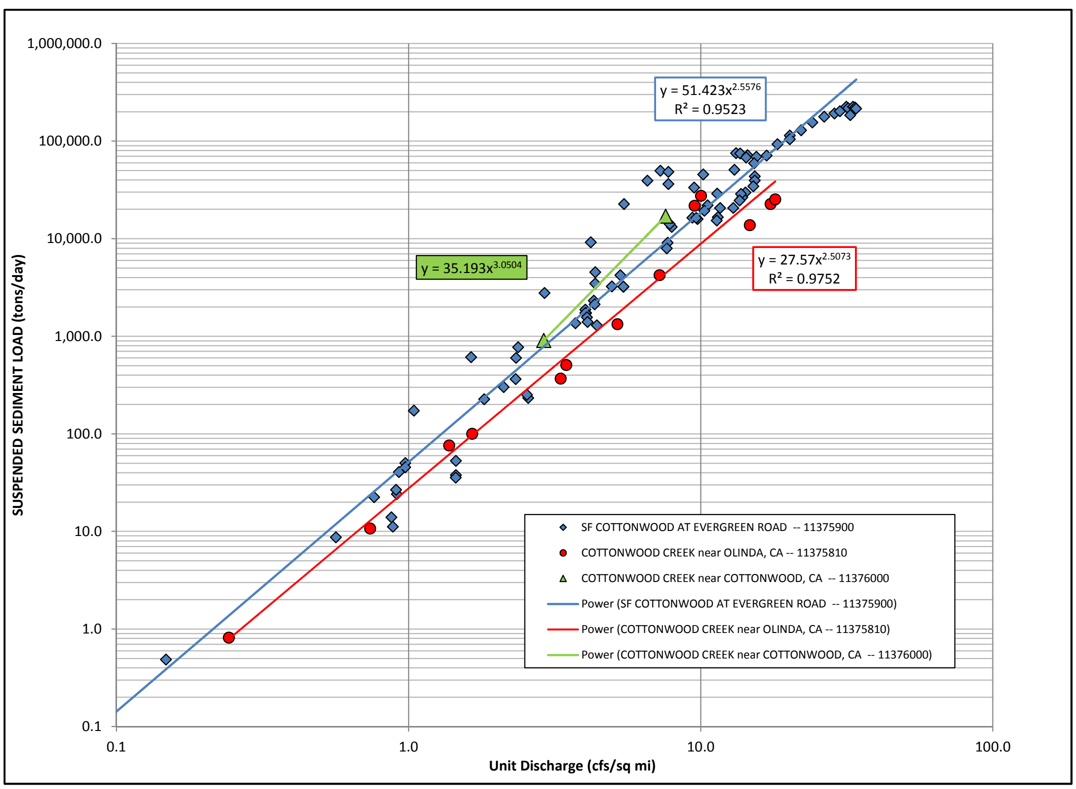

Figure 28. Unit-discharge suspended-sediment transport rates for all three Cottonwood stations during the WY2010-2014 study period.

3.2.8 Sediment Budget

Table 22 presents the relative basin area, total load yield and mean annual total load and relative contribution of the total load exiting the basin. These data suggest that the watershed downstream of the South Fork and the CCNO stations (Figure 29) generates a disproportionally high percentage of the sediment produced in the basin: the upstream stations represent 86 percent of the entire watershed area but only produce 48 percent of the total sediment load exiting Cottonwood Creek. These numbers are considered estimates and the relative error in our results is unknown.

Note:

1. For the upstream basins, the percent basin area (43 percent) and the relative contribution to the lower mainstem annual load (24 percent), happens to be the same. This is a coincidence; sediment loads were computed independent of basin-area relations -- except in the case of CCNO WY2010-2011 when the CCNC hydrograph was scaled, which would have virtually zero auto-corollary effect on the final product.
2. The mean values in the last column imply an extraordinary increase in yield within the lower 14 percent of the basin (>2,000 tons/mi^2). These numbers are only estimates however and serve merely to indicate the direction of change: toward an unknown magnitude but very apparent increase in in sediment production in the lower watershed.

Table 22. Mean annual total sediment yield (WY2010-2013) for Cottonwood sub-basins.

Gaging Location	USGS #	sq mi	% of basin area	Yield (t/mi^2)*	Mean Annual Load (tons)**	Percent of Entire Basin Load
USGS SFCC @ Evergreen	11375900	397	43%	367	145,699	24%
USGS CCNO	11375810	395	43%	360	142,200	24%
USGS CC nr CW	11376000	927	100%	644	596,988	100%
			*WY2010-13 average		**not rounded	

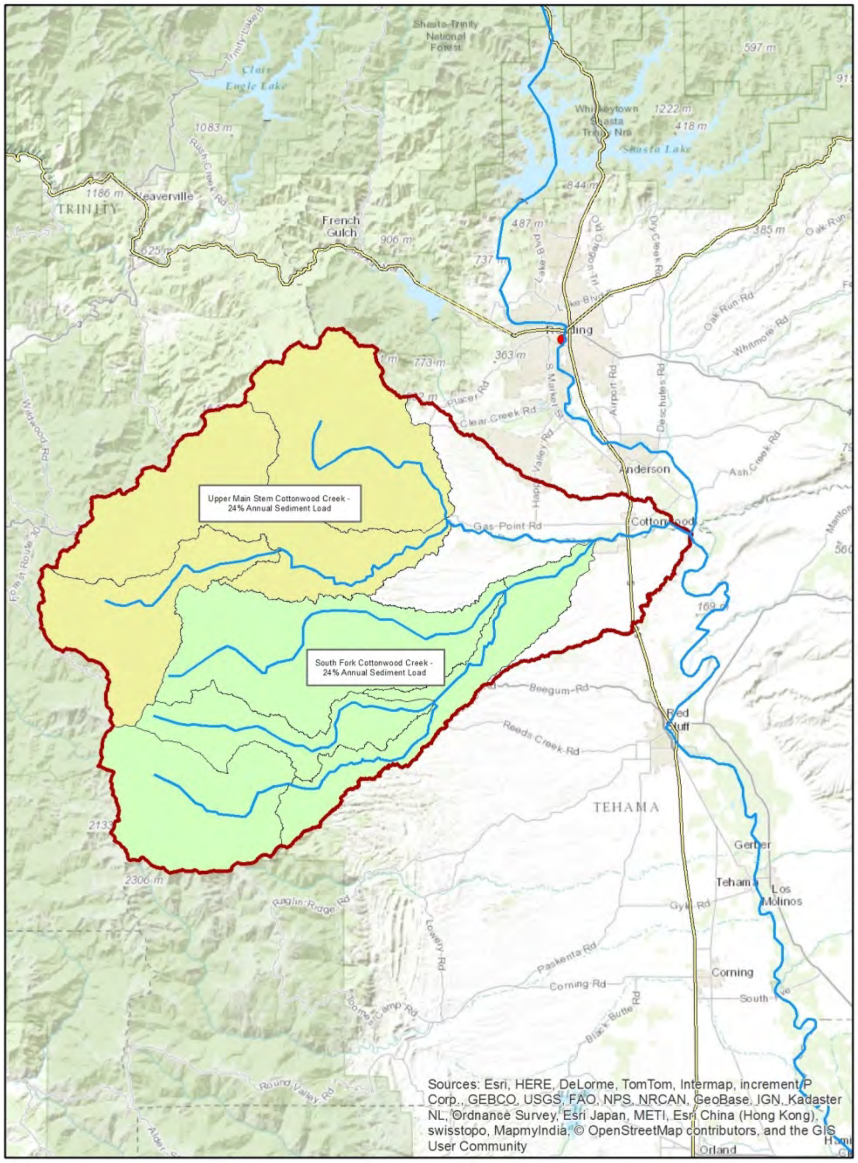

Figure 29. Sub-watershed sediment production for Cottonwood Creek, WY2010-2013.

3.2.9 Sediment Transport Trends over Time

We have insufficient historical data to compare bedload or total load trends over time so in this section we examine suspended sediment only.

<u>Suspended Sediment</u>

As discussed previously and as presented in Figure 26, we do not have sufficient evidence to suggest that the lower mainstem (CCNC) produces an appreciably different suspended sediment load than it did during the 1963-1980 period. The upper mainstem site near Olinda (CCNO) appears to be very similar to historic 1977-1983 rates (Figure 30) though the steeper slope of the WY2010-2014 trendline (exponents of 2.19 historic and 2.59 today) suggests that suspended sediment transport increases at a faster rate today than it did over the 1977-1983 period. The South Fork at Evergreen Road station has no historic data, so we compared the Evergreen Road site to the South Fork near Olinda (USGS 11375870) with a drainage area of 371 mi^2 and a mean daily suspended sediment discharge record dating from 1977-1980. While a simple power function developed from the WY2010-2014 data does show a higher rate of increase (steeper slope) than one developed from the 1977-1980 data, the older data set is much larger, especially with the number of samples at the lower end, and the upper end of the equation (Figure 31) falls below the sample data, under-predicting the higher transport rates. Qualitatively, the 2010-2014 data seem to plot with the historic data, especially in the higher transport end of the range.

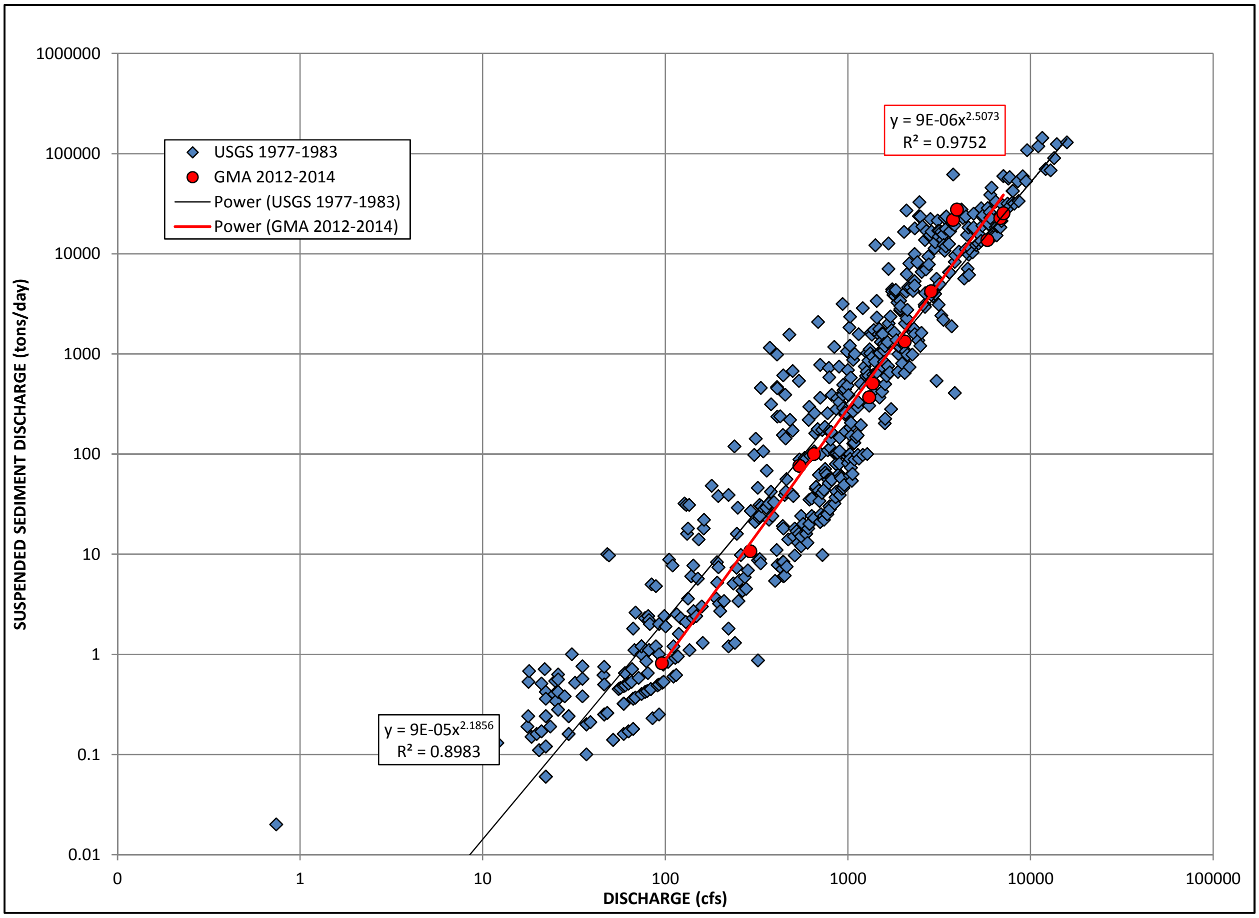

Figure 30. Cottonwood Creek near Olinda, historic USGS suspended sediment discharge and GMA 2012-2014 suspended sediment discharge

For the USGS site near Cottonwood, rather than develop piecewise regressions to analyze subjectively-determined subsets of data (as was done with the USGS 11376000 historic data to compute average annual loads), we simply acknowledge that the more recent data seem to fit within the cloud of historic points and do not represent a significant departure from historic rates (Figure 26).

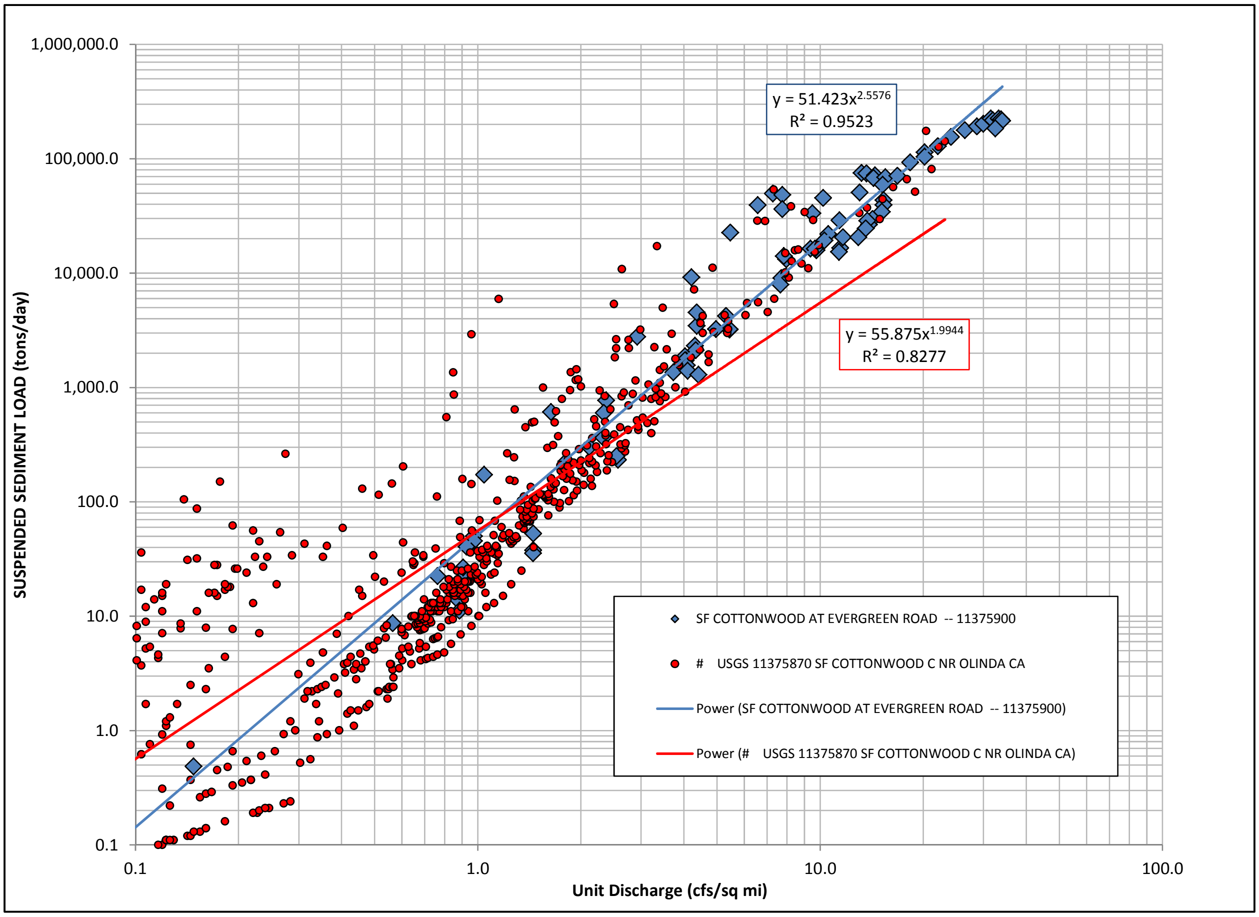

Figure 31. South Fork Cottonwood Creek normalized suspended sediment loads computed from sample data for the Evergreen Road site (instantaneous WY2010-2014, 397 mi^2) and the USGS site near Olinda (mean daily, 1977-1980, mi^2).

3.3 Geomorphic Mapping

3.3.1 Surveys

Long Profile

In July 2011, GMA surveyed the longitudinal profile from the North Fork confluence to the Sacramento River. The portion up to Station 63,000 (feet, above the confluence with the Sacramento River) was compared to the 2002 (above South Fork) and 1999 (below South Fork) profiles (GMA 2003). Both sections were primarily influenced by the 2003 and 2006 annual peak flows of 39,800 cfs and 46,700 cfs (RI = 4.6 and 6.7 years). The profile is broken up into three reaches of approximately equal length and is presented in Appendix 3 as: Downstream Section (0-20,000 feet); Middle Section (20,000-45,000 feet), and; Upper Section (45,000-63,000 feet).

Downstream Profile: Station 0 to 20,000 feet

With a few exceptions, every major bedform (gravel bar) in the lowermost reach shows scour. Some minor pools show fill but the larger bar features generally show scour from two to nearly five feet (Appendix 3-1). Above Station 16,000 the three largest bedforms appear to persist in approximately the same locations but have been scoured 1.5 to five feet. Below here, the bed appears to be largely reconfigured. The claypan exposure above the confluence (examined later in Section 3.3.2) shows bed scour in the longitudinal profile consistent with the findings from aerial photo analysis of claypan.

Middle Profile: Station 20,000 to 45,000 feet

Again, with few exceptions, the entire reach has degraded (Appendix 3-2). Below I5 (near station 19,000) begins a stretch of approximately four miles exhibiting bed lowering up to approximately ten feet. The profile data suggest that the claypan exposure upstream of I5 (Section 3.3.2) is contained within this four mile reach of bed lowering. Similarly, the claypan site below the South Fork shows over three feet of scour. Bed lowering in the 3,500 feet below the South Fork confluence appears to be less than most of the rest of the reach, on the order of 1-2 feet, with one small bar aggrading 2.5 feet at Station 43,845. The delivery of sediment from the South Fork may offset the magnitude of incision in the vicinity downstream of the confluence.

Upper Profile: Station 45,000 to 63,000

The 2011 data contains some gaps where GPS coverage was poor (Appendix 3-3). From 45,000 feet up to about 48,000 feet, the streambed shows 2-3 feet of scour even through the persistent pool at Station 46,450. From Station 48,000 to 61,000, scour and fill appear relatively balanced with the net bed elevation remaining approximately the same between surveys. Above Station 61,000 the profile reveals significant deposition (up to 5 feet), to Station 63,000.

Cross Sections

In July 2011, GMA re-surveyed cross sections (n=22) from the Sacramento River confluence to upstream of the South Fork confluence, with two additional cross sections located on the lower reach of the South Fork below Evergreen Road. The locations and alignments of the 2011 surveys are shown in Appendix 3-4 to 3-6 (Note: Upper/Middle/Lower scale differs from the longitudinal profile scale). Most of these cross sections had originally been established by the USGS in 1982-1983 and were first re-surveyed by GMA in 1999-2002. In this report, we only analyze the changes between the two GMA surveys, essentially from 2002 to 2011. As noted in previous sections, two significant annual peaks (WY2003 and 2006), though modest from a long-term geomorphic perspective at 4.6 and 6.7 year recurrence intervals, occurred between the GMA surveys and likely caused most of the geomorphic change observed. There are significant challenges in re-surveying and comparing cross sections on a large, dynamic river such as Cottonwood Creek. As the planform shifts, a cross section alignment that may have been perpendicular to the earlier active channel is now highly skewed, or in some extreme cases no longer even crosses the current channel. In addition, cross section pins may be eroded through lateral migration. Because of this, the 2011 cross section surveys sometimes had a slightly different alignment than the 2002 cross sections, and not all of the cross sections could be successfully re-occupied.

The original USGS cross sections on the mainstem were numbered 1-19 and began approximately 1,000 feet upstream of the Sacramento River confluence and progressed upstream for over 16 miles. In 2002 GMA added two cross sections on the lower South Fork, numbered 100 and 101. GMA also added additional cross sections, numbered 102-106 on the mainstem, all upstream of the SF confluence. Of the 19 original USGS cross sections re-surveyed in 2011, 13 showed the best alignment agreement and are included in this analysis. Likewise, six of the GMA 2002 cross sections were used. All cross sections used in the 2014 analysis (n=19) are as follows:

- USGS (mainstem) 1-10, 14, 16, and 17,
- GMA (mainstem) 102, 104-106, and
- GMA (South Fork) 100 and 101.

Graphics showing the comparison of the 2002 and 2011 cross section survey data are provided in Appendix 3-7 to 3-25. Cross sections 1-10 are located between I5 and the Sacramento River. Cross section 12 is between I5 and the South Fork, while the remaining sections are upstream of the South Fork (Appendix 3-4 to 3-6).

In order to examine whether incision has continued since 2002 (a trend identified in GMA 2003), we examined the lowest elevation along cross sections for 2002 and 2011 as an indicator of net vertical channel change (incision or aggradation). Table 23 summarizes the minimum bed elevation of each cross section and the difference between the two data sets. Significant differences between the datasets are present at many locations. The range of changes in the minimum bed elevation is from an increase of 3.36 feet to a decrease of 7.33 feet. Of the seventeen mainstem cross sections, fourteen showed declines (suggesting incision) while only three showed increases (suggesting aggradation). The average change of the seventeen mainstem cross sections was -1.89 feet. Both cross sections on the South Fork showed decreases, though smaller in magnitude than those on the mainstem, averaging -0.71 feet.

Further evaluation of the changes indicates that cross sections 1 and 2 near the confluence with the Sacramento River showed small changes (-0.31 and -0.53, respectively), with generally increasing changes as one moves upstream towards I5. The largest decline (-7.33 feet) was at cross section 7

(Station 23,600), located a little over a mile downstream of I5. Large declines were also present at cross sections 14, 104, and 105 (Upper Section, Appendix 3-6), while three out of the four most upstream cross sections (16, 106, and 17) showed much smaller changes. These results generally agree with the profile results, with the largest changes in the central portion of the profile, with smaller changes at the upstream and downstream ends.

Table 23. Minimum elevations along cross sections – 2002 vs 2011.

			XS Minimum Elevation (ft)		Difference
Section	XS #	Station (ft)	2002	2011	(2011-2002)
Mainstem	1	644	346.62	346.31	-0.31
	2	2,600	350.67	350.14	-0.53
	3	7,650	363.36	362.18	-1.18
	4	12,980	368.81	366.20	-2.61
	5	15,200	369.15	372.39	3.24
	6	18,700	378.03	375.26	-2.77
	7	23,600	385.90	378.57	-7.33
	8	29,080	389.99	385.77	-4.22
	9	29,300	391.44	389.49	-1.95
	10	29,600	390.69	386.08	-4.61
	102	48,900	421.84	425.20	3.36
	14	51,800	428.26	425.66	-2.6
	104	59,900	444.51	440.07	-4.44
	16	65,360	447.58	446.71	-0.87
	105	66,600	457.13	451.82	-5.31
	106	68,200	457.92	458.67	0.75
	17	71,550	460.24	459.50	-0.74
	Average				**-1.89**
South Fork	100	NA	422.44	422.12	-0.32
	101	NA	424.20	423.10	-1.1
	Average				**-0.71**

In addition to mostly showing an incising channel, cross sections also provide evidence of channel widening at most (all but three) locations and large net removal of alluvial material (e.g. sections 1 and 4). Table 24 compares the approximate "bankfull width" of selected cross sections in 2002 and 2011, along with the difference in width and the percentage change in width from 2002. "Bankfull width" was defined by breaks in slope along the sections where flow in the main channel would spill out onto a floodplain or other adjacent surface common to the two surveys. If the 2002 adjacent surface had completely eroded away, then the 2011 width was determined as the distance between the primary confining features, usually very tall steep banks (Figure 32). None of the cross section surveys show evidence of channel narrowing. Cross section width increased an average of 43 percent in the mainstem (Table 24). A similar examination of the two sections along the South Fork indicates less widening at seven percent. More quantitative analysis of volume changes would require complete topographic data that do not exist. The GMA 2011 LiDAR data would facilitate such future comparisons if the future LiDAR data were collected at a similar streamflow (250 cfs).

Table 24. Changes in apparent bankfull width between 2002 and 2011.

			XS Bankfull Width (ft)		Difference	
	XS #	Station (ft)	2002	2011	(feet)	(%)
Mainstem	1	644	468	1269	801	171%
	2	2,600	345	562	217	63%
	3	7,650	353	559	206	58%
	4	12,980	258	438	180	70%
	5	15,200	421	463	42	10%
	6	18,700	405	447	42	10%
	7	23,600	295	405	110	37%
	8	29,080	520	576	56	11%
	9	29,300	462	674	212	46%
	10	29,600	459	459	0	0%
	102	48,900	217	333	116	53%
	14	51,800	566	566	0	0%
	104	59,900	566	587	21	4%
	16	65,360	254	317	63	25%
	105	66,600	*NA*	*NA*	*NA*	*NA*
	106	68,200	524	670	146	28%
	17	71,550	141	218	77	55%
	Average				**141.17**	**40%**
South Fork	100	NA	447	495	48	11%
	101	NA	246	252	6	2%
	Average				**82.92**	**7%**

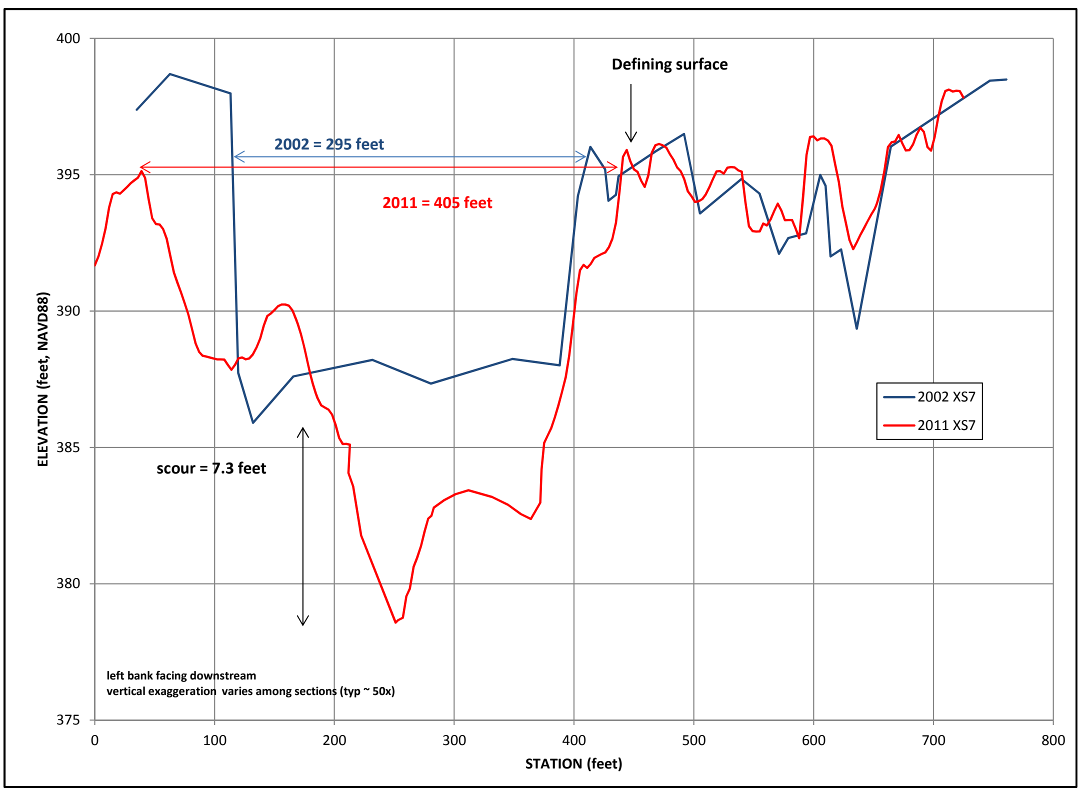

Figure 32. Cross section 7 showing increases in channel width and over seven feet of scour.

Table 25 provides a brief summary of observed changes to the longitudinal profile, cross sections and the planform geometry. Planform change was assessed by comparing channel centerline alignments for three different years (2002, 2006 and 2011) and is discussed in detail in Section 3.3.2.

Table 25. Summary of channel changes by longitudinal profile reach.

Reach (Longitudinal Profile Sections)	Longitudinal Profile Change	Cross Section Change	Planform Change
Downstream Section (0 - 20,000 ft)	Most bedforms show scour. Above Station 16,000 the three largest bedforms appear to persist in approximately the same locations but have been scoured 1.5 to five feet. Below 16,000, the bed appears to be largely reconfigured.	Little scour on XS's near the confluence but considerable widening. Generally increasing scour as one moves upstream to I5.	After the valley expands into a less confined reach, the 2006 alignment departs from the 2002 in the form of meander bend translation in the downstream direction. Post-2002 meander bend translation results in a considerably longer channel through the downstream area. The 2011 alignment very nearly follows the 2006 path again resulting in a longer channel.
Middle Section (20,000 - 45,000 ft)	Virtually the entire reach has degraded, much of it up to 10 feet. The claypan exposure upstream of I5 is contained within this four mile reach of bed lowering. The claypan site below the South Fork shows over three feet of scour. Bed lowering in the 3,500 feet below the South Fork confluence appears evident, yet less than most of the rest of the reach (0-2 ft).	Frew XS's in this reach. Cross sections near I5 showed scour in the range of 2-4 ft. The only of these 3 XS's which did not show widening was #10, presumably confined by the bridge structures. Greatest scour (>7 ft) was ~I mle below the I5 bridge (XS7).	In the more confined reach above the South Fork, all three alignments follow a similar path. Below the South Fork, the three alignments converge and diverge abruptly as they encounter controlling claypan elements. The aligments again converge at the 15 constriction.
Upper Section (45,000 - 63,000 ft)	From 45,000 feet up to about 48,000 feet, the streambed shows 2-3 feet of scour even through the persistent pool at Station 46,450. From Station 48,000 to 61,000, scour and fill appear more balanced. Above Station 61,000 the profile reveals significant deposition (up to 5 feet).	XS 102 (above SFCC) was one of only two XS to show appreciable fill (>3 ft). XS 14, 104 and 105 show large declines (2.5-5 ft). The other upstream XS's show little scour/fill but considerable widening.	The three centerlines occupy very similar paths through the upper section with two obvious exceptions. (1) The 2002 channel looped to the south around a vegetated bar and island complex. (2) Below the Baker Ranch, the channel migrated >1,000 ft to the east. Again, the three paths converged at a claypan exposure (Joanne Lane, 66,000) though this one also occurs at a natural valley constriction.

Valley Profile Departure

We explored the idea that the stream channel may become more incised in the downstream direction. Following visual observations of very high, over steepened banks in the creek near I5, we formulated the cursory hypothesis that the channel profile may depart from the valley profile in areas showing more incision. The analysis was performed for the reaches above and below the South Fork of Cottonwood Creek. An examination of the generalized valley slope showed the bed slope and the valley slope to be nearly parallel (Figure 33), indicating no progressive departure from the valley surface. The 1999 vs 2011 trendlines through the profiles provide a better description of incision over the 12 year period. The trendlines converge at the downstream end, suggesting that 2002-2011 incision may be less nearer the confluence with the Sacramento River.

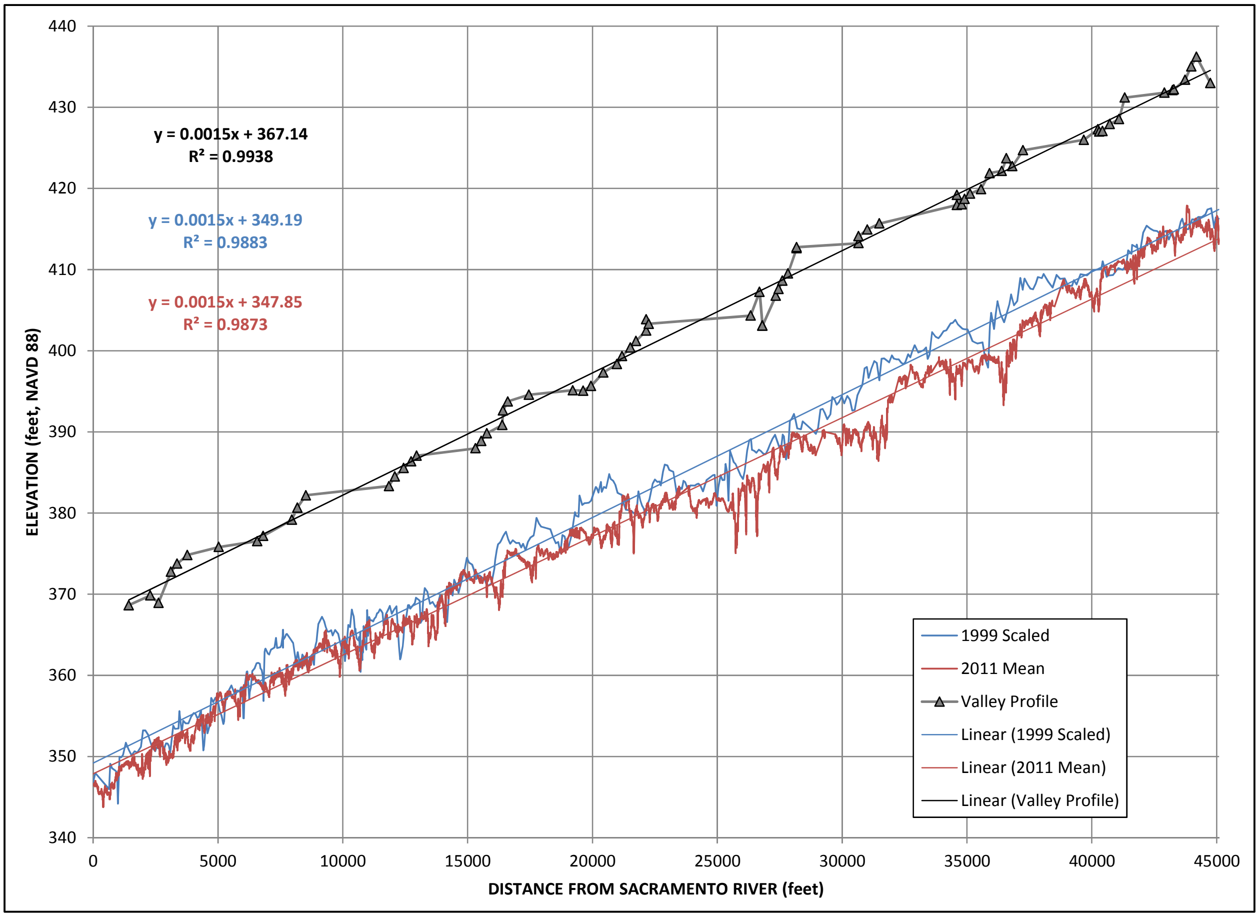

Figure 33. A comparison of the valley slope to the 1999 and 2011 bed slope.

3.3.2 Aerial Photo Analysis

Channel Planform Alignment

Stationing refers to distance upstream from the Sacramento River along the mean profile alignment described for the longitudinal profile. Centerline alignments were compared between the 2002, 2006 and 2011 aerial photographs (Appendix 4-17 to 4-19). Two large flow events occurred between the 2002 and 2006 photos: the 2003 annual peak (39,800 cfs, RI = 4.6 years) and the 2006 annual peak (46,700 cfs, RI = 6.7 years). The claypan exposure exercise (described in the next section) suggests that the 2006 event caused significant changes to the lower Cottonwood Creek stream channel. Following 2006, only the 2010 and 2011 annual peaks exceeded the 3 year RI, with 31,200 and 34,700 cfs respectively. Station labeling proved cumbersome so in the following descriptions we reference locations within the photographs, which in conjunction with the scale bar, should allow the reader to locate various points of interest in Appendix 4-17 to 4-19.

Downstream Section

In the 24,000 feet above the confluence with the Sacramento River, relatively minor changes occur in the upstream third of the reach (Appendix 4-17). After the valley expands into a less confined reach (around Station 16,000, directly above the North arrow) the 2006 alignment departs from the 2002 in the form of meander bend translation in the downstream direction. After the third bend, approximately mid-photo, the post-2002 centerline has migrated due south approximately 500 feet, orthogonal to the down-valley flow vector. The same phenomenon occurs in the next bend, but to the north. The net result is a considerably longer channel through this area. The 2011 alignment very nearly follows the 2006 path with one exception near mid-photo where the 2011 alignment has migrated downstream (east in this case), again resulting in a longer channel.

Middle Section

At the upstream end, in the more confined reach above the South Fork (Appendix 4-18), all three alignments follow a similar path. Below the South Fork (at 44,000 feet), the first meander shows the same 2002-2006 progression as was observed in the downstream section. Approximately 3,750 feet downstream of the South Fork, the three alignments converge and diverge abruptly, suggesting a controlling element (e.g. bedrock constriction). This is the location of the claypan exposure near Station 40,000 (Below South Fork, Appendix 4-10 -- discussed in the next section).

Below 40,000, the 2006 and 2011 alignments again depart in a downstream migrating meander and then re-converge near Station 36,500 (mid-photo, Appendix 4-18) which is (1) the location of another prominent claypan exposure (this one is not included in the next section) and (2) in the 2006 Google Earth © image, the location of a bar skimming operation. The three alignments again diverge though remain approximately parallel until reaching Station 31,600 (the Upstream I5 exposure) where they again abruptly re-converge against the south bank. The three alignments then show little divergence through and below the I5 constriction (29,500).

Upper Section

The three centerlines occupy very similar paths through the upper section (Appendix 4-19) with two obvious exceptions. One appears directly above the north arrow in the photograph, where the 2002 channel looped to the south around a vegetated bar and island complex. The floods prior to 2006 evidently caused the channel to cut off this meander, taking the straighter path along the northern flank of the valley. The 2011 channel follows the same alignment as the 2006. Again, the three paths converge at a claypan exposure (Joanne Lane, 66,000, see next section) though this one also occurs at a natural valley constriction.

The second exception occurs below The Baker Ranch which is located at Station 60,000 where Cottonwood Creek turns to the north in a very straight run for about 1,800 feet, then turns east for a run of similar length. Below this run to the east (above the word “Channel” in the caption), the 2006 and 2011 alignments diverge from the 2002, migrating well over 1,000 feet to the east, eroding into what appears to be an oak woodland pasture (2011 aerial photo).

Claypan Exposure

Using Google Earth © historical imagery we examined five locations along Cottonwood Creek where claypan has become increasingly more exposed since 1998. We attempted to examine claypan along the length of the study reach, rather than focus solely on areas where large areas have appeared (Figure

34). We chose locations throughout the length of lower Cottonwood Creek (Appendix 4-1) representing sub-reaches relative to tributaries, gravel mining disturbance and the Sacramento River confluence:

1. Creekside, 75,500 feet (14.3 miles) upstream of the Sacramento River, upstream of Dry Creek;
2. Joanne Lane, 66,000 feet (12.5 miles) upstream of Sacramento River, located between Dry Creek and South Fork Cottonwood Creek;
3. Below South Fork Cottonwood Creek, 40,000 feet (7.6 miles) above the Sacramento River;
4. Upstream of I5, 31,600 feet (6.0 miles) above the Sacramento River, adjacent to recent gravel mining activity;
5. Near Confluence, 3,600 feet (0.7 miles) above the Sacramento River.

Figure 34. Distribution of claypan exposure study sites. Google Earth 2014 image. North is toward top of page.

A table of peak discharges and their corresponding recurrence intervals for the 1997-2014 period is provided with each location map in Appendix 4. Intervening peak flow magnitudes may provide some context to the changes observed in the photographs. Streamflow varies in the photographs and we temper our interpretations with the understanding that features may be submerged or obscured in some photos and not in others. We recognize this analysis is somewhat subjective, and we therefore limit our conclusions to (1) the most obvious attributes in the photographs, and (2) interpretations verified by field observations.

Creekside (Appendix 4-2 to 4-4)

The earliest photograph in the Creekside sub-reach providing reasonable resolution was September 2002, which shows a relatively straight reach with gravel bars along either side of the channel. By 2005, following peak flow events in 2003 and 2004 (4.6 year and 3.7 year RI, respectively); the photographs show erosion along the south bank, which created a more sinuous planform. No claypan is clearly evident in the photographs, although the light areas in the downstream transverse riffle may indicate claypan. By 2006, following the 6.7 year flood (46,700 cfs), the channel eroded even more of the south bank and claypan clearly appears at downstream end of the eroding bend and in the transverse riffle. The outcrop at the bend is the dominant clay feature examined here and appears to have been mostly revealed (overlying sediment scoured) by the 2006 flood. By August 2010, following a 3 year flood (31,200 cfs, the largest peak since 2006), the large clay outcrop at the bend appears slightly larger and is clearly fissured (presumably by fluting induced by gravel transport over the clay). In 2013, following the 3.9 year flood in 2011, the exposure of downstream feature has expanded to include segments along each bank. The southward migration of the channel has slowed (if not stopped), as evidenced by the planform alignment in subsequent photos as well as by the appearance of riparian vegetation along the channel margin (Figure 35). While no flows have yet exceeded the 2006 flood, one possible explanation for the slowing of bank retreat is that the claypan (located at the effective apex of the meander bend) is impeding further erosion.

Figure 35. Upstream view of the (upper) Creekside claypan exposure. July 19, 2011.

Joanne Lane (Appendix 4-5 to 4-7)

The site near Joanne Lane occurs in a constriction below a wider series of meander bends. The earliest clear photo in Google Earth © is from November 2003 and no claypan is apparent until after the 2006 flood, appearing as a fluted structure in the July 2007 photo (in the channel near the top of photo in Appendix 4-6). In August 2010, following a 3.0 year event, the claypan has increased in areal extent and appears to be roughly 100 feet in length. In August 2012, following a 3.9 year flood, the areal and longitudinal extent appear to be about the same as in 2010. The feature occurs at the downstream end of a low gradient riffle and is exposed predominantly along the south bank with a deeper channel cut through its north side, accommodating most of the flow in summer (Figure 36).

Figure 36. Upstream view of the Joanne Lane claypan exposure in June 2014. Note the fluting evident beyond the backpack.

Below South Fork (Appendix 4-8 to 4-10)

The claypan exposure downstream of the South Fork confluence is located along the southern apex of a meander bend. The 1998 photograph shows a valley-wide (~800 feet) point bar with the active channel located along the south bank. In 2005, following floods up to 4.6 years in magnitude, the channel has changed from a more uniform grade through the gravel bar (as was suggested by the uniform shade and width of the 1998 channel) to plunge more steeply into a lateral scour pool against the south bank. In 2006, following a 6.7 year flood, a bar has been built against the south bank and most of the channel has been redirected toward mid-valley. In the downstream quarter of the 2006 photo (Appendix 4-9) however, the bank has retreated up to 100 feet and the large claypan feature has become exposed. A significant portion of this feature had been located beneath a high bank covered in older vegetation. While the claypan is dappled by shade from large trees in the 2006 photo, its presence is confirmed by the appearance of the distinct fluted channels common to claypan outcrops. By August 2010, the large pan at the downstream end has grown larger and several small, clay reef-like structures begin to protrude at the upstream end of the riffle. By 2011, after a 3.9 year flood, the downstream pan appears roughly the same size as in 2010 though it may be more fissured (this is difficult to say due to the glare in the 2010 photo). Most importantly, the upstream reef-like structures appear more prominently, are more deeply fissured and claypan appears to occur along the length of the riffle (Figure 37). By 2013, each of these attributes is even more pronounced (Appendix 4-10).

Figure 37. Claypan "reefs" protruding from the active channel below South Fork Cottonwood Creek, July 20, 2011.

Upstream of I5 (Appendix 4-11 to 4-13)

The Upstream I5 site occurs adjacent to a recent gravel extraction operation where a semi-anastomosed channel (multiple threads separated by vegetated islands) abruptly terminates into a prominent claypan ledge. In 1998, the main channel appears on the north side, though at least two other channels contain some flow through the middle of the bar. The quality of the 1998 photo precludes certain determination of claypan exposure. In 2003, following a 4.6 year flood, a large lobe of yellowish claypan can be seen along the southern margin. The same lobe in 2010, following the 2006 flood (6.7 year event) has grown to encompass the entire active channel width (Appendix 4-12). The medial channel through the bar has also scoured to claypan. The 2011 and 2012 photos reveal a progressive increase in the areal extent of claypan as well as the appearance of more claypan in other channels and within the bar complex. The existing channel through the claypan is over 6 feet deep in places and contains virtually all of the summer stream flow (Figure 38).

Figure 38. Ground photos of the claypan upstream of I5 showing (1) fluting and streamflow capture common to claypan areas within lower Cottonwood Creek, and (2) bedload arrested in motion as it slides over claypan exposure.

Near Confluence (Appendix 4-14 to4-16)

This site is situated 3,600 feet upstream from the Sacramento River confluence (Figure 39) and occurs in a reach where the migration corridor appears to be over ½ mile wide, as evidenced by the abandoned channels to the north versus the wet channel along the south bank in the 2013 (Appendix 4-14). The 1999 photo reveals a highly alluvial setting with what appears to be 100 percent gravel cover across the entire photo. In 2005, the channel alignment has changed considerably though no claypan is yet apparent. By June 2009, the channel alignment has changed again, riparian vegetation is somewhat better established and a small lobe of claypan appears in the upper half of the photo. By 2010, the channel alignment remains the same but numerous claypan outcroppings begin to appear, one of which confirms the small area which appeared in the 2009 photo. In 2013, the upstream most claypan outcrop has been buried in gravel while those downstream appear very similar in areal extent.

Figure 39. The Confluence site is the downstream most appearance of claypan, 3,600 feet upstream of the Sacramento River.

Claypan Exposure Summary

We examined a single claypan exposure in each of five representative reaches, though many more such exposures occur throughout lower Cottonwood Creek. The 2006 flood appeared to expose more claypan than any other single event. Claypan exposures appear primarily where bars and riffles have scoured, exposing the underlying Tehama Formation, but bank erosion also revealed considerable claypan. The claypan functions as geomorphic control in at least two ways, (1) eroded slots capture low flow threads which appear unlikely to change in their planform alignment; and (2) progressive claypan exposure along the outside of bends may slow erosion once the easily-eroded alluvium has been scoured from the bank (as in at the Creekside site). We did not assess the vertical distribution of claypan in such instances. In some cases (mostly closer to the confluence with the Sacramento River), claypan would become buried with gravel -- but this was generally not the case as most exposures, once exposed, tended to grow larger with time. Gravel transport over the claypan appears to be the primary mechanism by which the slots are cut and the fluted appearance develops. Claypan is increasing in areal extent over time, suggesting the progressive evacuation of alluvial material.

3.4 Hydraulic Modeling

3.4.1 Approach

The Baker site is situated along the mainstem approximately 3 miles upstream of the confluence with the South Fork (Figure 40). Between 1980 and 1981, Cottonwood Creek changed its course and the south bank retreated hundreds of feet, eroding into an upland surface of pasture land (GMA 2003). Though the bank has not retreated appreciably since 2006, the problem presented by the physical setting (lateral bar or “island feature” directs flood flows into the bank) and access considerations made the Baker site ideal for modeling the effects of island removal and pilot-channel redirection. McBain Associates (MA) performed the hydraulic modeling for the Baker site and their complete report is included in Appendix 5. The main points of MA’s analysis are included here.

Two hypothetical grading plans, for use in the comparative modeling analysis only, were developed as follows:

1. Alternative 1 lowers the right bank surface approximately 4 feet and fills in an existing high flow channel along the eroding right bank; and
2. Alternative 2 removes an existing left bank berm and associated vegetation, excavates a new high flow channel through the center of the right bank surface, and fills the existing high flow channel along the eroding right bank.

Existing conditions and the two hypothetical grading plans were modeled for the following flows (flow duration and flood frequency scaled by drainage area from analyses completed for USGS 11376000):

1. 1,800 cfs – the flow which is exceeded as the daily mean 5 percent of the time;
2. 4,800 cfs – a common high flow, typically occurring several timer per year; and
3. 7,800 cfs – the 1.5 year flood, as determined by flood frequency analysis.

To help isolate changes associated with the two alternative designs, the modeled reach was divided into two parts; upstream and downstream (*Figure 19 in Appendix 5*).

3.4.2 Hydraulics

Downstream boundary conditions were developed using rating curve developed in HEC RAS (Figure 41). An example of the 2-D model depth results is provided in Figure 42 for 4,800 cfs for existing conditions and the two alternative conditions. Similar products were generated for the other two flows for depth, velocity and shear stress to provide an evaluation of changes in the hydraulics caused by flow magnitude and hypothetical grading options (Appendix 5). Changes in hydraulic attributes were then used to evaluate the effect of flow and channel manipulation on habitat quality.

Figure 40. Upstream view of the Baker Ranch study site, April 18, 2012 (1,150 cfs at USGS 11376000). The primary area of interest is the eroding bend at the top of the photo, along the south bank. CDFW-sponsored flight, courtesy P. Bratcher.

3.4.3 Habitat

In addition to comparing changes in channel hydraulics, an analysis looking at differences in salmonid habitat between existing and alternative topography for each of the modeled flows was completed. Changes to salmonid habitat were evaluated using:

1. Weighted Usable Area (WUA) habitat values calculated from habitat suitability index developed by USFWS on Clear Creek in Northern California; and
2. Binary criterial established from the upper 60 percent of the same habitat suitability index used to calculate Weighted Usable Areas.

<u>Salmonid Habitat Comparison Using Weighted Usable Area</u>

WUA's were calculated from a habitat suitability index (SI) developed from data collected by USFWS on Clear Creek in Northern California, including fall-run Chinook salmon juvenile and fry rearing habitat and juvenile steelhead (*Table 4 in Appendix 5*) and adult spawning habitat (*Table 5 in Appendix 5*). Suitability indices for each life stage were applied to modeled output depth and velocity data resulting in a depth SI and velocity SI for each model node. The depth SI and velocity SI were then multiplied together to create the combined SI for each mesh node and associated polygon. For this comparative analysis, cover and substrate data was not available, therefore not included in the analysis. The area for each mesh node was then multiplied with the corresponding combined SI resulting in the WUA (Table 26).

<u>Salmonid Habitat Comparison Using Binary Criteria</u>

Binary thresholds were developed from observation frequency of fall-run Chinook fry, fall-run Chinook and steelhead juvenile and fall-run Chinook adult spawning (USFWS 2013a). Results were quantified at various increments of depth and velocity and reported in *Flow-Habitat Relationships for Juvenile Spring-Run and Fall-Run Chinook Salmon and Steelhead/Rainbow Trout Rearing in Clear Creek between Clear Creek Road and the Sacramento River* (USFWS 2013a). Binary criteria from the observed depth and velocity data using a SI of 0.6 were used. In general, these binary criteria account for 75 percent to 85 percent of all observations. Binary criteria were selected to show, in planform, how the areas of habitat changed between existing and alternative design topography. The MA report shows habitat differences between existing and alternative design topography for fall-run Chinook salmon fry and juvenile rearing and adult spawning habitat (*Appendix 5, Figures 22-30)*. Table 27 provides the combined upstream and downstream habitat area results for all model scenarios.

Figure 41. Hydraulic modeling project location map, 1-D HEC-RAS cross sections and stationing, 2-D modeling boundaries, and existing ground contours at the Baker site on Cottonwood Creek.

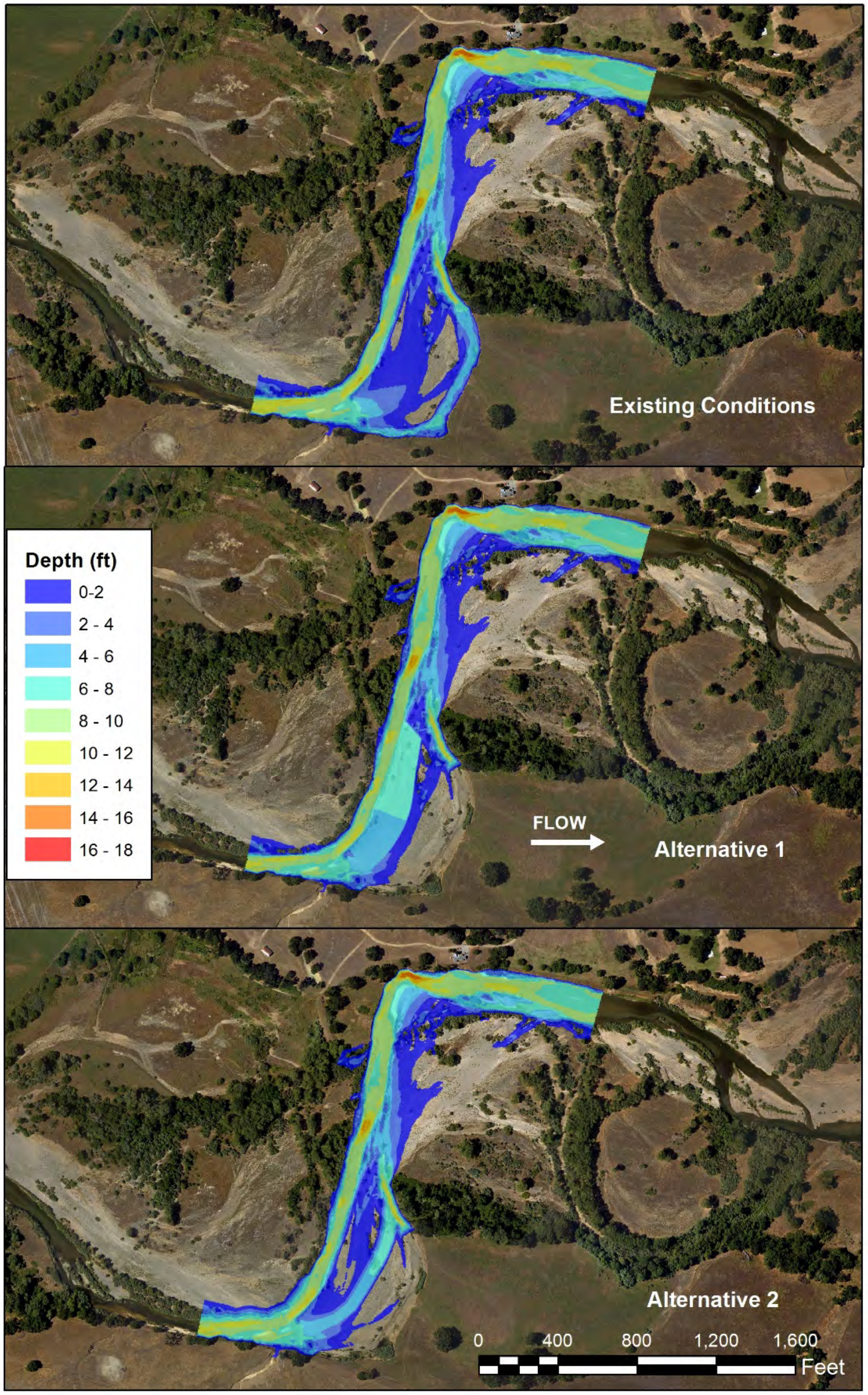

Figure 42. Modeling results showing depth at a flow of 4,800 cfs for existing, Alternative 1, and Alternative 2 topography.

Table 26. Weighted Usable Area for steelhead juvenile rearing and Fall-run Chinook fry and juvenile rearing and adult spawning at flows of 1,800 cfs, 4,800 cfs, and 7,800 cfs, calculated from 2-D modeling depth and velocity results.

	Fall-Run Chinook Fry Rearing Habitat		Fall-Run Chinook and Steelhead Juvenile Rearing Habitat		Fall-Run Chinook Adult Spawning Habitat	
1,800 cfs	**Upstream WUA (ft^2)**	**Downstream WUA (ft^2)**	**Upstream WUA (ft^2)**	**Downstream WUA (ft^2)**	**Upstream WUA (ft^2)**	**Downstream WUA (ft^2)**
Existing Conditions	25,478	18,167	103,270	132,139	54,347	88,761
Alternative 1	13,267	20,712	160,817	131,493	100,431.64	86,260
Alternative 2	16,666	15,504	122,157	133,095	79,326.07	99,118
4,800 cfs						
Existing Conditions	30,723	40,249	204,851	136,035	163,460	87,599
Alternative 1	22,436	40,238	105,973	136,627	64,663	86,672
Alternative 2	29,122	39,778	136,404	135,127	89,788	88,201
7,800 cfs						
Existing Conditions	18,350	54,707	240,103	248,164	206,355	179,682
Alternative 1	20,400	55,313	150,112	248,687	107,966	179,862
Alternative 2	18,772	57,414	189,437	249,575	148,184	179,126

Table 27. Total habitat area (combined upstream and downstream areas) for fall-run Chinook salmon fry and juvenile rearing and adult spawning and steelhead juvenile rearing using binary suitability criteria.

Fall Run Chinook Fry Rearing Habitat (ft^2)	1,800 cfs	4,800 cfs	7,800 cfs
Existing Conditions	47,844.69	74,539.22	74,720.06
Alternative 1	40,012.93	71,004.42	77,762.77
Alternative 2	34,930.64	77,868.85	79,484.30

Fall Run Chinook and Steelhead Juvenile Rearing Habitat (ft^2)	1,800 cfs	4,800 cfs	7,800 cfs
Existing Conditions	190,827.50	286,550.52	476,020.54
Alternative 1	259,099.02	189,281.24	362,520.81
Alternative 2	220,668.31	232,620.43	412,701.81

Fall Run Chinook Adult Spawning Habitat (ft^2)	1,800 cfs	4,800 cfs	7,800 cfs
Existing Conditions	9,431.95	33,342.27	38,613.58
Alternative 1	3,418.34	11,923.71	29,873.52
Alternative 2	9,398.50	15,442.63	30,760.35

Summary of Hydraulic Modeling Results

Findings focus on the relative changes to the channel hydraulics and WUA results associated with existing topography and alternatives 1 and 2 for the upstream portion of the 2-D modeling reach (Baker Site). The comparative analysis findings are:

- Both alternative right bank treatments reduce velocity and potential scour along the right bank terrace;
- The removal of the left bank riparian berm is effective in reducing velocity and potential scour within the mainstem channel that is directed towards the right bank;
- Alternative 1 is likely more depositional than Alternative 2;
- For a flow of 1,800 cfs the relative change in 2-D modeled WUA within the upstream portion of the project indicates that both alternatives increase habitat for fall-run Chinook and steelhead juvenile rearing and fall-run adult spawning, and a decrease habitat for fall-run Chinook fry habitat (Table 26);

- For a flow of 4,800 cfs the relative change in 2-D modeled WUA within the upstream portion of the project indicates that both alternatives decrease habitat for salmonid life stages modeled (Table 26); and
- For a flow of 7,800 cfs the relative change in 2-D modeled WUA within the upstream portion of the project indicates that both alternatives decrease habitat for fall-run Chinook and steelhead juvenile rearing and fall-run adult spawning, and show no-change in fall-run Chinook fry habitat (Table 26).

4. Synthesis

4.1 Geomorphic Summary

The results of hydrologic analyses set the stage for interpreting subsequent geomorphic analyses. Since 2006, the rainfall data indicate a progressively drier period (Figure 6). Annual water yield from Cottonwood Creek shows a similar pattern with a progressive decline in the cumulative departure curve (Figure 7) and with three of the five years within the study period registering “Dry” or “Critically Dry” (Figure 8). Annual peaks during the study period were largest in 2010 and 2011 but were still quite modest with recurrence intervals of 3.0 and 3.9 years respectively (Table 4). Since the GMA 2003 study, maximum annual peaks had recurrence intervals up to 4.6 and 6.7 years in WY2003 and 2006 (Table 4). Within this WY2010-2014 study, individual stream gages established for this project showed WY2010 and 2011 to be much stronger hydrologic years (higher peaks, more peaks, and higher yields) than WY2012-2014.

As might be expected, stronger water years transported considerably more sediment than did weaker ones. For the mainstem at the USGS gage (11376000), WY2010 and 2011 produced very similar suspended sediment loads at over 600,000 tons and roughly 50 times the annual load of WY2014. However, all water years fell below the long term average of 814,000 tons. Total sediment load (computed from the sum of the suspended and bedload fractions) for the combined upstream stations ranged from 61,300 tons to nearly 500,000 tons while the lower mainstem produced 108,000 to over 1,000,000 tons (Table 18– note that WY2014 was considered anomalous). Total annual sediment load increases between the upstream stations and the downstream station; between the combined upstream stations and the downstream gage, the annual total load increased 25-64 percent.

The lower watershed represents about 14 percent of the land area below the upstream gages. The 2011-2013 data suggest that the watershed downstream of the South Fork and the CCNO stations (Section 3.2.7 and 3.2.8 and Figure 29) generates a disproportionally high percentage of the sediment produced in the basin. The upstream stations represent 86 percent of the entire watershed area but our computations show this area only produces 48 percent of the total sediment load exiting Cottonwood Creek. These numbers are considered estimates and the relative error in our results is unknown. The actual numbers aren’t as important as the message they imply; the lower watershed produces considerably more sediment per unit area than does the upper watershed.

Our evaluation of the low-flow centerline alignment showed the largest adjustments occurred in response to the 6.7-year-magnitude 2006 event (though the response to the smaller 2003 flood is unknown, see Section 3.3.2). Channel migration oscillations are greatest outside of claypan areas where the channel is not influenced by structural control. Low flow channel capture due to vertical incision into claypan appears to have increased in frequency following the 2006 flood. Claypan features are increasing horizontally as well, primarily due to the removal of alluvial material from the 2003 and 2006 floods, but also related to bedload transport that occurs from smaller flood events (Section 3.3.2). This suggests Cottonwood Creek is sediment supply limited, where contemporary flows are of sufficient magnitude to mobilize and transport alluvium out of the study reaches, but sediment sources in the watershed are not resupplying coarse sediment at a proportional rate (supply < transport capacity).

Correspondingly, claypan exposure has increased, creating new geomorphic controls that influence channel pattern and form.

The longitudinal profile and cross section survey data support our observations of claypan exposure (and related geomorphic effects). Survey results illustrate a clear trend toward channel incision and channel widening. Cross sections scoured to their deepest point an average of nearly two feet between 2002 and 2011 (Table 23). These results generally agree with the longitudinal profile results, with the largest changes in the central portion of the profile (up to 10 feet), with smaller changes at the upstream and downstream ends (2-5 feet, Section 3.3.1). Bankfull channel top-width increased an average of 40 percent among the 17 mainstem cross sections (Table 24).

4.2 Habitat Summary

Spawning gravel of adequate depth and composition and the associated bedforms which provide the requisite hydraulic characteristics, are required for spawning habitat (Pittman 2002), the gravel matrix itself is required for primary (algae, phytoplankton) and secondary (benthic macroinvertebrate) biological productivity, critical as food sources for juvenile salmonids (Bjornn and Reiser, 1991). The large scale channel-bar-floodplain complex associated with alluvial river morphology provides the physical complexity required to support the spectrum of hydraulic conditions required for fry and rearing habitat (Pittman 2002). The evacuation of gravel and reduction of gravel bedforms to claypan substrate (from large-scale incision and channel widening) is clearly detrimental to anadromous salmonid habitat. Small scale channel alterations can impact habitat quality as well, primarily by modifying hydraulic qualities.

The 2-D modeling results for evaluating island-removal type strategies suggest that both alternatives are effective in reducing velocity and potential scour along the right bank terrace. Additionally, Alternative 2 results indicate that left bank berm removal would be effective in reducing mainstem velocity into either of the right bank alternative treatments. Although not evaluated, removal of the left bank berm alone may be effective at meeting project objectives without the excavation portion of the right bank treatments and should be considered if such options as the two modeled here are advanced.

Resulting trends in habitat for all salmonid life-stages are similar for both alternatives with fall-run Chinook fry rearing impacts greatest at 1,800 cfs and fall-run Chinook and steelhead juvenile rearing habitat and fall-run Chinook spawning habitat impacts greatest at the higher flows (4,800 cfs and 7,800 cfs). Even though some decreases in habitat are 50 percent or greater (Table 26 and Table 27), refinement of alternative grading options, the addition of large wood, and floodplain revegetation could reduce decreases in habitat predicted by the 2-D model. If additional modeling runs are considered, substrate and cover should be mapped and added to the WUA results for existing conditions allowing large wood habitat features to be included as part of the alternative grading plans. This could be effective at reducing habitat loses while still meeting management objectives.

4.3 Geomorphic Trajectory

While none of the monitoring tasks independently tells the complete story of Cottonwood Creek's *geomorphic trajectory*, the results all point in a similar direction:

- Hydrologic monitoring and historical analysis of gaging records indicates (1) the 2006 flood caused most of the change observed since 2002, and (2) the significant changes observed between 2002 and 2011 occurred in response to relatively small (less than 6.7 year) flood events.
- Sediment transport monitoring suggests much higher rates of sediment production occur in the lower watershed than in the upper reaches.
- Geomorphic mapping (longitudinal profiles and cross sections) shows large scale incision and channel widening.
- Aerial photo analysis illustrates a progressive trend toward claypan exposure and channel capture by incision into claypan.

In 1983, the USGS did not find any evidence of channel incision (GMA 2003). Since then however, the data clearly show substantial channel incision is occurring. USFWS (2013b) habitat data suggest downcutting: "Our qualitative assessment is that woody cover is the primary limiting habitat attribute for Cottonwood Creek, since in most locations, woody cover is not inundated until relatively high flows due to channel downcutting." The geomorphic trajectory is moving in the direction of an incising and widening channel with more of the flow contained within the banks, thus increasing energy (shear stress, the ratio of tractive forces to resisting forces) along those banks and increasing the potential for erosion. The data suggest a supply limited condition as well as an imbalance in sediment production. The progressive incision and bank erosion imply that the incised and widened reaches exhibit a sediment transport capacity higher than the available sediment load (transport capacity > sediment supply). The imbalance in sediment loads between the upper watershed and the lower watershed indicates that erosion rates increase in the lower part of the system. A likely explanation for the additional sediment supply in the lower watershed (since it is not coming from upstream) is that sediment is recruited locally from alluvial features (such as bars) which are being scoured and from banks being eroded.

Larger flood events (e.g. greater than 6.7 years) could accelerate the problems and processes described above. The trajectory observed over the last decade may take several more decades to affect most reaches of the creek. The system will likely eventually reach a new equilibrium with a channel deeply incised within the existing floodplain with a channel bed consisting largely of claypan. Such a system would provide very little salmonid habitat and though bank erosion is worsened in the short term (providing a short-term local sediment supply), long term rates of spawning gravel delivery to the Sacramento River may decline as the channel and bank sources become depleted. Incision and channel widening clearly threaten adjacent properties as well existing infrastructure such as bridge piers, bank protection, siphons etc.

Although the processes described here may take many years to achieve such a degraded equilibrium state, this geomorphic trajectory seems generally determined unless substantial intervention is undertaken. Once incision begins, the positive feedback loop created (more flows contained within channel leading to more bed and bank erosion, etc.) becomes increasingly difficult to interrupt or reverse. Similar situations have developed on other nearby systems including Stony Creek (Harvey

2006), Thomes Creek (CSUC 2005 as cited in Vestra 2006), and Clear Creek (McBain & Trush 2001). Of these, only restoration efforts on Clear Creek have successfully addressed incision, but at the cost of a $20M+ program.

The most likely triggers for Cottonwood Creek's geomorphic trajectory are (1) base level lowering in the Sacramento River, or (2) sediment imbalance induced by gravel extraction.

1. Sacramento River Base Level Lowering:
    - The sediment deficit induced by Shasta Dam construction could conceivably result in channel lowering along the Sacramento River which could in turn induce knickpoint migration (a steep drop in the stream profile which propagates upstream usually resulting in channel incision) up Cottonwood Creek. The fact that the mapping data show (1) convergence in the long profiles toward the Sacramento River confluence and (2) the cross sections exhibit less change in the most downstream areas, suggests that base level lowering is not the primary driver.
2. Sediment imbalances due to gravel extraction:
    - The USGS 1988 and the DWR 1999 reports indicate that the large pits created by gravel mining near Cottonwood "act as sediment traps." The GMA 2003 report identified numerous negative impacts resulting from gravel mining including: bed degradation, exposure of the Tehama Formation and reduced overbank flooding. Data collected for this 2010-2014 study further strengthen the findings in the 2003 report by documenting the ongoing trends in the geomorphic trajectory (i.e. continued incision, bank erosion etc.). Historic gravel extraction rates and volumes along Cottonwood Creek were not available for this study but the implication is clearly an evolution toward a supply limited state in which the quantity of gravel extracted exceeds the quantity delivered from upstream. To our knowledge, in-channel gravel mining is not currently being conducted. However, incision and channel widening are clearly ongoing.

5. RECOMMENDATIONS:

5.1 RESTORATION

The lowest cost and most probable strategies to deal with Cottonwood Creek's geomorphic trajectory are (1) no action and (2) piecemeal restoration. The likely outcome of no action was discussed in the previous section and is not recommended. Piecemeal management strategies (i.e. individual or local treatments) include bank armoring, island removal, high flow deflection structures as discussed in Harvey (2006), GMA (2003). If properly designed, such strategies might prevent local damage to specific properties but are often short lived. These strategies can also have negative impacts on biological resources (e.g. habitat quality for aquatic species, as shown by the modeling results in Section 3.4), and may propagate erosional issues upstream or downstream (Kondolf 1998).

Clearly, any restoration strategy should include the immediate cessation of gravel mining if it is occurring, though this alone would not likely reverse the geomorphic trajectory. Two conceivable scenarios which might reverse or mitigate Cottonwood Creek's geomorphic trajectory are (1) a natural large scale sediment delivery from the upper watershed, such as might occur in a very large flood event, sufficient to "recharge" the downstream alluvial deposits or (2) active restoration work. The first scenario seems unlikely, due to the disparity in transport capacity described previously.

The only remotely feasible approach to addressing this degradational geomorphic trajectory is a comprehensive restoration effort that would have to be enormous in scope. A complete analysis of existing piecemeal strategies should be conducted so that this knowledge (e.g. biological and geomorphic ramifications of various practices) could be applied to future projects. Large scale restoration would involve installation of grade control structures, injection of hundreds of thousands of cubic yards of gravel, channel realignment and revegetation. The scale of such an effort could easily exceed $100M.

Whether property owners could come together to accomplish this, given that the entire creek channel and floodplain is privately owned (more restoration funds are typically available for use on public lands), is unknown and certainly presents a difficult hurdle. The funding for such a program is unlikely to come from private sources; whether government agencies would be willing to invest in such a large scale restoration program for the potential habitat improvements is also unknown. To date, Cottonwood Creek has not been as high a priority as other streams in the area with larger fisheries resources or more restoration potential including Mill, Deer, Butte, Battle, and Clear Creeks.

Property owners should consider working with a local land trust to develop conservation easements within the creek migration corridor. Including active floodplain management land in such a program would likely encourage government agencies to become more involved as well as providing potential tax benefits to property owners. Active floodplain management would likely include the allowance of only certain activities in the maximum channel migration corridor.

The channel incision upstream of I5 is contributing to the bank erosion pressure at the Southern Pacific Railroad (SPRR) bridge. An engineered solution to this erosion (undercutting which directly threatens the railroad tracks and southerly bridge abutment) will be needed in the near term. Working together (land owners, resource agencies, and the SPRR), prior to when an emergency erosional situation develops, could lead to an improved result in this reach. If emergency actions are required to be taken by SPRR, it will likely only involve riprap placement along the bank, which would further lock in an undesirable (highly skewed) alignment upstream of the SPRR bridge, the I5 bridge, and the recently replaced Main Street (old Highway 99) bridge.

The USFWS (2013b) evaluation of baseline conditions suggests that given current mean rates of escapement (1992-2010), that in order to reach the AFRP's population doubling goals (for fall-run chinook and steelhead), fish would require 2.7 times more habitat than currently exists. The study suggests that "…physical habitat for fry and juvenile rearing is limiting the population of fall-run Chinook salmon in Cottonwood Creek. Habitat enhancement measures should focus on creating habitat with optimal conditions for fry and juvenile rearing (shallow, slow areas with woody cover). Our qualitative assessment is that woody cover is the primary limiting habitat attribute for Cottonwood Creek, since in most locations, woody cover is not inundated until relatively high flows due to channel downcutting" (USFWS 2013b).

5.2 MONITORING:

The monitoring completed during the course of this 2010-2014 study served to validate and quantify the conclusions from the 2002 geomorphic study (GMA 2003) and identified additional critical elements to define Cottonwood Creek's geomorphic trajectory. Given (1) the importance of Cottonwood Creek as a primary natural spawning gravel source for the upper Sacramento River (Stillwater, 2007); (2) Cottonwood Creek's ecological value as one of the largest un-dammed tributaries in the northern Central Valley supporting natural runs of anadromous salmonids; (3) monitoring data is generally requisite to support restoration funding programs; and (4) USFWS has devoted considerable effort to quantify baseline chinook and steelhead rearing habitat in Cottonwood Creek (USFWS 2013), ongoing geomorphic monitoring in Cottonwood Creek might be of considerable importance. Further, if restoration actions are implemented, geomorphic monitoring is one of the most effective tools for evaluating project success. This project was conducted during a relatively dry period; wetter years with higher peak flows could produce more change than was observed during this study.

The 2006 flood had a greater effect on channel morphology than any other flood event since 2002. The 2006 flood peaked at 47,600 cfs with a recurrence interval of 6.7 years. On December 11, 2014, Cottonwood Creek sustained a (USGS 11376000 provisional) peak streamflow of 41,800 cfs which is approximately a 5.2 year event and by far the highest flow since 2006 (Figure 43). Based on the data presented in this report, it seems reasonable to assume that this flood likely caused large changes to cross sections, planform, longitudinal profile and claypan exposure.

Figure 43. Views on Cottonwood Creek during the rising limb on December 11, 2014. (L) upstream view toward the I5 and SPRR bridges, (R) downstream view from the south side of the Evergreen road Bridge along the South Fork. Flow is approximately 38,000 cfs in the mainstem (assuming a 30 minute lag to USGS 11376000). Photos courtesy P. Bratcher, CDFW.

Given the situation described above, we recommend the following:

- The longitudinal profile of Cottonwood Creek should be re-surveyed every decade or after large storm events (> 5 year). This type of survey is relatively inexpensive for the amount of information gained. It is the single most important geomorphic monitoring tool.
- Future LiDAR mapping could provide useful volumetric comparisons to track the overall geomorphic trajectory and would be extremely useful if a restoration program is undertaken.
- Cross section surveys along the 2011 alignments (easily supported by the longitudinal profile survey and/or LiDAR acquisition) provide a vital tool for monitoring changes in channel width and bank erosion. Additional cross sections could be extracted from 2011 and future LiDAR data sets in areas of interest (e.g. specific private parcels).
- Landowners continue to report substantial land losses due to channel widening (CCWG public meetings, various dates and venues). Mapping the area of exposed claypan through a combination of field surveys and from aerial photographs (or Google Earth) would also be a useful method to demonstrate progressive changes.
- Mapping progressive bank retreat could also be performed relatively inexpensively in Google Earth.
- If gravel delivery to the Sacramento River continues to be of concern, additional sediment transport monitoring efforts at USGS 11376000, coupled with repeat topographic surveys (again, supported by LiDAR) and bathymetric surveys at the confluence of Cottonwood Creek and the Sacramento River, could facilitate gravel recruitment rate estimates.

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