SWAMP
Surface Water Ambient Monitoring Program

Final Technical Report | **2016**

Colusa Basin Drainage Area Fluvial Sediments: Dynamics, Environmental Impacts and Recommendations for Future Monitoring of The Colusa Basin Suspended Sediment Project

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SWAMP-MR-RB5-2016-0002

March 2016

California Water Boards

www.waterboards.ca.gov/swamp

Colusa Basin Drainage Area Fluvial Sediments: Dynamics, Environmental Impacts and Recommendations for Future Monitoring

Final Report

of

The Colusa Basin Suspended Sediment Project

to

The Central Valley Regional Water Quality Control Board

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December 1st, 2015

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Executive Summary

Human activity in the Colusa Basin watershed has resulted in drastic changes to the magnitude, timing and mode of sediment transported through the basin and into the lower Sacramento River. Averaged over decadal and longer time scales, most of the fluvial sediment transported through the Colusa Basin originates from the higher elevation/relief Coast Ranges foothills in the western third of the Colusa Basin watershed during the non-irrigation (winter) season. However, agriculture has increased the erosion rate of the lower elevation valley and basin lands between the foothills and the Sacramento River. Eroded sediments are also more efficiently delivered through agriculturally motivated drainage networks to the highest order channel of the watershed – the Colusa Basin Drain (CBD), which itself is an engineered drainage structure. As the Colusa Basin watershed had no discreet outlet to the Sacramento River before the construction of the CBD, the delivery of sediment to its two proximal receiving basins, the Yolo Bypass and the Sacramento River, may be considered as entirely anthropogenic. Of potentially greater concern than the magnitude and time of fluvial sediment occurrence in the system and delivery to its receiving basins are the pollutants that are transported in association with these sediments, particularly those that originate from agricultural fields.

Beyond these major finding, many questions remain regarding current sediment production dynamics, which must be addressed if present system function and environmental impacts are to be rigorously assessed. Despite several scientific studies regarding sediment production in the Colusa Basin watershed in the mid-to-late 20th century, a new comprehensive fluvial sediment monitoring program would be required to adequately assess the environmental impacts of Colusa Basin sediments in the 21st century. The preliminary findings of this study are based on the integration of a review of results of previous studies and a suite of additional analyses applied to their data sets. Most inferences of process are based on the results of intensive monitoring and analysis in the late 1970s and early 1980s, which produced high quality characterizations of sediment production and transport dynamics in the Colusa Basin drainage area, and the majority of suspended sediment data. Some system characterizations rely solely on the monitoring and analyses from this period. These aging sediment data sets and insights into sediment production and transport processes also form the foundation of sediment impact assessments for the Colusa Basin drainage area and its receiving bodies. Thus, the present understanding of Colusa Basin sediment dynamics and the environmental impacts of those sediments are highly dependent on data collected 35-40 years ago. Historical and modern data sets from this region also contain very little information on the chemical and microbiological constituents that are present in association with fine grained suspended sediments. Together these issues point toward the need for a comprehensive monitoring campaign to better understand the production of sediments in the Colusa Basina drainage area, the timing and magnitude of their presence throughout the fluvial system, their physical, chemical and biotic characteristics, and the impacts that all of these factors have on the regional environment and human beneficial uses.

Water and Sediment Dynamics

Large scale alteration of the Colusa Basin drainage area over the last 150 years in terms of land use, vegetation, hydrology and geomorphology have changed its relationship with the greater Sacramento River from that of a net sediment sink to a net sediment source. Before western settlement the Colusa Basin was a recipient of water and sediment from Coast Range foothill tributaries, and Sacramento River overbank flooding events and distributary sloughs, with surface connectivity for drainage from the basin prevented by the intersection of the natural western Sacramento River levee and the Knights Landing Ridge. During this period the Colusa Basin itself likely acted as a sediment sink over annual to interdecadal time scales, with sediment influx greater than efflux. Most net sediment efflux was likely limited to erosive periods of Sacramento River channel bend migrations through the basin lands over centennial to millennial time scales.

The Colusa Basin watershed is now a net exporter of sediment. Wet season Sacramento River overbank flood waters have been largely occluded through flood control projects. The influx of Sacramento River water to the Colusa Basin drainage area is now solely through irrigation withdrawals during the dry (irrigation) season. The construction of the CBD introduced a highest order stream collecting the drainage of the entire watershed, a hydrologic feature that the system previously lacked. Storm runoff and irrigation return flows are now more effectively exported from the Colusa Basin watershed through the CBD to the Yolo Bypass and the Sacramento River. A high proportion of instability has been found along the lengths of CBD tributary channel banks, which may be a significant contributor to CBD sediment load, particularly during higher discharge runoff events. Lower reaches of foothill stream channels have been universally subsumed by the complex of irrigated agriculture water delivery and drainage system, with channels often straightened to conform to property boundaries and impacted by numerous road crossings. Moderate elevation reaches of foothill streams are incising into alluvial fans upstream of the influence of irrigated agriculture producing additional sediments, perhaps due to lowering of the base level of the watershed after the construction of the CBD and/or increases in runoff from headwater catchments due to grazing impacts.

The CBD is subject to two seasonal hydrologic regimes: (i) storm flow during the wet (non-irrigation) season (November – April), and (ii) irrigation return flows during the dry (irrigation) season (May – October). Average annual water and sediment flux from the CBD is larger during non-irrigation season than during the irrigation season, but irrigation season fluxes are significant and can exceed non-irrigation season fluxes during times of drought. Of the two major components of fluvial sediment, suspended sediment and bedload, only suspended sediment has been monitored directly in the Colusa Basin drainage area. However, bedload is typically a smaller proportion (approximately 5 to 20%) of total fluvial sediment flux in such systems.

Fluvial sediments are deposited and resuspended in channel reaches of the CBD and its tributaries on event (individual rainfall /runoff sequence), seasonal, and interannual scales, which complicates the assignment of sediment provenance. A major control on sedimentation in the CBD is backwater effects caused by the raising of outfall gates in response to Sacramento River stage, which result in long periods of ponding and overbank flooding in the lower CBD during rainfall/runoff events. Estimation of water and sediment flux from the CBD to its two major receiving bodies, the Yolo Bypass and the Sacramento River above Knights Landing, is complicated by outfall gate operations and a lack of monitoring in the lower reaches of the CBD and in the Yolo Bypass.

Suspended sediment composition in the CBD was monitored from 1977-1981 and found to be approximately 60% mineral, 30% organic and 10% algal. Mineral sediment particle size distributions were on average > 50% clay, < 40% silt, and < 10% sand. Organic matter was on average 60% easily biodegradable and 40% refractory (not easily biodegradable). CBD bedload sediment composition inferred from deposited bed sediment was 70-90% mineral and 10-30% organic. Mineral bed sediments were primarily sand, with smaller proportions of silt, clay and gravel.

The higher elevation, higher relief portion of the watershed located in the Coast Range foothills most likely produces more sediment than the valley and basin lands. Sediment yields during the irrigation season mostly resulted from field, row and orchard crops using boarder and furrow irrigation methods. Increases in furrow slope and water application resulted in increases in sediment discharge from row crop fields. Rice fields have been found to generally serve as sediment sinks during the irrigation season, and as sinks or minor sources of sediment during the non-irrigation season depending on local conditions and management decisions. A significant portion of agricultural sediment flux from irrigation return flows was found to erode from field to subbasin scale drainage canals, which may in part be influenced by deposition and resuspension dynamics from off-field transported sediments. Erosion from unpaved roadways is a significant source of sediment. Small scale gully erosion associated with roadways, agricultural fields and drainage ditches in the valley lands, and small to large scale gully erosion in the foothills may be significant sources of sediment as well.

Sediment Impact Assessment Methodology

An impact assessment methodology was developed for Colusa Basin watershed sediments on the basis of physical, biological and human components of the system. The sediment impact assessment grouped into the following categories: (i) erosional effects in the Colusa Basin drainage area, and fluvial sediment effects on (ii) the Colusa Basin drainage area lands and channelized system, (iii) the lower Sacramento River, (iv) the Yolo Bypass, and (v) the Sacramento- San Joaquin Delta and San Francisco Bay. Potential impacts of fluvial sediment were evaluated in the context of each of the following sediment impact modes: (i) effects of sediments in suspension, (ii) effects of deposited sediment, and (iii) effects of sediment mediated pollutants.

The states of the aquatic systems were considered first in terms of unaltered reference scenarios. The effects of each mode of sediment interaction with the aquatic environment were then evaluated in terms of the needs of local aquatic biota, human beneficial uses and geomorphology, using methods deemed appropriate to the specific water body type. The potential effects of suspended sediment and sediment mediated pollutants were then evaluated using a generalized toxicological dose-response methodology.

Evaluation of Sediment Impacts

Use of reference systems to develop baseline sediment conditions was deemed impractical for all reaches except the upper foothill streams, due to the highly altered nature of the system and lack of data. However, consideration of reference system conditions highlighted the finding that all sediment export to the Yolo Bypass and the Sacramento River are essentially the result of human alteration of the Colusa Basin drainage area and the Sacramento River. The Coast Ranges foothill streams, now and historically, were only wetted on a seasonal, and more frequently, an individual runoff event basis. Upper foothill stream reaches certainly contain suspended sediment concentrations and turbidity levels that pose the potential for acute impacts on aquatic biota during rainfall-runoff events. However periodic, high concentration- discharge events are typical of such systems. Chronic (long duration) suspended sediment concentrations in upper foothill stream reaches may also have significant impacts on aquatic biota, but there is limited data to support this finding.

Acutely and chronically high suspended sediment and turbidity levels in terms of established aquatic biota thresholds were found at certain times and locations in the lower foothill streams and drainage network, and throughout the spatial and temporal record for the CBD. Suspended sediment concentrations and turbidity were not found to be significant impairments to the human beneficial uses of waterways in the Colusa Basin watershed, including irrigation water withdrawals and recreation (e.g. fishing and hunting). A possible future issue for human use may be decreased thresholds for suspended sediment concentration imposed by changes in irrigation technologies, namely to sub-surface drip irrigation. Deposited fine sediments in Colusa Basin waterways appear to follow event, seasonal and interannual patterns that have not resulted in large scale aggradation, with the possible exception of lower reaches of the CBD. Information on dredging demands in the lower CBD to maintain conveyance of drainage and storm waters were not found during the preparation of this report, but may represent a small but significant expense to local drainage districts.

Local effects of turbidity and suspended and deposited fine sediment in the Sacramento River at the outfall of the CBD may include chronic impacts on aquatic biota such as benthic invertebrates. The turbid plume that emanates from the CBD outfall may pose a hazard to adult cold water fish migrating up the Sacramento River for spawning and outmigration of juveniles. However, deposition of Colusa Basin fine sediment is not a concern for the spawning habitat of salmonids such as Cutthroat Trout (*Oncorhynchus clarkii*) and Chinook salmon (*Oncorhynchus tshawytscha*), as the CBD enters the Sacramento River well below the transition of Sacramento River channel substrate composition from gravel to sand.

Characterization of mercury and pesticide flux from the Colusa Basin drainage area is hampered by very little sediment composition data regarding these pollutants. Noting these limitations, it appears that Colusa Basin sediments delivered to the Yolo Bypass, the Sacramento River and Sacramento-San Joaquin Delta/San Francisco Bay represent a small proportion of the sediment and mercury budgets of each waterway. However, Colusa Basin suspended sediment is likely a significant source of sediment mediated agricultural pollutants, such as hydrophobic herbicides and pesticides to all recipients. Fluvial sediments from the Colusa Basin drainage area contribute a relatively small amount of the average annual total mercury budget of the Yolo Bypass (approximately 3%), but a large proportion of the total fluvial pesticide load. Colusa Basin sediment load represent approximately 10-20% of those delivered to the Sacramento-San Joaquin Delta, and approximately 3-7% of the SF Bay sediment budget. Both the Sacramento-San Joaquin Delta and San Francisco Bay sediment budgets are likely reduced in comparison to pre-European settlement and San Francisco Bay is now dominated by local watersheds rather than Central Valley sediments. These changes in sediment production and sources, along with legacy sediments contaminated with mining, agricultural and industrial wastes that remain in channel and wetland deposits represent a need for "clean" sediment sources for the Delta and SF Bay. Sediments from the Colusa Basin drainage area may therefore be beneficial to the Delta and SF Bay if surface associated pollutant loads are low. Further characterization of sediment associated pollutants are required to make this determination

Data Gaps

Understanding the production and transport dynamics of sediment and sediment associated contaminants in the Colusa Basin is essential to assessing the roles that these material play in the environment, and determining the best management strategies to moderate adverse impacts. Initiation of a comprehensive fluvial sediment monitoring campaign in the Colusa Basin watershed would be essential to adequately inform the process of sediment impact evaluation and management due to deficiencies in previous and ongoing monitoring.

The identified data gaps motivating the recommendation for enhanced monitoring inform two categories of interest: the characterization of (i) hydrological processes and (ii) sediment mediated pollutants. Sediment production and transport in the Colusa Basin watershed was well characterized during a snapshot of monitoring over a four year period that ended about 35 years ago. Several changes in the human utilization of the Colusa Basin watershed have occurred over the past 35 years, including shifting agricultural crops types, land management and irrigation techniques, and the completion of the Tehama-Colusa Canal, which increased the delivery of Sacramento River water for irrigation within the basin by approximately 250,000 acre-feet. Current and recent monitoring of aquatic sediment parameters in the Colusa Basin watershed is not sufficient for the elucidation of sediment production and transport processes as they operate today. This hampers both the accurate assessment of environmental impacts of these sediments, and the formulation of appropriate sediment management strategies. Changes in the production, transport, and composition of sediment in light of changing land use factors can only be assessed with the re-application of processes based monitoring and analysis in the region.

Moreover, it should be recognized that understanding the dynamics determining sediment production and transport in terms of magnitude and timing is insufficient for fully assessing environmental impacts. The composition of these sediments, and the sediment associated materials that travel with them, are perhaps even more important in the context of assessing adverse impacts to aquatic health and human beneficial uses. Little information has been collected on the composition and magnitudes of agricultural chemicals that are transported in association with the suspended sediment discharged from the CBD. It is critical to close this gap in observation and understanding of sediment mediated pollutant transport through and from the Colusa Basin watershed if the impacts of Colusa Basin sediments are to be assessed to a level sufficient to inform proper management decisions.

Monitoring Suggestions

Flux based monitoring of discharge and suspended sediment at stations strategically chosen to characterize sediment production processes and sources is required to understand the roles/impacts of Colusa Basin sediments in/on aquatic environments. The general approach will include:

1. Hydrologic Monitoring
    - High resolution discharge monitoring at the CBD outfall, the entrance to the Knights Landing Ridge Cut, and near the outflows of key CBD tributaries.
    - High resolution turbidity monitoring at discharge gauging stations.
    - Collection of suspended sediment samples of the size and frequency sufficient to establish turbidity-C_{SS} rating curves, and characterize sediment composition.
2. Fluvial Sediment Composition Analysis
    - Sediment composition analysis with sufficient sampling density to resolve flux dynamics of the following sediment associated pollutants:
        - Pesticides currently utilized in the Colusa Basin drainage area.
        - Legacy pesticides such as DDT and their decomposition products.
        - Total mercury.
3. Sediment Source Evaluation
    - High resolution topographic analysis of uplands to evaluate the contribution of mass wasting and gully erosion.
    - Sediment provenance analysis on the basis of cosmogenic radio-nuclides to discriminate between sediment eroded from shallow and deeply erosive processes.
4. Hydrodynamic Characterization
    - Development of a digital elevation model for the lower CBD and its outlets.
    - Construction of a 2-D hydrodynamic model for the lower CBD.
    - Monitoring of 3-D current velocities in the lower CBD and its outlets.
5. Environmental Impact Assessment
    - An aquatic organism impact assessment including:

- Development of ambient sediment concentration thresholds based on the most sensitive aquatic species of interest in the Colusa Basin drainage area.
- Toxicological testing of suspended sediments collected during the monitoring program on benthic invertebrates.

Acronyms and Abbreviations

Acronym	Complete term	Definition
ac	acre	A US Customary unit of area equivalent to 0.00153 square miles, or 0.405 hectares.
ac-ft	acre-feet	A unit of volume equivalent to a one acre area filled to a depth of one foot.
APHA	American Public Health Association	A professional association dedicated to improving the public's health through education and advocacy.
BAT or BATEA	Best available control technology economically achievable	A required application from an EPA mandate under PL 92-500 related to control of discharge to navigable waters by July, 1983. Point source only.
BCF	Bias correction factor	Factors used to correct for systematic bias involved in the estimation of suspended sediment load on the basis of discharge records applied to C_{SS}-Q rating curves.
BCF_d	Daily discharge bias correction factor	Factor used to correct for the bias introduced by the use of daily discharge records when estimating suspended sediment load with rating curves that have been fit to instantaneous discharge data.
BCF_l	Log-tranform bias correction factor	Factor used to correct for the bias introduced to sediment load estimates through the use rating curves fitted to log-transformed data.
BCF_{ld}	Duane smearing log-transform correction factor	Factor used to correct for the bias introduced to sediment load estimates through the use rating curves fitted to log-transformed data (see Rasmussen *et al.*, 2009).
BCF_{lf}	Ferguson's log-transform bias correction factor	Factor used to correct for the bias introduced to sediment load estimates through the use rating curves fitted to log-transformed data (see Ferguson, 1986).
BOD	biological oxygen demand	The amount of dissolved oxygen required to oxidize the organic materials present in a given volume of water or water body through aerobic microbial processes.
BPT or BPTCA	Best practicable control technology currently available	A required application from an EPA mandate under PL 92-500 related to control of discharge to navigable waters by July, 1977. Point source only.
CBD	Colusa Basin Drain	70 mile long man made canal that drains the Colusa Basin into the Sacramento River near Knights Landing.
CCC	Criterion Continuous Concentration	CCC = 0.5 x FCV
CCRCD	Colusa County Resource Conservation District	Local district of the NRCS.
cfs	ft^3s^{-1}	Cubic feet per second; a US Customary unit of unit of *Q*.
cm	centimeter	An SI unit for distance which is equivalent to 0.01 meters, or 0.394 inches.
CMC	Criterion Continuous Concentration	CMC = 0.5 x FAV

Coalition	Sacramento Valley Water Quality Coalition	An agricultural industry alliance formed in 2002 to comply with the CVRWQCB Conditional Waiver for the ILRP.
CRBRWQCB	Colorado River Basin Regional Water Quality Control Board	The branch of the SWRCB responsible for water quality in the southeastern most portion of the state, which includes the Salton Sea and most of its watershed.
CSI	Channel Sedimentation Index	In the context of US EPA (1995), a quantification of the deviation of channel fines content from expected conditions.
C_{SS}	Suspended sediment concentration	The unit mass of sediment transported by water in suspension divided by unit volume of the transporting water.
CSWRCB No. 4091400	CSWRCB Standard Agreement No. 4091400	Supplemental funding to the Tanji group at UC Davis for Irrigation Tailwater Management project (June, 1975 - March, 1976). See EPA No. 803603-01-1.
CVP	Central Valley Project	A federal water resources project in California's Central Valley that involves an array of engineered infrastructure for water storage and transport, primarily for irrigated agriculture.
CVRWQCB	Central Valley Regional Water Quality Control Board	The branch of the SWRCB responsible for water quality in the Central Valley region of California, which includes the CBD.
D	diameter	The length across a circle or a sphere.
Delta, the	The Sacramento/San Joaquin Delta	The inland delta formed by the confluence of the Sacramento and San Joaquin River, which empties into SF Bay
DEM	Digital Elevation Model	Three-dimensional digital maps, usually of Earth surface topography.
DFG	California Department of Fish and Game (now DFW)	See DFW.
DFW	California Department of Fish and Wildlife	The California agency in charge of managing freshwater aquatic and terrestrial wildlife.
DPR	California Department of Pesticide Regulation	A department of California EPA charged with regulating pesticide use.
DWR	California Department of Water Resources	The California agency in charge of managing water supply
e_i	Residual value for observation i	The observed value subtracted by a value predicted from a rating curve.
EC50	Effective Concentration 50	The dose of a given substance found to have a given effect on 50% of a population of a given organism.
EMAP	Environmental Monitoring and Assessment Program	A USEPA monitoring program for the environmental characterization of water bodies and assessment of environmental impacts of water quality impairments.
EOD	Elimination of discharge of pollutants	A required application from an EPA mandate under PL 92-500 related to control of discharge to navigable waters by 1985. Point source only.
EPA 80360-01-1	EPA Grant No. R 803603-01-1	Irrigation Tailwater Management grant from US EPA to Tanji group at UC Davis (March, 1975 - 1977). Supplemented by CSWRCB No. 4091400.
FAV	Final Acute Value	An estimate of the 5^{th} percentile of a sensitivity distribution of the average LC50/EC50 of the tested organism for short term exposure to the substance in question.

FCV	Final Chronic Value	An estimate of the 5th percentile of a sensitivity distribution of the average LC50/EC50 of the tested organism for long term exposure to the substance in question.
ft.	Feet	A US Customary unit of distance equivalent to 12 in. or 0.035 meters.
g	gravitational acceleration	9.81 m/s^2
GCID	Glenn-Colusa Irrigation District	A large irrigation district with the largest water rights to the Sacramento River and Stoney Creek watersheds in the Colusa Basin watershed, and supplies these waters through the GCID Main Canal.
GCID Main	The Glenn-Colusa Irrigation District Main Canal	The main irrigation supply water canal operated by the GCID.
ha	hectares	An SI unit of area equivalent to 10,000 square meters or 2.47 acres.
Hg	Mercury	A toxic heavy metal
ILRP	Irrigated Lands Regulatory Program	An SWB program for regulation of irrigated agricultural return flows in California, with provisions for monitoring and environmental impact assessment.
in.	inch	A US Customary unit of distance equivalent to 2.54 centimeters or 1/12 of a foot.
KLRC	Knights Landing Ridge Cut	An engineered floodway connecting the CBD to the Yolo Bypass located 1 mile upstream of the CBD outfall gates.
km	kilometer	An SI unit of distance equivalent to 1000 meters or 0.621 miles.
km^2	square kilometer	An SI unit of area equivalent to 100 hectares or 0.386 square miles.
LC50	Lethal Concentration 50	The dose of a given substance found to kill 50% of a population of a given organism.
MPCA	Minnesota Pollution Control Agency	A Minnesota state agency that has published guidelines for turbidity levels in water bodies.
mi.	mile	A US Customary unit of distance equivalent to 5280 feet or 1.60 kilometers.
n	Number of observations	Number of observations
NAS	National Academy of Sciences	A private, nonprofit organization of high ranking researchers in the US
NAWQA	National Water Quality Assessment Program	The USGS program to systematically collect chemical, biological, and physical water quality data from 51 study watersheds in the US.
NODOS	North of Delta Offstream Storage project	A proposed project to create a reservoir on Stone Corral Creek for storage of Sacramento River water by placing a dam near the town of Sites, CA.
NPDES	National Pollutant Discharge Elimination System permit program	Applies to all point sources of pollution, including surface irrigation return flows discharged from an identifiable source. Administered in CA by the SWRCB and regional boards.
NRCS	National Resource Conservation District	A federal agency under the USDA that provides agriculture with financial and technical assistance to improve conservation.
NTAC	National Technical Advisory Committee	A US committee that advised on the development of water quality criteria associated with the Clean Water Act.
PAH	Polyaromatic hydrocarbon	Combustion byproducts that are composed of rings of hydrogen and carbon, and transported primarily in association with sediment surfaces.
PCB	Polychlorinated biphenyl	Synthetic compounds composed of two benzene rings and a chlorine that are known as persistent organic pollutants, and transported primarily in association with sediment surfaces.

PL92-500	Public Law 92-500	An amendment to the Federal Water Pollution Control Act (October, 1972) with the goal of eliminating pollution discharge to navigable rivers in the US by 1985.
P(Y|X*)	Conditional probability	The conditional probability that impact Y has occurred given that event X* has occurred.
Q	Discharge	Volumetric water flux rate (volume/time).
Q_d	Daily discharge	Average discharge through a given channel station over the period of a day.
Q_{SS}	suspended sediment flux	The unit mass of sediment transported in suspension past a given station on a river or stream over a given unit of time.
RIVPACS	River Invertebrate Prediction and Classification System	A site specific approach using empirical models to estimate 'natural' non-impacted reference conditions for aquatic communities developed by Wright *et al.* (1984).
s	Mean squared error of the residual	Mean squared error of the residual.
SABS	Suspended and Bed Sediments	An acronym introduced by US EPA (2003a), as part of their latest initiative to develop more thorough, science based sediment impact methodologies for fluvial systems.
SF Bay	San Francisco Bay	The large embayment situated between the Sacramento/San Joaquin Delta and the Pacific Ocean.
SFEI	San Francisco Estuary Institute	A non-profit scientific institute oriented toward providing scientific support for environmental decision making, particularly in SF Bay and the Delta
SI	System International	The most common international system for of units of measure, which is also commonly used in U.S. scientific fields.
SRFCP	Sacramento River Flood Control Project	A state and federal hydraulic engineering project that finally prevented interannual to decadal scale flooding of the Colusa Basin by the Sacramento River through levee improvements and out of channel flood diversion structures.
SWAMP	Surface Water Ambient Monitoring Program	An SWB and program for the monitoring water quality parameters in the surface water bodies of California.
SWB	State Water Resources Control Board (*syn.* State Water Board)	The California agency responsible for water resources and water quality in the state of California. Also comprised of nine regional water boards, including one for the Central Valley.
SWP	State Water Project	A network of water transport and storage facilities that supply southern California with water from the Sacramento-San Joaquin Delta.
TCC	Tehama-Colusa Canal	A 111 mile long canal supplying up to 250,000 ac-ft/yr of irrigation water to the Colusa Basin watershed.
TCCA	Tehama-Colusa Canal Authority	A consortium of 17 water contractors that supply Sacramento River and Stoney Creek waters to the Colusa Basin watershed through the Tehama-Colusa Canal.
USACE	U.S. Army Corps of Engineers	The main federal civil engineering agency, responsible for the construction, maintenance and operation of many large flood control and water storage structures throughout the U.S. and California.
UCD	University of California, Davis	The University of California campus located in Davis, CA, which has been historically a preeminent center of agricultural research.
UCD/US EPA ITM	UCD/US EPA Irrigation Tailwater Management Study.	A study on the off field flux of materials in irrigation tailwaters based on field scale studies in the Central Valley of California,

		including row crops and rice fields in the Colusa Basin watershed conducted between 1974 and 1976.
UCD/US EPA NSP CBD	UCD/US EPA Study on Nonpoint Source Sediment Production in the Colusa Basin Drainage Area	The most comprehensive study on the production and transport of fluvial sediments in watershed of the Colusa Basin Drain; conducted between 1977 and 1981.
US Customary	United States Customary	A system of units of measurement commonly used in the US.
USDA	US Department of Agriculture	The federal executive department responsible for policy related to farming, agriculture, forestry and food.
US EPA	US Environmental Protection Agency	The main federal agency charged with monitoring and protecting environmental quality in the USA, include that of surface water bodies.
WARSS	Watershed Assessment of River Stability and Sediment Supply	A sediment assessment framework based on geomorphic analysis developed by a research team led by David L. Rosgen for the US EPA.
X	A water quality parameter	In the context of establishing water quality thresholds, X is the water quality parameter that influences impact Y.
X*	A given water quality parameter state or range	In the context of conditional probability P(Y|X*), X* is the water quality stressor on that influences the probability of impact Y.
X_c	The water quality criterion threshold	The threshold level of water quality parameter X, where X* indicates a given $X > X_c$ scenario.
Y	A given impact	In the context of conditional probability P(Y|X*), Y is the impact whose probability in influences by X*.
ρ_f	fluid density	mass/volume of a given fluid
ρ_s	particle density	mass/volume of a given solid particle
μ	dynamic viscosity	The tangential force per unit area required to move one horizontal plane with respect to another plane at a unit velocity with a unit distance apart within the fluid.
µm	micrometer	$1x10^{-6}$ meters
ω_s	terminal settling velocity	The velocity obtained by a particle settling through a fluid were the accelerations due to gravity and friction are in balance.

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1. Project Overview

The Colusa Basin Drain (CBD) has been recognized as the largest point source contributor of agricultural drain water and suspended sediment to the Sacramento River. While the presence of high suspended sediment loads in the CBD has engendered a number of previous studies and reports over the past 50 years, this work has not resulted in basin scale sediment management. The Central Valley Regional Water Quality Control Board (CVRWQCB) initiated the Colusa Basin Suspended Sediment Project and contracted with the University of California, Davis under Agreement # 13-104-150 to address the need for a synthesis of previous findings and data to inform sediment management and monitoring decisions moving forward. This project was conducted primarily by Dr. Andrew Gray under the supervision of Professor Gregory Pasternack at the University of California, Davis (UCD), with oversight from CVRWQCB Senior Environmental Scientist Susan Fregien. Dr. Gray began the project as a Postdoctoral Scholar at UCD and transitioned to an Assistant Professor position at the University of California, Riverside for the latter portion of the project. The goals of the project were to (i) review and provide a synopsis of previously published literature, (ii) visit the study region and photo-document points of interest, (iii) compile all available sediment associated water quality data for the CBD and its tributaries, (iv) assimilate sediment impact assessment methodologies from a literature review and propose assessment methodology for future studies, (v) characterize sediment production and transport processes operating in the basin using the compiled literature and data, (vi) determine if sediments eroded from and transported out of the Colusa Basin watershed result in adverse water quality and environmental impacts within the Colusa system and downstream, and (vii) identify data gaps and provide recommendations for additional monitoring to address them (Table 1.1).

Table 1.1. Objectives, methods and deliverables of the Colusa Basin Sediment Project

Objective	Method	Deliverables
Literature Review, Compilation, and Synopsis	A review of all literature related to sediment in the Colusa Basin Drain, its tributaries and drainage area prepared as a synopsis, and a digital assembly of these literature.	Section 4.1; Section 10.1: 2 flash drives containing electronic copies of literature.
Study Region Visit	The authors and CVRWQCB staff traveled to specific locations along the CBD and tributaries to observe and photo-document points of interest.	Section 4.2; Section 10.2: 2 flash drives containing digital photos taken by the Contractor during visits to the study region.
Water Quality Data Compilation and Analysis	Discovery, extraction, compilation and quality control of all water quality data relevant to the sediment in the Colusa Basin Drain and its tributaries and to sediment discharge from the CBD to the Sacramento River. Water quality data was then analyzed in terms of temporal and spatial variation, which included the developing suspended sediment concentration-discharge rating curves and computations of ambient conditions by season.	Section 4.3; Section 10.3: 2 flash drives containing electronic copies of the Excel spreadsheet with water quality data, R codes for suspended sediment analyses, and a GIS database for geospatial data.
Sediment Impact Assessment Methodology	A literature review of sediment impact methodologies was based on readily available published articles and reports. This review was then used with information obtained from previous steps to propose an appropriate methodology for the assessment of sediment impacts to the CBD, its tributaries, and the Sacramento River.	Section 5; Section 10.1: 2 flash drives containing electronic copies of literature.
Evaluation of Sediment Impacts	Utilizing results from previous steps, sediment impacts in the CBD, its tributaries and the Sacramento River system were identified and characterized. The known types and sources of sediment were evaluated, and the spatial and temporal patterns of erosion and sediment impacts analyzed. Impacts of land use and management changes on erosion and sediment dynamics in the basin were evaluated as constrained by available data.	Section 6
Data Gaps	Results from previous steps were review to identify potential data gaps and evaluate how these gaps affect the characterization of sediment impacts	Section 7
Sediment Monitoring Recommendations	The conclusions of the previous steps were used to inform the drafting of recommendations for additional monitoring needs in the Colusa Basin drainage area.	Section 8

The following draft report presents the background, method and results of the Colusa Basin Suspended Sediment Project as follows:

Section 1. Project Overview. This section presents the motivation, objectives of the Colusa Basin Drainage Area Suspended Sediment Project.

Section 2. Study Region. This section contains an overview of the geographic setting, the physical and biological characteristics of the watershed and the history of its development in relation to sediment production and transport.

Section 3. Scientific Background. This is an introduction to the scientific approach to studying watershed sediment production, transport and deposition, along with a survey of common monitoring and analytical techniques.

Section 4. Suspended Sediment Production in the Colusa Basin Watershed. The first part of this section includes a review of previous studies related to sediment dynamics in the region, a presentation of the site visit conducted by the authors and CVRWQCB staff on 10/23/2014, and an examination of temporal patterns and trends in sediment production characteristics. The second part of Section 4 presents a synthesis of all available sediment data for the CBD to characterize sediment production and transport in the system. The results of this analysis are considered in concert with those of previous studies and climate and land use data to determine if systematic controls on sediment production could be identified.

Section 5. Sediment Impact Assessment Methodology. This section presents the development of a sediment impact methodology, beginning with an overview of the known environmental impacts of sediment, followed by a review of modern sediment impact assessment methodologies, and the development of a methodology relevant to the physical, biological and human dimensions of the Colusa Basin watershed.

Section 6. Evaluation of Sediment Impacts. The methodology introduced in Section 5 is applied to evaluate sediment impacts in the basin. The ranges of Colusa Basin and Sacramento River water quality and sediment load values are considered in terms of potential physical, biological and human health impacts to areas of (a) sediment sources, (b) sediment in transport and (c) sediment deposition. In turn, spatial and temporal patterns of sediment impacts are then used to conceptually evaluate the potential effects of changing land use and management on basin scale sediment dynamics.

Section 7. Data Gaps. The previous sections culminated in an evaluation of sediment impacts that was ultimately hampered by lack of data, which is explored explicitly in this section. The results of previous sections are reviewed in terms of the influence and limitations imposed by gaps in data collected by historical and ongoing monitoring programs to prioritize future data collection.

Section 8. Sediment Monitoring Recommendations. Here recommendations are presented for a comprehensive monitoring plan to provide the data necessary for understanding the processes that control the production and composition of sediments, and their environmental impacts.

Section 9. References. This section contains bibliographical information for all published sources of information used in the report.

Section 10: Supplemental Materials. This section provides reference to the location and storage of an electronic literature compilation and all data sets developed for this.

2. Study Region

This section presents an overview of the Colusa Basin drainage area in terms of the broad set of environmental and human imposed characteristics that form the basis upon which sediment production and transport processes operate. We begin with a brief summary of the physiography of the Colusa Basin watershed and the greater Central Valley system (Section 2.1). This is followed by more detailed information on the natural physical characteristics of the watershed before human development (Section 2.2) in terms of geology and soils (Section 2.2.1), hydrology (Section 2.2.2) the interaction of these two components as expressed by fluvial geomorphology (Section 2.2.3), and the biological characteristics of the Colusa Basin watershed (Section 2.2.4). The history of human land use and development from the Native American to modern eras are presented (Section 2.3), and the effects of human activities on the natural setting are discussed (Section 2.4). Electronic copies of much of the literature cited in this section are available in Section 10.1.

2.1 The Colusa Basin Watershed

The Colusa Basin drainage area is a subbasin of the Sacramento River watershed located in Glenn, Colusa (primarily), and Yolo counties of northern California (Figure 2.1.1). The catchment is bounded to the north and south by the Stony Creek and Cache Creek watersheds, respectively, and extends from an eastern boundary with the Sacramento River to the crest of the Inner Coast Range foothills in the west (Figure 2.1.2). The watershed area is 1,045,445 acres (4231 square kilometers (km^2)), with a maximum elevation of approximately 2800 feet (ft.) (850 meters (m)), and a minimum elevation of approximately 30 ft. (9 m) at the CBD outfall near Knights Landing (Table 2.1.1, Figure 2.1.3). Temperature and precipitation gradients generally follow land surface elevation. The average summer high temperatures in the basin and valley lands are approximately 90 degrees Fahrenheit (°F) (32 degrees Celsius (°C)), with average winter lows of approximately 40°F (4°C), while the temperatures near the western divide are approximately 10°F (5.5°C) lower (NOAA National Climatic Data Center, 2015). Conversely, average annual precipitation follows topography, and ranges from approximately 27 inches (in.) (70 centimeters (cm)) at the highest elevations in the Coast Ranges foothills along the northwestern watershed boundary, to approximately 17 in. (40 cm) at Knights Landing (DWR, 2006). The annual climate cycle features a pronounced winter wet season (November-April) typified by cool temperatures and precipitation as rain, and a summer dry season during which most irrigation waters are delivered to the basin (Tanji *et al.*, 1978; US Department of Agriculture/National Resource Conservation Service (USDA/NRCS), 1998). For this reason, and in keeping with previous regional studies, the summer dry season is hereafter referred to as the ‘irrigation season’, and the wet season as the ‘non-irrigation season’.

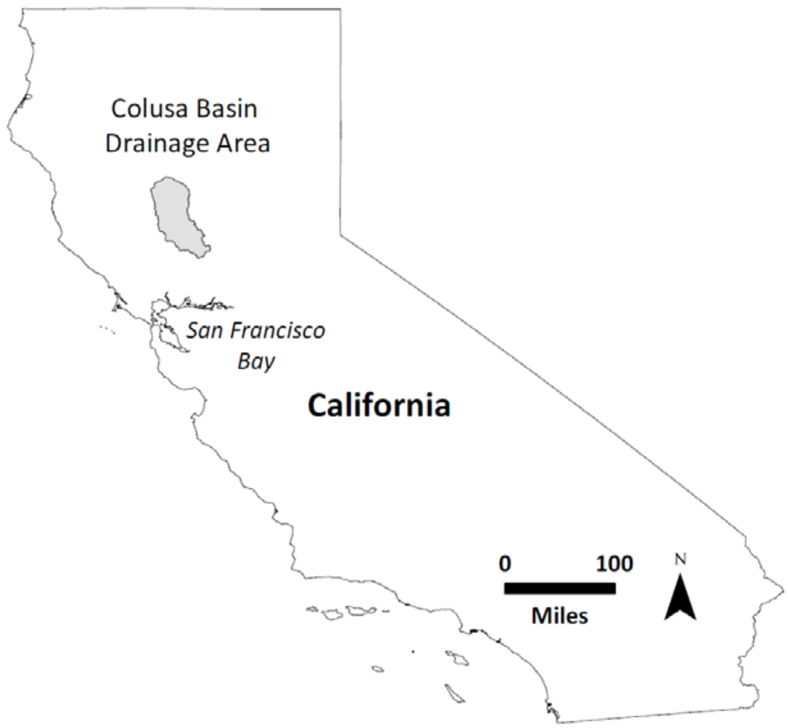

Figure 2.1.1. The Colusa Basin drainage area in northern California.

Table 2.1.1. Physiographic characteristics of the Colusa Basin watershed.

Region	Characteristic	Value	
Colusa Basin watershed	Wet/Non-irrigation Season	November- April	
	Dry/Irrigation Season	May-October	
		US Customary Unit	SI Unit
	Watershed area	1,045,445 ac	4,231 km^2
	Maximum elevation	2800 ft.	850 m
	Minimum elevation	30 ft.	9 m
Basin/valley lands	Temp., average summer high	90^{o}F	32^{o}C
	Temp., average winter low	40^{o}F	4^{o}C
	Precipitation	17 in.	40 cm
Coast Ranges divide	Temp., average summer high	80^{o}F	27^{o}C
	Temp., average winter low	30^{o}F	-1^{o}C
	Precipitation	27 in.	70 cm

Today the highest order stream draining the Colusa Basin watershed is the unlined, engineered channel known as the CBD (see Figure 2.1.2). The CBD serves as the ultimate collection of drainage during both the irrigation and non-irrigation seasons, and also is an important water source for irrigation in the lower Colusa Basin. Alternatively referred to as the Trough, the 2047 Main Canal, or just the Drain, the CBD begins southeast of Orland and runs 70 miles (mi.) (113 km) south, generally parallel to and approximately 3-8 mi. (5-13 km) west of the Sacramento River, to their confluence at the CBD outfall just north of Knights Landing. Lower CBD water levels are controlled by the operation of outfall gates to maintain adequate stage heights for irrigation withdrawals, and to prevent water intrusion into the lower basin during high Sacramento River stage. Additional overflow capacity for the CBD is afforded by the Knights Landing Ridge Cut (KLRC), which is located 1 mi. (1.6 km) upstream of the outfall gates and delivers CBD waters to the Yolo Bypass when stage increases above its passive entrance.

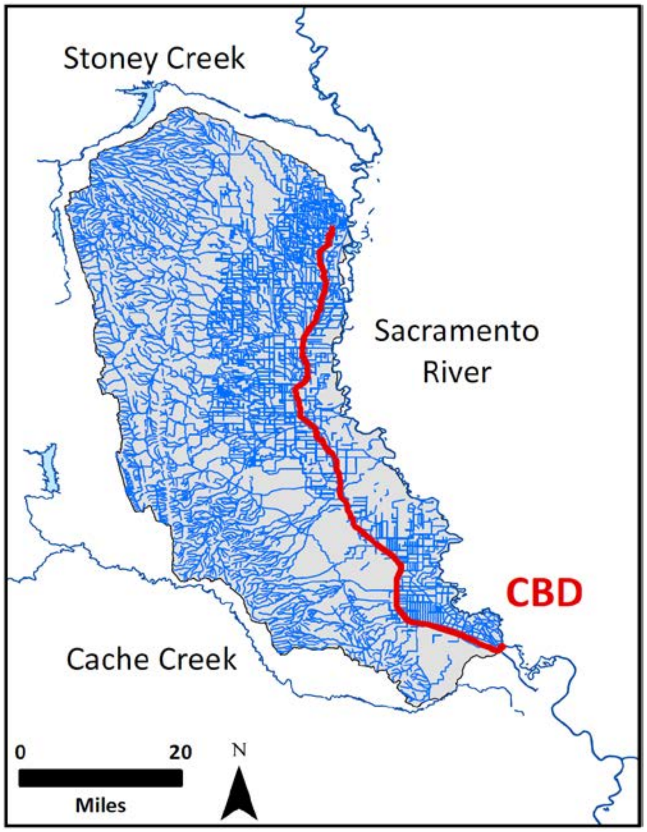

Figure 2.1.2. The Colusa Basin drainage area with bounding hydrologic features, internal drainage network and the Colusa Basin Drain (CBD).

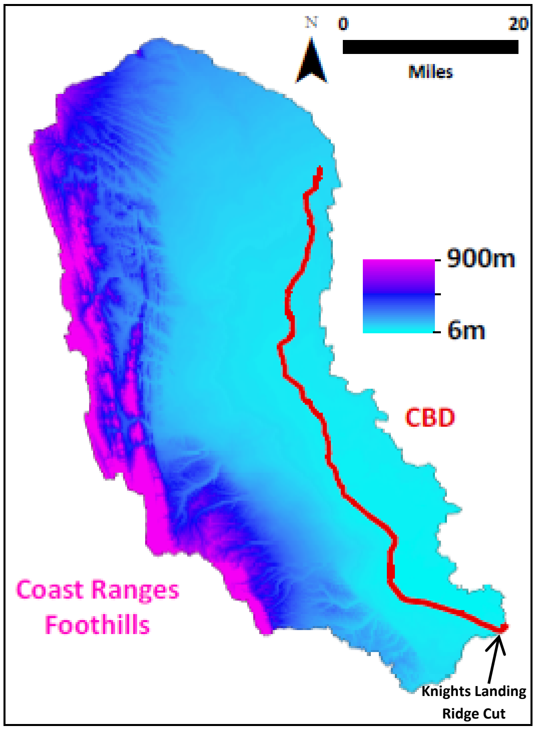

Figure 2.1.3. Land surface elevations in the Colusa Basin drainage area.

2.2 Natural Setting

The following subsections present background information on the natural setting of the Colusa Basin drainage area before the effects of European colonization, including brief overviews of the geology and soils (Section 2.2.1), hydrology (Section 2.2.2), fluvial geomorphology (Section 2.2.3), and habitat and ecological characteristics (Section 2.2.4). After presenting the history of land use and development (Section 2.3), the natural setting is revisited in term of human impacts (Section 2.4).

2.2.1 Geology and Soils

The Colusa Basin drainage area is set within the Great Valley geological province, which includes the geographic extent of the Sacramento River Valley and the surrounding foothills (H.T. Harvey and Associates *et al.*, 2008; Bailey and Jones, 1973) (Figure 2.2.1). This region is underlain by marine sedimentary rocks known as the Great Valley Sequence, which were formed during a transgressive period in the Cretaceous when the Sacramento River Valley was a large inland sea. These Cretaceous rocks have since been warped and faulted, resulting in uplift along the outer boundary of the Sacramento River watershed and subsidence of the central valley axis. Tertiary and Quaternary streams dissected the uplifting outer elements of the Sacramento River watershed and deposited some of these sediments into their own valleys as well as the Sacramento River valley. Erosion of foothill streams fronting the Coast Ranges that form the western portion of the Colusa Basin watershed generally follow the pattern of highly warped marine strata, with more erodible sequences composed of silts and muds dissected into valleys, and more competent layers of sandstones and conglomerates forming ridgelines. This resulted in the formation of the long, linear valleys characteristic of the western Coast Ranges Foothills in the Colusa Basin drainage area. The same rivers and streams generally exist today and continue to drain and erode the Coast Ranges foothills.

Some of the sediments eroded and transported by these drainages formed very thick deposits in the Sacramento River valley, with depths up to perhaps 1000 ft. (300 m) in thickness near the valley center, as well as alluvial fans ushering from the foothill streams where they drain into valley lands (Bryan, 1923; Helley and Harwood, 1985) (Figure 2.2.1). The older Tertiary sediments deposits are known as the Tehama Formation, which are deeply buried in the Valley lands beneath Holocene and more recent sediment, but have been uplifted near the foothill/valley transition to form the western terraces of the Colusa Basin drainage area. Some fraction of the alluvial sediments from the Holocene remain on the slopes of the interior foothill valleys as alluvial terrace deposits, and form the alluvial fans that usher out of the western foothills and terraces where they drain into the valley lands and mantle Tertiary deposits with another 50 to perhaps 150 ft. (15-40 m) of sediments.

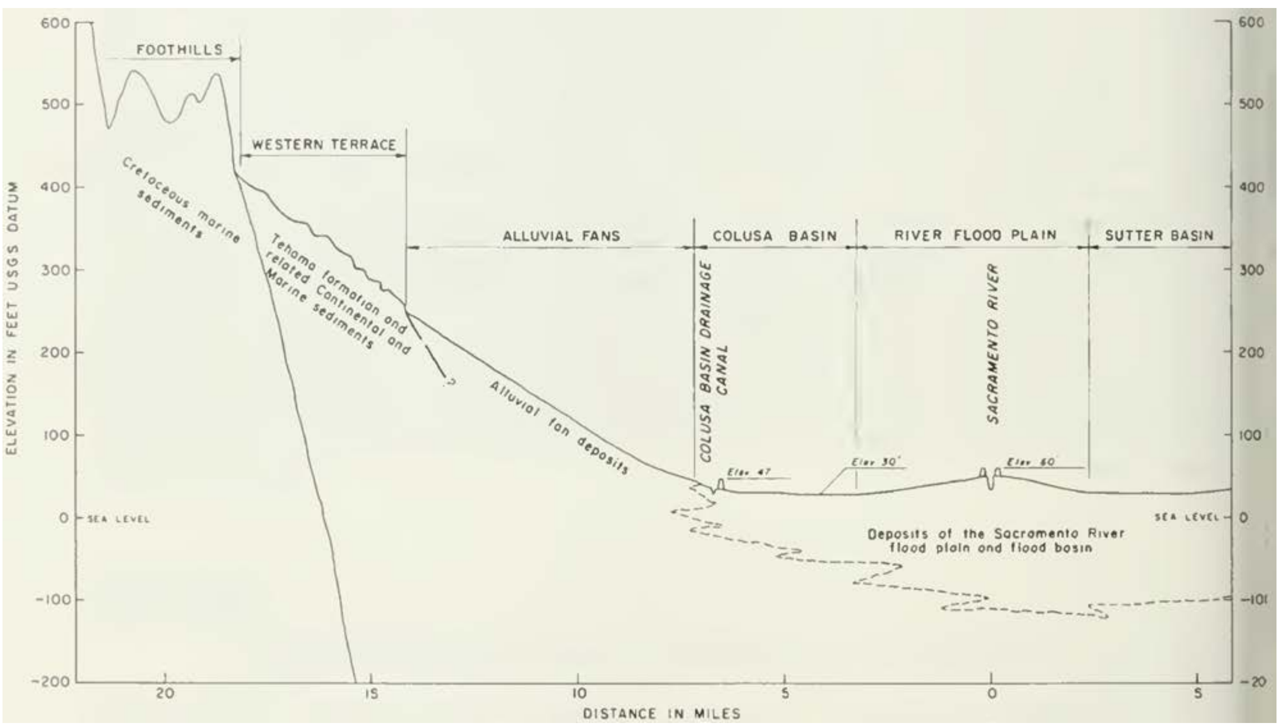

Figure 2.2.1. General geological section of the Colusa Basin drainage area (from DWR, 1964).

The development of soils in the Colusa Basin drainage area follows regional geologic and geomorphic development as driven by the interaction of substrate and landforms with climate and vegetation over time. A generalized grouping of soil types in the region can be organized by the following sub-regions: foothill uplands, terrace lands, valley lands, and valley basin lands (USDA/NRCS, 1968; 1979; 1998; H.T. Harvey and Associates *et al.*, 2008).

Foothill upland soils developed on the residual regolith that remains from erosion of the steep to rolling topography of this sub-region. These soils generally have fairly shallow depths to bedrock and low organic content. They support grasses and shrubs and are prone to erosion when disturbed or un-vegetated.

Terrace land soils are formed on alluvium in foothill valleys, alluvial terraces and alluvial fans. These soils can be further broken up into two subgroups: those that have dense subsoils due a high amount of clay illuviation, and those that have moderately dense subsoils. The poor drainage of terrace land soils with dense sublayers render them compatible only with grasses and shallow rooted crops. Those with moderately dense subsoils have developed on younger alluvium, tend to drain better, and support stands of trees.

Valley land soils have also developed on sandy alluvium but tend to have much less clay translocation, and as such are better drained and more suitable for orchard, vineyards and row crops. These soils are found on alluvial fans of the Tehama formation, along the Sacramento River, and near the natural levees built up by the larger foothill streams.

Valley basin land soils have developed on more alluvial deposits generally composed of finer sediments with a higher proportion of clay and silt. These soils developed in the basin lands in the distal flood plain along the axis of the Sacramento River, which were regularly flooded by the Sacramento River and the foothill tributaries during wet season before development. The low hydraulic conductivity of these soils is related to the particle size characteristics of the mineral substrate as well as the relatively high organic content derived from wetland vegetation. Poor drainage characteristics and evaporative processes have rendered some of these soils too saline for effective cropping (many of the worst areas of which have been converted to wildlife refuges in the region), while much of the rest is utilized for flooded rice production (Tanji *et al.*, 1981b).

2.2.2 Hydrology

Prior to human intervention, the highlands of the Colusa Basin watershed were drained by seasonal foothill streams that debauched, along with frequent Sacramento River overflow, into the vast complex of wetlands that made up the Colusa Basin (Bryan, 1923; USBR, 1974; H.T. Harvey and Associates, 2008). No permanent channelized drainage through the natural right (western) levee of the Sacramento River existed until the 20th century. The high natural levees of the Sacramento River generally precluded individual confluences with foothill streams. Although the general slope of basin lands followed that of the Sacramento River, with the lowest elevation at the southeastern end of the watershed, this position was coterminous with the intersection of the elevated Knights Landing Ridge and the natural western levee of the Sacramento River. Thus, seasonal inundation of basin and floodplain areas during the late fall and early winter rains and floods was generally followed by a slow drawdown as waters receded through the spring and summer due to seepage and evapotranspiration.

Before human development, the hydrology of the Colusa Basin drainage area was dominated by the wet and dry seasons that typify the semi-arid Mediterranean climatic regime found in north-central California. Rains during cool, wet winters drastically increased the late dry season flows of the Sacramento River and returned flows to the seasonally dry foothill tributaries (Bryan, 1923). The Sacramento River regularly overtopped its banks and flooded the Colusa Basin lands through crevasses in its natural levees and long term distributary sloughs, such as Sycamore Slough. This seasonal flooding led to a seasonal expansion of wetlands in the basin lands, into which the foothill tributaries also emptied, further expanding the seasonal extent of inundation. During most years the basin lands remained flooded through the wet season, and slowly drained and away through the late spring and into the early summer. Most of the foothill streams remained dry in their upper reaches between winter storms, as base flow was usually not sufficient to support them. The streams would be once again dry after the last rains in the spring, long before the flood of the basin lands receded.

2.2.3 Fluvial Geomorphology

Fluvial geomorphology is the study of land surfaces shaped by the erosive and depositional effects of water (Leopold *et al.*, 1964). Notable geomorphic features of the Colusa Basin watershed from east to west include the western levees and relic distributary sloughs of the Sacramento River, the trough of flat basin lands known as the 'Colusa Basin' running parallel to the river, and more distal floodplains grading into a mosaic of alluvial fans ushering out of the valleys of the Inner Coast Ranges foothills (H.T. Harvey and Associates, 2008; Colusa County Resource Conservation District (CCRCD), 2012). Historically the Coast Range foothill channels formed ridges in the low gradient basin lands through natural deposition of coarse materials proximal to the channel during overbank events (Bryan, 1923; Kelley, 1989; H. T. Harvey and Associates, 2008). Rogers (1891) observed that, "Wherever these streams meander, their banks… are frequently from an eighth to a quarter of a mile wide, and from ten to fifteen feet deep." Channel avulsions led to networks of active and abandoned foothill stream channel ridges across the distal fans and basin lands, which interacted with each other and the similar ridge structures of the various Sacramento River distributary sloughs to produce a mosaic of smaller flood basins (Bryan, 1923). Before human intervention the upper reaches of the foothill streams stored very little modern alluvium, while the lower reaches deposited mostly gravel and sand clasts in the channel, and a significant proportion of the sand and fines (silt and clay) were deposited in the natural levees and adjacent flood plains/basin during overbank events. With little in the way of channelized connectivity to the Sacramento River, only very large flood periods would have been expected to effectively deliver upper watershed sediment loads to the Sacramento mainstem (Bryan, 1923). Thus, prior to human influence, the physiographic regions of the Colusa Basin watershed can be broadly classified generally as zones of sediment production (Coast Ranges foothills) and zones of sediment deposition (alluvial fans, and valley and basin lands).

2.2.4 Habitat and Ecological Characteristics

Native vegetation assemblages in the Colusa Basin drainage area generally followed geologic, geomorphic and soil developmental patterns in collusion with climate, hydrology and wildfire before the influence of human development. Upland foothill regions were dominated by a mosaic of native grasslands, chaparral and stands of blue oak depending on soil characteristics, soil moisture, and aspect (H.T. Harvey and Associates *et al.*, 2008). Better drained valley lands adjacent to rivers, streams and sloughs supported riparian corridors of willow, cottonwood, sycamore, alder, and valley oaks. Basin lands supported mostly monotypic tule stands (Bryan, 1923; H.T. Harvey and Associates, *et al.*, 2008).

The pre-development habitats of the Colusa Basin drainage area supported a wide range of animal life including many mammals, reptiles and birds in upland areas, and fish, amphibians and waterfowl in the streams and particularly wetlands (DWR, 1964). Although previously thought to not be present in lowland California, beavers, otters, and other mammals with valuable pelts are now believed to have been abundant, but extirpated prior to 1850 by American and European trappers and hunters as part of the California fur trade (Lanman et al., 2013). Many other animals persist to the present day despite, and in some cases supported by, human changes to the landscape. The Central Valley of California is a major stopping point on the Pacific Flyway, which is a major route of North-South waterfowl migration through North America. The pre-development wetlands of the Colusa Basin were a large component of the ecological services that the Central Valley provided to migratory birds as they moved through the region.

2.3 Land Use and Development

Development of the Colusa Basin watershed primarily for irrigated agriculture, rangeland, flood control and the transportation of humans and goods has resulted in significant changes to the bio-physical composition and functionality of the system, including the production, storage and transport of sediment. Native plant communities have been largely replaced with European and Asian invasive plants and cultivars (Geomorph *et al.*., 2010). The routing of energy and mass through the landscape have also been significantly altered through the construction and operation of flood control measures, irrigation and drainage infrastructure, irrigation agricultural practices, and road building (DWR, 1964). Human land use in the Colusa Basin drainage area is dominated by agriculture and livestock (approximately 60 to 80% of each county's land use), with only 1% occupied by urban development (CCRCD, 2012). Approximately 40,000 people live within the boundaries of the Colusa Basin watershed (US census, 2010). The largest concentrations of people are found in the towns of Willows, Colusa, and Williams, each of which have 5,000-6,000 residents (CCRCD, 2012).

Pre-Europeans settlement of the region by Native Americans began at least 10,000 years ago. The population of these peoples in the Colusa Basin watershed was relatively low compared to present, with seasonally fluctuating numbers on the order of 100s to a few 1,000s of individuals. Despite transitions from hunting/gathering lifestyles to some sedentary farming activities between 800 and 300 years ago, low populations and low impact subsistence farming probably had little effect on the bio-physical functionality of the region (Blackburn *et al.*, 1993). One possible exception was the practice of rotational burning of grasslands/chaparral systems, which may have increased fire frequency regimes over significant proportions of the basin, including high relief areas that are particularly important for sediment production (Keeley, 2002). However, no studies have been conducted in this basin to address such possible effects, so they remain plausible but unexamined.

Early European settlement primarily impacted the landscape through dryland farming of cereal crops such as wheat and barley, and small scale livestock operations (DWR, 1964). European settlers were initially sparse, but came to displace Native populations over the course of the 19th century. Human impacts on the landscape, including acceleration of sediment erosion/transport regimes remained very low up to the mid-19th century, with much of the Colusa Basin Wetlands and the hydrologic regime of the region intact. The loss of beaver prior to 1850 likely impacted channels and sediment flux, as beaver dams increase sediment retention time (Lanman *et al.*, 2013). This would have gone hand in hand with increasing modification of channels, including removal of large wood, viewed as debris problematic for flood conveyance instead of essential aquatic habitat.

The pace of reclamation in the basin drastically increased with the Federal Arkansas Act of 1850, which transferred approximately 1.75 million acres of wetlands to the ownership of the State of California with the mandate that they be drained and developed to the greatest degree practicable (DWR, 1964; Tanji *et al.*, 1978). Land was sold to private individuals and corporations that formed numerous drainage districts. This resulted in a patchwork of levees and dikes, with much of the drainage in the basin conducted by local reclamation districts beginning in 1868. Another significant advancement in the progression of reclamation and flood control in the basin was the advent of the Sacramento River Flood Control Project (SRFCP) in 1917, which eventually resulted in the first regional improvement of Sacramento River levees to a level that eliminated regular flooding of the Colusa Basin by the Sacramento River in the mid-20th century.

Over the last 170 years myriad land surface engineering projects have been wrought upon the landscape, from the manipulation of individual agricultural fields to large scale drainage and flood control. As a result the dynamics of sediment production and deposition in Colusa Basin watershed have been substantially altered (CCRCD, 2012). Disorganized levee construction by individual farmers and drainage districts eventually gave way to larger state controlled projects, culminating in the SRFCP, which resulted in the disconnection of the Sacramento distributaries entering the Colusa Basin such as Sycamore Slough, Dry Creek Slough, Corbiere Slough, Byers Slough, Tule Slough, Hopkins Slough, etc. (H.T. Harvey and Associates *et al.*, 2008). Agricultural development, particularly on the distal alluvial fans, Colusa Basin and Sacramento Floodplain resulted in widespread modification of distal foothill stream channels, drainage and reclamation of wetlands, and the artificial introduction of Sacramento River and Stony Creek waters for irrigation through supply canals. Channel modifications included some small scale impoundments (Funks Creek), channelization, and rerouting to local drainage canals. Drainage of the basin was developed with increasing hydrologic connectivity throughout the early 20th century, resulting in the contiguous 70 mi. (113 km) of the CBD.

The outfall of the CBD into the Sacramento River just above Knights landing most likely coincides closely with the location of the terminus of Sycamore Slough, replacing and augmenting its role in basin drainage. Although Sycamore Slough acted as a conveyance of basin drainage in its lower reaches before development, its terminal area was impounded by convergence of the natural western levee of the Sacramento River and Cache Creek Slough ridge, both of which stood some 20 feet above the floodplain. Thus the completion of CBD construction created a general lowering of the Colusa Basin watershed base level. This action may have influenced widespread channel incision in the foothill streams (H.T. Harvey and Associates *et al.*, 2008).

2.3.1 Drainage, Irrigation and Flood Control

Early Euro-American settlement in the Colusa Basin dates back to the 1840s with farmers introducing fields of non-irrigated wheat and barley (Rogers, 1891; Tanji *et al.*, 1978). Production of anything beyond such cereal crops or livestock feed would require irrigation, and much of the early interest in natural water systems in California were motivated by potential development of water resources. For this reason, the foothill streams of the Colusa Basin watershed were of little interest to the early surveyors and hydrographers of California, as most were not productive enough to maintain base flow between storm events, much less through the summer months of potential irrigation demands (H.T. Harvey and Associates *et al.*, 2008). In one of the earliest accounts of regional hydrography, Rogers (1891) waxed poetically over the quality and quantity of water in the foothill streams, noting that, "In journeying through the western part of the (Colusa) county, no one is exposed to any inconvenience from want of water, as these streams, clear and sparkling, and refreshing to both sight and taste, are met with everywhere at short intervals." However, he may have been primarily focusing on Cache and Stoney Creeks, as he later discounts several of the larger Colusa Basin watershed foothill streams as being of little importance for agricultural development. Furthermore, when mentioned later, the foothill streams were again viewed in terms of their low potential for water supply development, such as the intermittent nature of their flow (Bryan, 1923) and their potential threat to Colusa Basin flood control (McGlashan and Henshaw, 1912; Etcheverry, 1903-1954).

Developments toward irrigated agriculture began in earnest in the mid to late-19th century. Lowland basins began to be reclaimed throughout the Central Valley after the federal Arkansas Act of 1850 resulted in financial incentives for the draining of swamps and overflow lands (DWR, 1964). As state legislation developed to address the regional issues of land ownership and drainage, the early developers of the Colusa basin formed numerous drainage districts in the mid to late 19th century. Due to the ephemeral nature of the foothill streams which emptied into the morass of wetlands bordering the natural western levees of the Sacramento River, there was no highest order drainage (i.e. a stream collecting runoff from the entire watershed) emptying into the Sacramento River until the early 20th century. This changed with the construction of the CBD (Figure 2.3.1).

Reclamation District 2047 (RD 2047) was formed in 1919 and began constructing drainage systems for the combined agricultural drainage in the vicinity of Willows, which was beginning construction of what would become the CBD (USBR, 1967). The CBD, also known as the RD 2047 Main Canal, Colusa Trough, the Colusa Basin Drainage Canal, or just the Drain, was expanded over the next 40 years primarily by connecting levee barrow pits left by Reclamation District 108 work on the SRFCP. By 1958 the CBD was in its current form, spanning some 70 miles (113 km) from south of Orland to Knights Landing, with a bypass through the KLRC connecting to the Yolo Bypass and the Tule Canal (Figure 2.3.1). The KLRC was planned and executed by the Knights Landing Ridge Drainage District beginning in 1913 and was in operation by 1915 (USBR, 1967).

Control of drainage from the Colusa Basin to the Sacramento River was manipulated by humans in the vicinity of Knights Landing as early as 1883 (USBR, 1973c). Early methods involved simply breaching the levee. Today, flood gates control the CDB outfall to the Sacramento River. The outfall gates were constructed in their present location by the California Corps of Engineers in 1930 during the Sacramento Flood Control Project, with subsequent modifications over the following decades (USBR, 1973c). The objectives of flood gate operation are seasonal in nature. During the irrigation season operations are set to maintain a 24.5 ft. water elevation behind the gates to facilitate irrigation withdrawals, which induces a backwater ponding effect that can extend as far upstream as College City (USBR, 1973c). During the non-irrigation season, the gates are closed during high Sacramento River stages to prevent Sacramento River water from flowing up the CBD during high water events. If CBD flow is too great, drain waters are routed through the KLRC and into the Yolo Bypass, with the threshold usually set at discharge (Q) > 8,500 ft^3s^{-1} (cfs) (241 m^3s^{-1}) (Tanji *et al.*, 1978).

The CBD floods frequently, with some level of overbank flow occurring nearly every winter storm season. The CBD is relatively shallow in its upper reaches, and its banks can be over topped by relatively low flows along this portion of the drain. For example, the Highway 20 bridge overpass site near Colusa (CBD-5, see Figure 2.3.1) experiences overbank flooding when Q exceeds 2,100 cfs (59 m^3s^{-1}) (Mirbagheri, 1981). The highest Q recorded at this station was 23,900 cfs (677 m^3s^{-1}) on February 21st, 1958, while the highest Q recorded in the lower reaches near Knights Landing (station CBD-1) was > 8,500 cfs (241 m^3s^{-1}) (January 17, 1978). As noted above, lower drain flood waters are routed through the KLRC into the Yolo Bypass during such conditions, and as such are not easily quantified. Spring flooding also occurs if rice irrigation ponds are partially drained in order to prevent wave erosion of rice field levees during high winds. Flooding from these spring releases can be disproportionately costly in comparison to winter flooding due to coincidence with the predominant crop season (Mirbagheri, 1981). Responsibility and expense for maintenance of the CBD falls to each irrigation district through which it passes, previously including the Glenn-Colusa, Provident, Princeton-Codora-Glenn, Compton-Delevan, Jacinto, and Maxwell Irrigation Districts, of which the Provident and Compton-Delevan districts have been consolidated with Glenn-Colusa.

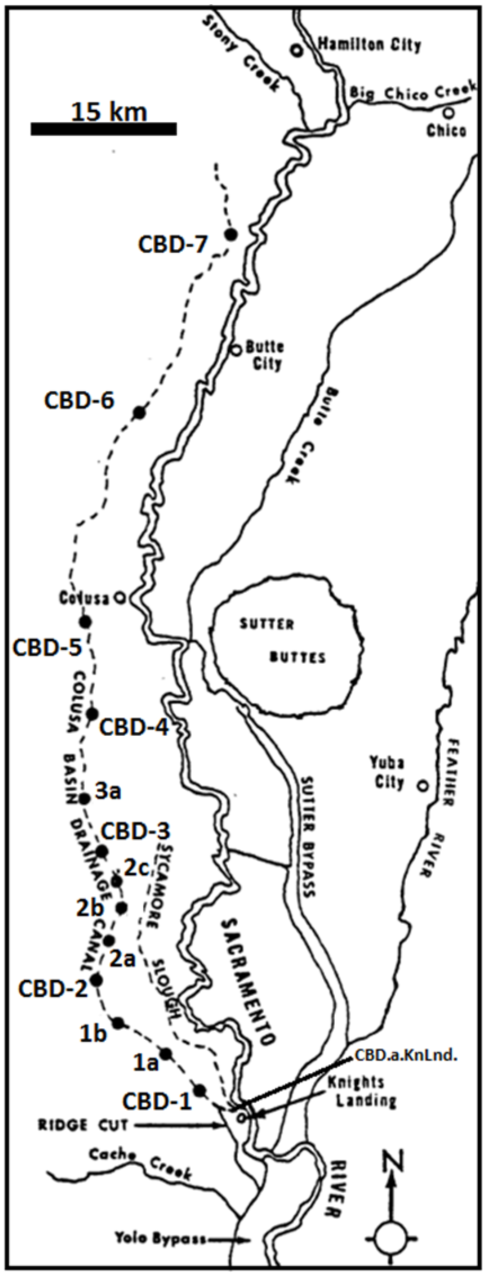

Figure 2.3.1. Suspended sediment sampling stations on the CBD. Stations labeled with an alpha-numeric pair are also 'CBD' prefix stations. 'CBD.a.KnLnd.' indicates the lowest three stations in the CBD (CBD Outfall, CBD at Knights Landing downstream , and CBD at Knights Landing upstream) are all downstream of the CBD outfall gates and are located at the outfall of the CBD into the Sacramento River, and 300 and 400 meters upstream, respectively. (Adapted from Tanji *et al.*, 1978).

2.3.2 Agriculture

The most prevalent land use in the Colusa Basin watershed is agriculture, including land used for cereal and row crops, orchards and vineyards, and rangelands (CCRCD, 2012). The Colusa Basin watershed contains a significant proportion of the California rice crop, utilizing the aforementioned low permeability soils with 242,209 acres (980 km^2) in rice production in Colusa and Glenn Counties alone in 2010 (CCRCD, 2012). Better drained soils in the watershed support a large row crop and orchard industry. Most of the agricultural production in the basin is irrigated with waters supplied from irrigation districts with state water rights and water supply agreements with the Central Valley Project (CVP), a federal water resources project in California's Central Valley that involves an array of engineered infrastructure for water storage and transport, primarily for irrigated agriculture.

Irrigation waters are imported to the basin primarily by two irrigation canals: the Glenn-Colusa Irrigation District (GCID) Main Canal (GCID Main) and the Tehama-Colusa Canal (TCC), and a smaller amount of direct pumping from the Sacramento River (Figure 2.3.2). On average, the GCID Main and the TCC supply at total of approximately 1,000,000 ac-ft (1.23×10^7 m^3) of irrigation water annually from the Sacramento River and Stoney Creek. The GCID is the largest irrigation district in the Central Valley of California. Since its inception in 1920 the GCID has amassed some of the largest and oldest claims to Sacramento River water, with water rights extending back to 1883 (GCID, 2015; Tanji *et al.*, 1978). Today the GCID has rights to between 618,000 and 825,000 ac-ft of Sacramento River water during the irrigation season, depending on storage conditions in Shasta Reservoir. These waters are abstracted mostly from the Sacramento River at the GCID pumping station near Hamilton City, with a much smaller contribution from Stoney Creek, and then distributed through the 65-mile GCID Main Canal and laterals, a system which was primarily built in the early 20th century and remain as unlined, earthen channels. The Tehama-Colusa Canal Authority (TCCA) is a consortium of 17 water contractors that supply irrigation waters from the Sacramento River (primarily CVP allocated water) to the Colusa watershed through the TCC (TCCA, 2015; Tanji *et al.*, 1978). The TCC system extends south for 111 miles from the Red Bluff Diversion Dam on the Sacramento River, and delivers up to 250,000 acre feet of water to the Colusa Basin watershed during the irrigation season, although delivery volumes can be less than 100,000 acre feet during times of drought (USBR, 2014).

While irrigated agriculture dominates the valley and basin lands, land use in the Coast Ranges foothills portion of the Colusa Basin watershed is largely managed as rangelands for the rearing of livestock (DWR, 1964; Tanji *et al.*, 1978). Livestock density in this steep country is relatively low (Betsy Karle, Dairy Advisor and County Director, UC CE Glenn County, *personal communication*). However, the importance of this region in terms of sediment production has lead previous studies to emphasize the need for changes in rangeland management to reduce sediment production from the Colusa Basin drainage area (Tanji *et al.*, 1981c).

A further result of agricultural development is the network of roadways in the Colusa Basin watershed. Colusa County contains 1,067 miles of roads, half of which are predominantly dirt and gravel surfaced local roads (Sedway Cooke Associates *et al.*, 1989). Commercial traffic, most of which is connected to agriculture, is primarily conveyed by these local roads, which results in maintenance costs in excess of local budgets (H.T. Harvey and Associates *et al.* 2008, pp. 32-33). The network of relic streams, drainage and irrigation ditches extending across the valley floor have numerous road crossings, which can act as points of hydrologic restriction, resulting in a wide distribution of potential backwater effects, particularly during the non-irrigation season. These roads have been identified as significant sources of fluvial sediment (Tanji *et al.*, 1983; this study, Section 4).

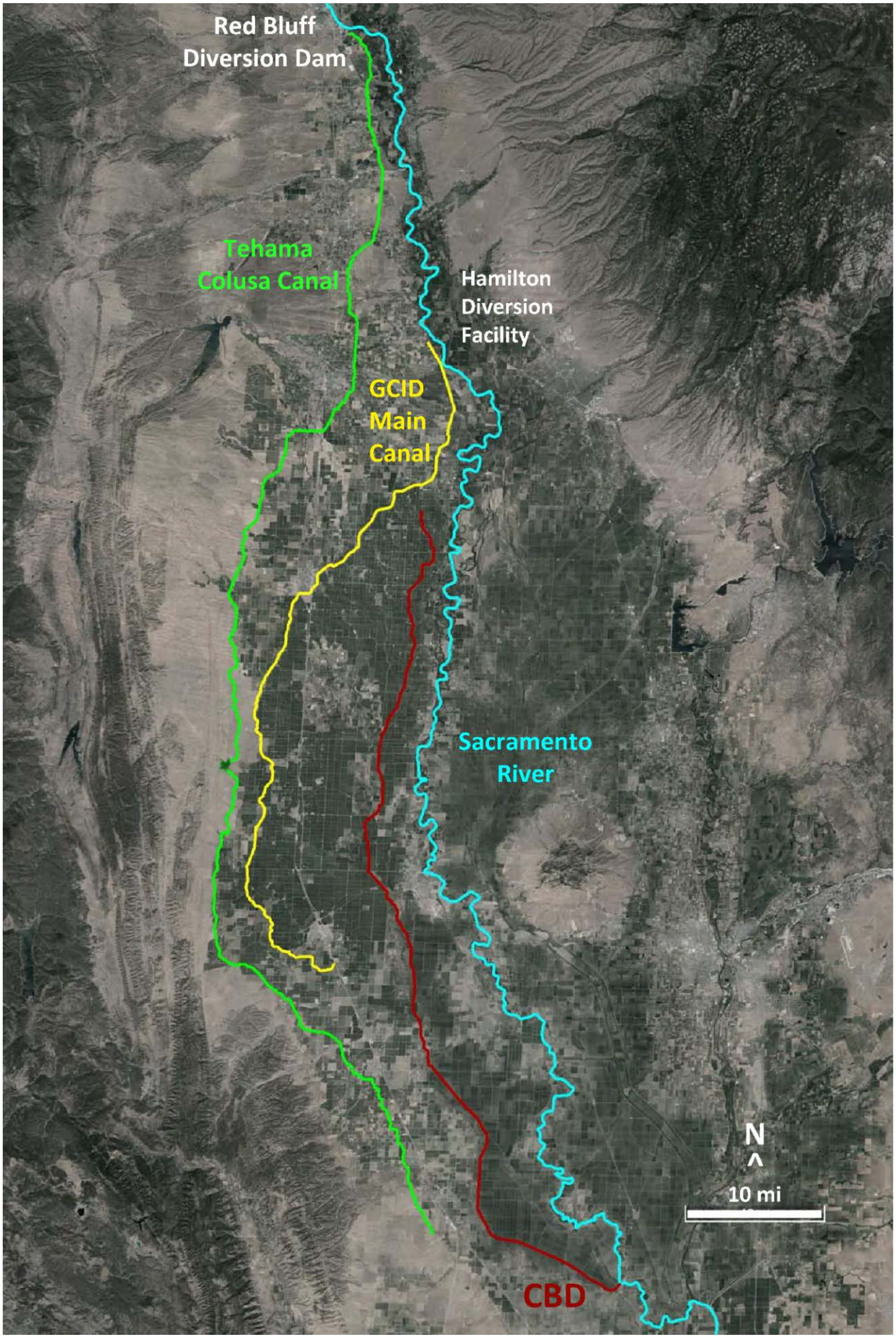

Figure 2.3.2. The two main canals that supply irrigation waters to the Colusa Basin: The Tehama-Colusa Canal and the GCID Main Canal.

2.3.3 National Wildlife Refuges

Waterfowl habitat from rice fields, private gun club, and National Wildlife Refuges render this area of great importance as a stopping point in the Great Pacific Flyway, while foothill lands primarily used for grazing also serve as important habitat for many animals, including valuable game birds such as pheasant. Three national wildlife refuges are present in the Colusa Basin: (1) Delevan National Wildlife Refuge, (2) Colusa National Wildlife Refuge, and (3) Sacramento National Wildlife Refuge (Figure 2.3.3). The wildlife refuges are supplied with water primarily by: (1) CBD or directly pumped Sacramento River waters via Maxwell Irrigation District, (2) CBD by direct pumping, and (3) Glenn-Colusa Irrigation Canal water via the District, respectively (USBR, 1973b). The Delevan National Wildlife Refuge also purchases small amounts water from the Glenn-Colusa Irrigation District (GCID), and also diverts sporadic runoff from seasonally tributaries, as does the Sacramento National Wildlife Refuge.

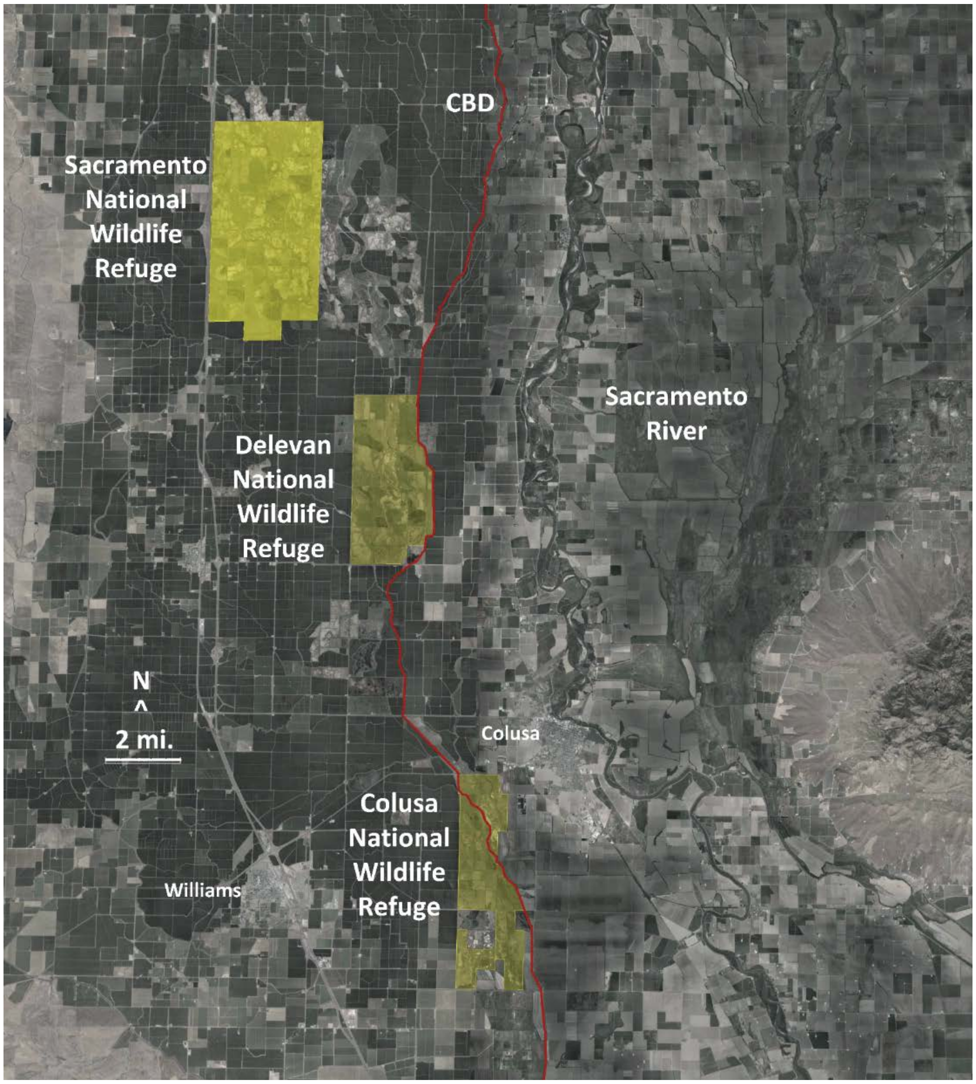

Figure 2.3.3. The National Wildlife Refuges of the Colusa Basin region.

2.3.4 Potential Future Development in the Colusa Basin Drainage Area

Additional hydrologic projects in the Colusa Basin watershed have been investigated over the last 50 years, with an emphasis on flood control and additional water delivery and storage. Watershed scale flood control projects in the Colusa Basin were proposed and investigated between 1964 and 2010 in response to the high frequency of internal flooding issues that were not addressed by the SRFCP. Interest in flood control remains high to this day, particularly in the lower Colusa Basin, where flooding frequencies and intensities are generally highest. Early project proposals focused on engineered approaches to increasing water discharge and storage capacities in the drainage network, while recent studies have focused on management approaches to decrease runoff. None of these projects have come to fruition, primarily due to high cost/benefit ratios and lack of funding. The only large scale hydrologic development in the region that may reach the construction phase in the near future is the North of Delta Offstream Storage project (NODOS). This would involve the storage of Sacramento River water in a new reservoir occupying two of the interior Coast Ranges valleys in the watershed.

Despite the significant decrease in flooding from Sacramento waters by the mid-20th century, internal flooding from stormwaters and irrigation return flows has continued to be an impediment to the local population and economy (CCRCD, 2012). Many foothill streams frequently overtop their banks as they convey storm waters to the CBD, which in turn often floods adjacent lands during the non-irrigation season. Releases of rice pond waters can also easily exceed the design capacity of the lower CBD during the early and late irrigation season, when rice irrigation waters can be rapidly drained to protect rice pond levees from wave erosion during high intensity wind storms in the spring and for harvest in the fall (Tanji *et al.*, 1978).

Local demand for improvements in flood control continue, primarily motivated by recurrent agricultural losses in the lower Colusa Basin, but have not resulted in any new state or federal flood control projects in the latter half of the 20th nor early 21st centuries due to high estimated cost/benefit ratios. However, this demand has resulted in a number of flood control feasibility studies performed by DWR, USBR, and CBDD (DWR, 1964; USBR, 1973a,b,c; Landon and Lerch, 1981; DWR, 1990a,c; CBDD, 1993; CBDD, 1995; CBDD and USBR, 2001). The first of these studies (DWR, 1964) is summarized here as it is typical of the general findings and conclusions of subsequent studies. The DWR Colusa Basin Investigation (1964) was conducted “to make a comprehensive study of the ‘Colusa Basin’ for the purpose of determining the best manner for alleviating the problems resulting from inadequate drainage and flood control facilities, seepage and storm water disposal, giving due consideration to the protection of established water rights in the area as per California Senate Resolution No. 79, 1959.” This study was motivated by persistent shallow flooding in the Colusa Basin caused by storm flow from foothill streams in the winter, and irrigation return flows, primarily from rice fields, in the spring, both of which are exacerbated by inadequate drainage in the lower basin. Winter flooding is most pronounced in the northern reaches, while irrigation return flow based flooding is most pronounced in the southern reaches. Maximum flooding in recent years inundated approximately 100,000 acres, mostly concentrated along Willow Creek and a 50 mile reach of the CBD. Solutions to flooding problems were explored in the form of (1) levees, (2) flood control reservoirs, (3) watershed management to reduce runoff rates, (4) drainage improvements. The levee and flood control projects were determined to not be economically justified, with estimated costs much higher than benefit. Watershed management was found to have potential benefits, but was unlikely to have large impacts on flooding reduction, and analytical demands to predict impacts were found to be far beyond the scope of the study. Improved drainage was found to be economically justified with benefits approximately 34% greater than costs, but only a very limited amount of protection would be provided and only to the lower basin.

More recent studies have focused on watershed management rather than engineering solutions to flooding issues in the lower Colusa Basin (CCRCD, 2012). The CCRCD recently completed a Colusa Basin Watershed Management Plan (CCRCD, 2012) with support from studies conducted by consultants (H.T. Harvey and Associates *et al.*, 2008; Geomorph *et al.*, 2010). These studies also made a number of observations and recommendations regarding watershed scale sediment management (see Section 4.1.3). The conclusions of these studies suggested that changes in land management techniques to decrease storm runoff generation during the non-irrigation season, and coordination of rice field releases were the only economically feasible flood control mitigation measures for the Colusa Basin watershed. Changes in vegetation management in rangelands and agricultural fields that increased infiltration would decrease runoff during the non-irrigation season and decrease flood peaks (CCRCD, 2012). It remains to be seen whether large-scale implementation of these recommendations will be carried out by the numerous land holders in the Colusa Basin watershed.

The only large scale hydraulic engineering project in the Colusa Basin watershed that may take place in the near future is motivated by storage for water resources rather than flood control. Interest in developing additional storage for Sacramento River waters has led to preliminary studies in upper Stone Corral and Funk Creeks for the potential placement of dams at their foothill outlets under the NODOS project. The current scope of the project would involve the development of a contiguous reservoir with up to a 1.4 M ac-ft increase of average annual storage for the CVP and the State Water Project (SWP) – a California State managed system of water storage and transport facilities that supply water from the Sacramento-San Joaquin Delta to southern California (DWR, 2014a).

Plans for off-stream storage of Sacramento River waters began in the mid-20th century as part of initial plans for the TCC, and were also explicitly included in phase II of the CVP, but never came to fruition under either project (DWR, 2014b). The basic premise was the diversion and transport of Sacramento River waters to storage facilities outside of the channelized network of the Sacramento River itself. Beginning in the late 1990s the CALFED Bay-Delta Program, DWR and USBR returned to such storage considerations with the initiation of the NODOS Investigation (DWR, 2010; 2014a,b; DWR *et al.*, 2002; 2014; URS, 2006; 2008; USBR and DWR, 2013). The primary benefits of a NODOS facility would be increased water storage and management flexibility, with potential additional power storage, recreation and ecosystem services benefits including the ability to divert water at times that would not impact migratory fishes (DWR *et al.*, 2014).

The site selection process settled on Antelope Valley, a subbasin of the Stone Corral Creek watershed in the Coast Ranges foothills as the primary location of the potential storage facilities (Figure 2.3.3; USBR and DWR, 2013). The current form of the proposed project includes the creation of the 'Sites Reservoir' by damming Stone Corral Creek near the town of Sites, CA, and Funks Creek near its outlet from the Coast Ranges, with a number of additional dikes to block water gaps through the Coast Ranges (USBR and DWR, 2013). Water would be transported to the Sites Reservoir through the TCC and GCID Main with additional lateral canals and pumping. The full scope of the project also includes two smaller reservoirs for water management and power generation purposes (URS, 2008). Completion of the project would result in environmental impacts that include effects on perhaps 20 endangered or threatened species, with plans to offset environmental impacts (DWR, 2014b). Although not a main objective of the project, capture of upper Stone Corral and Funks Creek runoff would reduce flood risks along the lower reaches of these systems and the lower CBD, and decrease sediment supply (URS, 2008).

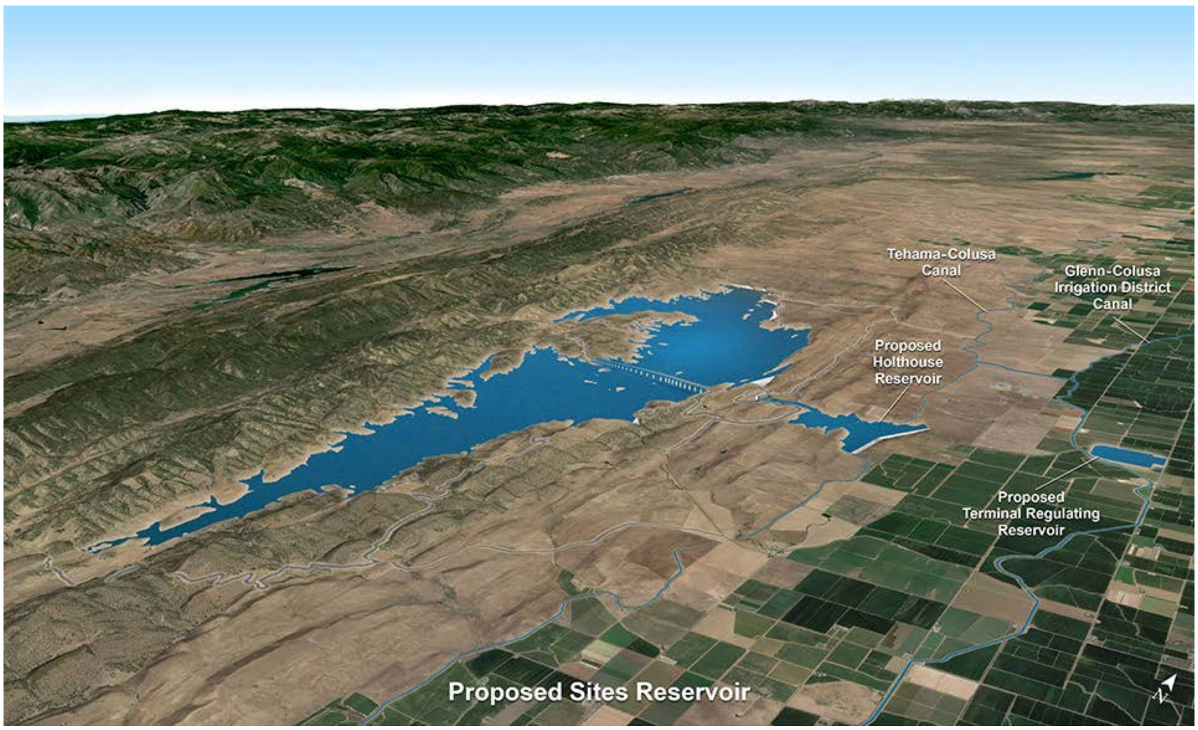

Figure 2.3.4. Artist's rendering of the latest proposed design for the NODOS, including the Sites, Holthouse, and Terminal Regulating Reservoirs (from DWR, 2014a).

2.4 Human Impacts on the Natural Setting of the Colusa Basin Watershed

Widespread cultivation of alluvial fans, drainage of basin lands for irrigated agriculture, and livestock grazing in the foothills have resulted in significant economic development, with concomitant impacts on geophysical and ecosystem characteristics and services. These impacts include alterations to the production, storage and transport of Colusa Basin watershed sediments (Section 2.4.1), which in turn influence geomorphic evolution (Section 2.4.2), and result in ecological impacts (Section 2.4.3).

2.4.1 Hydrological Impacts of Human Development

A significant reworking of the landscape for agriculture and flood control over the last 150 years has altered the sources, distribution and drainage of waters in the Colusa Basin watershed. Flood control measures largely resulted in the removal of Sacramento flood waters from the system by the middle of the 20th century, which included the expansion of levees and disconnection of distributary sloughs. Sacramento River (and to a lesser degree Stoney Creek) waters are now imported primarily for agricultural irrigation through the GCID Main and TCC, and direct pumping from the Sacramento River. Sacramento River distributary sloughs have been either co-opted for irrigation water delivery and drainage, or tilled over. Foothill stream reaches in the floodplain and basin lands have been generally divested of riparian vegetation, routed around land parcel boundaries, channelized, and otherwise modified for the delivery and/or drainage of irrigation waters. While winter storms continue to result in seasonally flowing foothill streams, which continue to regularly flood portions of the valley floor, some of these channels are now wetted by irrigation return flows during the irrigation season.

More recent irrigation developments have further affected the post development hydrology. There have been reports that the addition of the TCC irrigation supply waters to the system in the late 1970s/early 1980s has decreased the CBD flood peak lag time from approximately 72 to 24 hours (H.T Harvey and Associates, 2008). Channel bed incision and flood plain disconnection, likely due to a combination of rangeland impacts on rainfall/runoff relationships and base level reductions due to drainage modifications may have also in turn increased the peak storm flow of foothill streams (Navigant Consulting, Inc., 2000; CH2MHill, 2003; H.T Harvey and Associates, 2008).

2.4.2 Geomorphological Impacts of Human Development

A few studies have recorded observations and interpretations regarding the effects of land use on channel incision, channel morphology, and upper watershed sediment production in the South Fork of Willow Creek and neighboring subbasins (CH2M Hill, 2003; H.T. Harvey and Associates, 2008; Geomorph *et al.*, 2010). The general consensus is that three waves of increased hillslope sediment production may have occurred due to: (i) increased upland erosion with the transition from native grassland/chaparral/oak mosaics to domination of European annual invasive grasses supported and impacted by grazing, (ii) widespread conversion to dryland agriculture followed by irrigated agriculture, and (iii) the recent increase in irrigated agriculture with the increase in irrigation water deliveries through the building of the TCC in the 1970s. These activities, in combination with large scale drainage of wetlands, channelization of tributaries, and completion of a highest order drainage for the basin (the CBD), seem to have also led to incision of foothill tributaries into alluvial fans throughout the western portion of the watershed, and widespread destabilization of channel banks. Such observations are mostly based on expert opinion rather than rigorous scientific inquiry, however they do follow the fundamental concepts of geomorphology and are supported by numerous observations throughout the watershed.

Before human intervention, Sacramento River distributaries and foothill streams generally constructed their own coarse levees and overbank depositional sequences. Periodic avulsion of these channels resulted in splay deposition and further levee building, which over time developed into a network of elevated and better drained soils across the valley floor, particularly at the eastern and western margins of the basin lands (Tanji *et al.*, 1981b, H.T. Harvey *et al.*, 2008). Areas with these better drained soils have been mostly converted to irrigated row crops and orchards. Foothill soils tend to be shallow and well drained, with the exception of interior valley bottom lands, and are primarily used for grazing.

Recent studies have indicated that most of the Inner Coast Range foothill streams have incised into their proximal fans, and thus store little sediment from the basin divide to the transition to distal alluvial fans near the western edge of the Colusa Basin (H.T. Harvey and Associates *et al.*, 2008). Channels are generally less incised and may be aggrading in some of the reaches that traverse the distal alluvial fans, with gravel to sand bedded, broad meandering to anastomosing channel structures that were most likely prevalent before human intervention (Geomorph *et al.*, 2010). Many reaches of foothill streams upstream from irrigated agriculture appear to have destabilized as a result of shifting hydrologic and sediment regimes. Upper foothill streams seem to be incising alluvial fans at the base of the foothills due to some combination of (i) increases in runoff and sediment loads driven by changes in land cover/land use in the Coast Range foothills, and (ii) the migration of knickpoints upstream from a fallen base level caused by the introduction of the CBD (H.T. Harvey and Associates *et al.*, 2008). A knickpoint is an abrupt step in a river's longitudinal elevation profile, such as would occur at a waterfalls, rapid, or smaller such feature. Knickpoints are foci for erosion along the stream, and they erode on the step face more than the riverbed, causing them to shift upstream through time. Depending on the erodibility of the material and the flow regime, they can migrate as fast as meters to tens of meters per year or as slow as a meter in one million years.

2.4.3 Habitat and Ecological Impacts of Human Development

Patterns of vegetation found by European settlers were already impacted to some degree by Native American land management, particularly in the upland areas through intentional burning (H.T. Harvey and Associates *et al.*, 2008). Native American burning was used to clear lands for several reasons, including to stimulate faster growth of food producing trees (e.g., acorns), remove undesirably foliage competing with food-producing foliage, and decrease cover for dangerous large predators.

However, ecological impacts of Native American practices enacted over millennia were small in comparison to the changes that came with European settlement. The European era of land use has drastically altered the vegetation found in the Colusa Basin drainage area over the past 150 years. Dry grain farming and grazing began to supplant native grasslands with European annual grasses in the mid-19th century (DWR, 1964; H.T. Harvey and Associates *et al.*, 2008). Coast range foothill uplands are now dominated by invasive grasses, and woodland areas have been highly reduced.

Valley lands have been mostly converted to rangelands and croplands. Basin lands, once seasonally flooded in the winter by natural processes, are now leveed and intentionally flooded in the summer for rice cultivation. From a certain perspective, Colusa Basin wetlands still exist to some degree, mainly as rice fields and wildlife refuges. Reoperation of rice fields during the winter to provide more services to migratory waterfowl has received a lot of attention in the region over the last 20 years (Salcido, 2012).

3. Scientific Background

This section provides an overview of the study of fluvial sediments with an emphasis on those sediments transported in suspension, which are the focus of this study. Total fluvial sediment is generally subdivided on the basis of whether a given particle is in a state of motion or repose. Fluvial sediments that are not transported over a given period of time are those that were deposited by fluid flow during a previous time period. These sediments are often defined in terms of the geomorphic structures to which they belong, such as channel bed or bank sediments, floodplain sediments, or wetland sediments, etc.

Here we focus on sediments in fluvial sediments in motion. Among sediments in motion, these may be divided on the basis of their mode of transport. Section 3.1 summarizes the characteristics of fluvial sediments including their modes of transport, compositions, the role of sediment surface area in the environment, and eventual fate as sediment deposits. Section 3.2 presents the fundamental approaches employed to monitor, measure and characterize fluvial sediments. Section 3.3 delves into the topic of suspended sediment dynamics, or the patterns of changes in suspended sediment magnitudes over time and the controls of these patterns. Section 3.4 then details how suspended sediment flux is estimated. Electronic copies of much of the literature cited in this section are available in Section 10.1.

3.1 Fluvial Sediments

Fluvial sediments are particles of mineral and organic matter transported by water flowing through channelized systems such as rivers and streams (Sundborg, 1967). These particles can be more specifically defined on the basis of their mode of transport and particle size characteristics (Section 3.1.1), and their composition (Section 3.1.2), which have ramifications on their roles in the environment (Section 3.1.3), and their eventual fate (Section 3.1.4).

3.1.1 Bedload and Suspended Load

Total fluvial sediments in transport over a given period of time or through a given spatial domain are known as the fluvial sediment load (Walling and Fang, 2003). Fluvial sediment load is commonly subdivided on the basis of how the downward motion of the particles due to gravity is counteracted, which is to say, the fluvial mode of transport. There are two general fluvial modes of transport: bedload and suspended load. Bedload sediments are the coarsest (largest diameter) fraction of fluvial sediments, which interact directly with the channel bed, essentially rolling, skipping or impacting the channel surface at the end of discreet arcs of trajectory through the field of fluid flow – all of which can be termed as 'bed supported' or components of bedload transport (Garcia and Parker, 1991). Bedload sediments are usually the minority component of sediment transport -generally thought to account for only 5–20% of the total fluvial sediment load at most river outlets, although very little data supports this claim (Turowski *et al.*, 2010).

Suspended sediments are a finer (smaller particle diameter) and generally more abundant fraction of sediment than bedload. Rather than requiring direct impingement on the channel bed, suspended sediments are supported by the turbulence of the fluid flow itself (Garcia and Parker, 1991). In other words, the downward motions of particles due to gravitational acceleration are in these cases retarded by the turbulent fluctuations of the flow field, which maintain their suspension. As turbulent fluctuations are essentially counteracting the momentum of settling particles, the settling velocity of a given particle is a critical determinant of how much turbulent intensity is required to maintain its suspension. The major factors inherent to the sediment particles themselves that controls the partitioning of fluvial sediments into bedload and suspended load are those that influence the fall velocity of the particles through a given fluid. Terminal settling velocity (ω_s) for an idealized spherical particle through a still fluid is estimated through the following equation:

$$\omega_s = \frac{(\rho_s - \rho_f) g D^2}{18\mu} \quad (1)$$

where ρ_s and ρ_f are the densities of the particle and the fluid, respectively, g is acceleration due to gravity, D is the particle diameter, and μ is the dynamic viscosity of the fluid. From this equation it follows that settling velocity increases with increasing particle density and/or diameter. If we assume that mineral particles generally have similar densities, then the major internal (particle specific) factor in determining the settling velocity of a particle becomes particle size (diameter).

Shear velocity, which is essentially the transfer of momentum between layers of fluid flow and is driven by differences in the velocity of the layers of fluid, is one means of describing the conditions that control turbulent intensity (Vanoni, 1975). Due to the natural state of a near 'no-slip' boundary condition at the interfaces between flowing water and the channel bed and banks, shear velocity increases with depth. As particle diameter increases, higher turbulence intensities/shear velocities are required to maintain suspension. Thus, particle concentrations are expected to increase with depth, and the concentration gradient along the depth axis is more pronounced with greater particle size. This is the case for larger particles where shear stresses in the shallower portion of the flow field are generally insufficient for suspension. Indeed the largest particles in motion (bedload) do not have sufficient turbulent intensities to maintain any suspension, but only enough to move them generally along the bed. However, for a flow field of any given characteristics there is also a particle size threshold where particles of a given diameter or smaller are expected to have a uniformed concentration profile with depth, as shear velocities throughout the depth profile are sufficient to maintain suspension (Rouse, 1937).

Suspended sediments that display invariant concentration profiles with depth are often labeled as 'washload.' Washload sediment is generally considered to be supply rather than transport limited, as its abundance is not related to the flow field, but rather to sediment erosion and delivery mechanisms (Gabet and Dunne, 2003). Washload has been found to account for the majority of suspended sediment in most rivers of a scale large enough to develop floodplains

(Naden, 2010). As suspended sediment is also the major component of total fluvial load, it becomes apparent that most, or at least a very significant proportion, of fluvial sediment flux is controlled by the delivery of sediment to the channel rather than the ability of channelized flow to transport the load. This has important ramifications in the approaches used to investigate the production and transport of suspended sediment at the watershed scale, as it shifts focus from channelized flow characteristics to the mechanism governing the delivery of sediment to the channelized system (see Section 3.3). Note that channel banks can be major proximal sources of washload, especially where lateral migration cuts into floodplains, so washload is not solely an indicator of upland sediment supply.

3.1.2 Suspended Sediment Composition

Suspended sediment can be further subdivided on the basis of particle composition. The primary subdivision is usually between mineral and organic sediments. The mineral component usually makes up the largest proportion of suspended sediment, although proportional contribution between mineral and organic matter can vary widely between rivers and within a given river over space and time (Meybeck, 1982; Hedges *et al.*, 1997). Partitioning of minerals by particle size is commonly observed in suspended sediments and the deposited fluvial, colluvial, and hillslope sediments that ultimately supply the fluvial load (e.g. Blatt, 1967; Nesbitt *et al.*, 1996; Whitmore *et al.*, 2004; Zhou *et al.*, 2015). Larger clasts in the gravel to cobble range (nominally $D \geq 2$mm) are generally pieces of regolith or bedrock from within the watershed, and usually composed of collections of crystals if the source material was igneous or metamorphic, or cemented particles if the source material was sedimentary in origin (Boggs, 1968). Such large clasts are generally transported as bedload in all but the most energetic discharge scenarios (Rouse, 1937). Most suspended sediment in rivers is composed of sand (63 μm $\leq D <$ 2000 μm), silt (4 μm $\leq D <$ 63 μm), and clay ($D <$ 4 μm) particle size fractions (Naden, 2010). Sands and silts are mostly composed of individual mineral crystals or are small clasts of sedimentary rocks composed of even finer grains (Nesbitt and Young, 1996; Whitmore *et al.*, 2004). In the fine silt through clay size fraction most particles are in fact clay minerals, which have mechanically weathered out of sedimentary rocks in the watershed and/or are produced from igneous, metamorphic or sedimentary rocks through chemical weathering processes (Nesbitt *et al.*, 1996).

Organic matter transported in suspension can be further subdivided from several perspectives. A common consideration is the level of susceptibility to microbially mediated oxidation (Hedges and Keil, 1995). Organic materials easily consumed by such processes are considered 'labile', while those that resist consumption are 'refractory.' The labile component of organic material is mostly composed of particles of relatively recently produced plant material, while refractory particles are often sources from sedimentary regolith materials (i.e. 'fossil carbon'), or older plant materials that have had the more labile components consumed during the interval between production and entering the fluvial transport stream (Hedges *et al.*, 1997). Labile carbon particles in suspension and in sediment deposits, such as those in a channel, lake or ocean bed exert direct control on the biological oxygen demand (BOD) for a given body of water, and can lead to the development of anoxic conditions detrimental to aquatic biota (APHA, 1993).

Provenance of organic material is also often of interest. Labile organic materials are produced within the fluvial/lacustrine network itself, including most/all of the algal material found in fluvial sediments and a portion of the load of vascular plant detritus (e.g. Etcheber *et al.*, 2007; Goni *et al.*, 2005). Vascular plant material is also delivered to the channelized network from recent vegetation produced in the watershed, and materials that have been incorporated into soils and eventually eroded. Most recalcitrant material is sourced from bedrock, regolith and soil pools within the watershed (Gomez *et al.*, 2004).

3.1.3 Environmental Implications of Fluvial Sediment Surface Area.

Fluvial suspended sediments are important components of the geophysical and bio-geochemical cycles of coupled terrestrial, freshwater aquatic and coastal marine systems. The flux of most solid material from the terrestrial to oceanic spheres is transported through rivers in suspension (Milliman and Meade, 1983; Milliman and Syvitski, 1992). Total surface area scales with an inverse, geometric relationship to particle size for a given unit of mass and a given particle shape. The finest fraction of fluvial sediments (fine silts and clays), all of which are transported in suspension, generally have flattened or platy shapes, as compared to the more spherical shapes of larger particles. The flattened shapes of clay and fine silt particles further exacerbate their impact on the total fluvial sediment surface area. For these reasons suspended sediments also represent most of the surface area of solid material moving through the freshwater and coastal marine aquatic environments (Naden, 2010).

Suspended sediment surface area has a number of consequences for the aquatic environment, including strong control on the optical properties of water and domination of surface mediated transport (Martin and Meybeck, 1979). Fine suspended sediment absorbs and reflects light, which contributes to turbidity, or the ability of water to attenuate light (APHA, 1992). By reducing the penetration of light into surface waters, turbidity in turn moderates aquatic primary productivity, and contributes to additional effects of on light or vision mediated behaviors of aquatic biota (Mirbagheri and Tanji, 2007; 1981; Bash *et al.*, 2001; MPCA, 2008).

Fine suspended sediments also play a large role in mediating the transport and availability of many substances that are adsorbed to or associated with particle surfaces. Fine sediment particles, particularly those of clay minerals, tend to have negatively charged surfaces which attract positively charged ions (Tisdall and Oades, 1988). Although many chemicals in aquatic systems are transported in solution (i.e. a dissolved state), many others are attracted to the charged surfaces of fine suspended sediments and move through the aquatic environment primarily in association with individual particles and their aggregates. Thus fine suspended sediment dynamics play a large role in the aquatic flux of nutrients, particularly phosphates (Reddy *et al.*, 1999; Bowes and House, 2001; Clarke and Wharton, 2001; House, 2003; Bowes *et al.*, 2005; Warrick *et al.*, 2005), contaminants such as persistent organic pollutants (POPs) (Jones and de Voogt, 1999; Lohman *et al.*, 2007; Zhang *et al.*, 2005), heavy metals (Bryan and Langston, 1992; Macklin *et al.*, 1997; Kronvang *et al.*, 2003; Springborn *et al.*, 2011), and much of the aquatic microbia, including pathogenic bacteria such as *E. coli* (Harmel *et al.*, 2010; Pandey and Soupir, 2013). These compounds and organisms are very important in terms of water quality, the biogeochemical cycling of nutrients and organic matter from terrestrial to freshwater aquatic and coastal marine environments. Turbidity and surface mediated constituents also play a large role in determining the suitability of surface waters for given water quality criteria in terms of ecosystem services and human beneficial uses (US EPA, 2003a).

The high surface area and surface charge of fine sediment particles results not only in the attraction of other compounds and microorganisms, but attraction between mineral particles as well. Much of the fine sediment fraction, particularly clay minerals, are known to be 'cohesive', in the sense that they adhere to one another, generally traveling as aggregates of multiple particles. These aggregates of fine mineral sediments often incorporate organic particles, as well as other surface associated constituents mentioned above. Aggregates develop in soils and can be delivered in aggregated form to the channelized network (Tisdall and Oates, 1989), but fine sediment aggregation and dispersion dynamics are also influenced by the physical and chemical properties of the surface waters through which they are transported (Droppo and Ongley, 1994; Slattery and Burt, 1997; Winterwerp, 2002). Changes in the energetics and dissolved chemical characteristics of surface waters influence the aggregation or dispersion of fine particles by controlling the frequency and energy of particle to particle interactions, as well as the surface charge and abundance and type of surface associated ions (Einstein and Krone, 1962; Mehta *et al.*, 1989). Changes in aggregate size and composition in turn affect settling characteristics of cohesive fine particles (Krone, 1962; Mehta *et al.*, 2014). Aggregates are larger in diameter than their constituent particles, which leads to higher settling velocities despite some offset in this effect due to lower relative densities. After deposition, attraction between cohesive particles also makes them much more difficult to suspend than would be expected from their particle size alone. The stress threshold for initiation of particle motion can increase further with time as compaction and dewatering progress, which can lead to closer association between particles.

3.1.4 Fate of Fluvial Sediments

Although much of suspended sediment is transported by flows that are more than competent to maintain their suspension, portions of the suspended load are deposited within the freshwater aquatic system and onto adjacent terrestrial systems (Owens *et al.*, 1999; Walling *et al.*, 2003). Sediments settle out of suspension and when the hydro-dynamics of flow no longer counteract downward motion due to gravity. This generally results due to changes in the flow field, and in some instances due to changes in particle characteristics, such as through increased aggregate size. Changes in the flow field in the channelized system itself can lead to deposition of suspended sediments on channel banks, fringing wetlands, and the channel bed (e.g. Smith and Griffin, 1997). As water stage recedes toward the end of a given rainfall runoff event or cluster of events suspended sediments may be deposited during the falling limb of the hydrograph as flow depths and velocities decrease (Walling *et al.*, 2000). Transfer of channelized flow into hyporheic flow, or the movement of waters through the channel bed, can also result in the deposition of formerly suspended sediments in coarser bed sediment matrix (Owens *et al.*, 1999; Boulton, 2007). Vegetation on channel banks and margins can also increase suspended sediment trapping due to increases in roughness, slowing down flows (Arcement and Schneider, 1989).

Overbank flooding, whereby the magnitude of flow exceeds the capacity of the channel and inundates channel adjacent lands such as wetlands and floodplains, generally results in deposition of suspended sediments. Flow depth and shear stresses generally decrease rapidly away from the channel, resulting in the deposition of coarser sediments closer to the channel and finer sediments further from the channel (Asselman and Middelkoop, 1995). A similar process occur when river levees (natural or otherwise) are breached, creating 'crevasse splay deposits', with coarser material (including in some cases bedload) deposited near the levee breach or 'crevasse' and finer sediments deposited further away as the escaping flow spreads out, becomes shallower and slows (Makaske, 2001). Similarly, channelized flow entering standing water such as lakes or reservoirs also experiences changes in flow characteristics, which generally lead to the deposition of coarser material near the river entrance, with finer materials settling out into in the less hydro-dynamically active portions of the water body, or transported downstream (Blum and Tornqvist, 2000).

Alluvium, or deposited fluvial sediment, is a critical component of aquatic and terrestrial environments with far reaching effects for the global biosphere. Much of the most productive soils in the world have developed from alluvium deposited in wetlands and floodplains (Troeh, 2005; Buol *et al.*, 2011). Indeed, the maintenance of wetland elevations in most freshwater, estuarine and coastal settings is highly dependent on fluvial fine sediment fluxes (Krone, 1962; Syvitski, 2008). Fluvial sediments also provide key nutrients, substrate and sediment sources to coastal and benthic communities (Kaul and Froelich, 1984; Hedges, 1992; Lebo and Sharp, 1992; Kamer *et al.*, 2004). Fluvial sands are also required to maintain coastal beaches (Slagel and Griggs, 2008). However, the deposition of fluvial suspended sediment can also adversely impact ecosystems and aquatic biota through the release of surface mediated constituents that have harmful water quality effects such as the methylation of elemental mercury in wetland sediment deposits (Bryan and Langston, 1992; Boening, 2000; Marvin-DiPasquale *et al.*, 2014) or excess nutrients leading to eutrophication (Horwath *et al.*, 1996; Correll, 1998; Cloern, 2001).

3.2 Monitoring, Measuring and Characterizing Suspended Sediment

Monitoring of suspended sediment generally begins with the estimation of suspended sediment concentration (C_{SS}) for a given location or station in a given surface water body at a given time. Estimating C_{SS} without paired measurement of water Q is 'ambient monitoring', whereas the addition of Q measurements allows for further inquiry into suspended sediment dynamics, suspended sediment flux, and estimation of the processes controlling sediment production and transport (Edwards and Glysson, 1999). Suspended sediment concentration measurement can occur through direct means, which involves the collection and analysis of surface water samples, or by indirectly measuring a proxy for C_{SS}. Water samples collected for direct monitoring of C_{SS} are subsequently processed to determine the mass of sediment relative to water volume. The most widely used proxy for C_{SS} is turbidity, a measure of water's ability to attenuate light penetration (Rasmussen *et al.*, 2009). Many different measurement methods and units have been developed to describe turbidity, but here only the most recent will be discussed. Four turbidity measurement units were encountered as sample data for this project: (i) Turbidity as SiO_2 (mg/L), (ii) Formazine Turbidity Units (FTU), (iii) Nephalometric Turbidity Units (NTU), and (iv) Jackson Turbidity Units (JTU). Of these three NTU and JTU are generally equivalent (Anderson, 2005). Turbidity as SiO_2 is no longer generally measured, and is not easily translated other systems of turbidity measurement (USGS, 1965, p. 289-290).

Collecting a representative sample or proxy measurement of the sediment that is passing a given station on a river or stream is not a trivial undertaking. For an overview of USGS protocols for field collection of suspended sediment samples from surface waters see Edwards and Glysson (1999). As discussed in Section 3.1, C_{SS} for coarser particles in suspension will vary with the energetics of the flow field. The cross section of channelized flow from bank to bank (normal to the net direction of flow) at a given station on a river contains spatial variations in turbulence and shear velocity, which result in spatial variations in the C_{SS} of coarser particles. This variation in C_{SS} with position in the flow field complicates attempts to obtain a representative suspended sediment sample from a given Q at a given station.

Attempts to monitor suspended sediment at a given station generally fall into two categories: those that explicitly account for variations in C_{SS} within the cross section of flow, and those that ignore it. The most common method used to account for variation in C_{SS} through the flow field is 'flow integrated sampling', a technique commonly employed by the most prolific suspended sediment monitoring agency in the US – the USGS (Edwards and Glysson, 1999). Flow integrated samples are collected continuously through depth, usually at multiple points along a transect normal to mean flow direction. Potential drawbacks of this comprehensive sampling scheme include the need for costly specialized equipment, and complex time-consuming sampling operations which generally produce a large sample that requires longer processing time in the laboratory. It is also impossible to know if the amount of time spent sampling each depth is kept equal and velocity differences with depth mean that the amount of flow sampled at each depth is unequal even if sampling time is somehow kept constant. Characterization of a given Q using this approach may also not be possible if the amount of time required to obtain a spatially representative sample is long relative to the time scale of hydrologic change. This problem can be particularly acute in small, flashy systems.

In contrast, the simplest approach for obtaining C_{SS} is the 'grab sample', where a single sample is collected from the flow field, generally at or just beneath the water surface at some point along the transect normal to mean flow. A grab sample can generally be considered representative only of the range of particle sizes that are expected to express uniform concentration across the entire flow field. If general information regarding the hydrodynamics of the range of flows likely to be sampled at a given station is known, simple calculations can provide an estimation of the maximum particle size expected to express a uniform concentration under the least energetic flow conditions (Rouse, 1937).

Similarly, in situ sampling apparatuses are also usually installed to collect suspended sediment from a given point in the flow field. In situ sampling approaches generally employ an automated sampler with either multiple chambers installed in the channel, or a pumping apparatus that draws sample water from a hose inserted in the flow field, such as ISCO samplers (Teledyne ISCO Inc., 2007). In some cases simple containers designed to passively fill with sample water just beneath the water surface on the rising limb of the hydrograph (aka single-stage samplers) are deployed (USGS, 1961). Such passive fill bottles are designed not to exchange water and sediment after their initial filling, and several bottles can be deployed at successive elevations in order to capture samples at different stages of the rising limb of the hydrograph.

Turbidity measurements can be performed on water samples using laboratory instrumentation or in the field using optical sensors (i.e. turbidity meters) that can be lowered into the monitored water body, or even installed for continuous monitoring (Rasmussen *et al.*, 2009). Fixed turbidity meters provide the opportunity of collecting higher temporal resolution data over longer periods of time than would generally be practical for an in situ auto collector of water samples, which are limited by sample collection space. This has value, because turbidity fluctuates rapidly over a wide range, warranting more frequent sampling than the 15 minutes commonly used for stage measurement and discharge gaging. The same issues related to spatial variation in suspended sediment concentration through the flow field apply to the point collection of turbidity measurements, illustrating that there is a trade-off between resolving temporal variation and spatial variation- no approach does both.

Characterization of suspended sediment concentration using turbidity is further complicated by the need to transform turbidity measurements into units of C_{SS} (i.e. mg/L sediment). Although C_{SS} is usually a dominant control on turbidity, other factors also contribute to turbidity values, particularly the amount and type of dissolved organic compounds present (Rasmussen *et al.*, 2009). The composition of the suspended load in terms of mineral/organic content, particle size, mineralogy and organic character also play large roles in determining turbidity. For this reason, turbidity-C_{SS} relationships are usually developed on a site specific basis, which may require further refinements if suspended sediment composition effects are significant. Thus, even monitoring regimes that rely extensively on turbidity measurements require collection of suspended sediment samples to develop turbidity-C_{SS} rating/calibration curves.

Actual samples are also required for most sediment composition characterization, with the exception of relatively rare in situ measurement devices, such as flow through particle size distribution systems (Francis *et al.*, 2006). Laboratory analyses can be performed for any of the sediment characteristics mentioned above (see Section 3.1.2) such as mineral particle size distribution (Walling and Morehead, 1987; 1989), mineralogy (Griggs and Hein, 1980), organic content (Tanji *et al.*, 1978), many forms of organic material characterization (e.g. Gomez *et al.*, 2004; Goñi *et al.*, 2005 Leithold *et al.*, 2006) and analyses of trace and bulk geochemistry (Ingraham and Lin, 2002), as well as the characterization of the types and amounts of surface associated materials (Weston *et al.*, 2004). Each approach to characterizing suspended sediment requires additional sample material, which places increased demands on sample number and/or sample size for a given station and Q. Further details on the many different sediment characterization analyses are not provided here, but are prevalent in the literature.

3.3 Suspended Sediment Dynamics

Changes in watershed-scale suspended sediment concentration and flux over time is an integrated expression of the internal and external factors controlling the delivery of water and sediment to a given water body (Walling and Fang, 2003). Internal factors are aspects of the watershed itself, including topography, substrate (geology and soils), channel dynamics, and vegetation. External factors are those that arise from outside of the watershed and exert influence often though fluxes of mass and energy, such as climate/weather delivered moisture and wind, earthquakes, and electromagnetic radiation from the sun. Internal and external factors interact with and influence one another, with external factors such as climate playing a large role in mediating internal factors such as vegetation. Changes in internal and external factors over time lead to changes in the biological and geophysical expression of the watershed, including the delivery of water and sediment to the channel, and the conveyance of both, which in turn controls the concentration and flux of suspended sediments at the watershed scale.

From the previous exposition it becomes clear that watershed-scale suspended sediment dynamics, much like any watershed-scale expression, are integrated expressions of multiple factors. Data-driven, watershed-scale hydrologic analysis must then be a forensic process of inquiry, whereby all of the major factors controlling a given expression are at least considered, if not explicitly tested, to decipher the driving forces behind changes in watershed expression over time (Gray *et al.*, 2014). As mentioned in Section 3.2, the most basic approach to examining suspended sediment is to measure C_{SS}. However, as C_{SS} has been found to highly correlate with the Q of channelized flow, and as Q is perhaps the most common metric obtained when examining stream function, the next step in suspended sediment analysis is to examine the C_{SS}-Q relationship. This analysis involves plotting C_{SS} and instantaneous Q at the time and location of sample measurement/collection in bivariate space as dependent and independent variables, respectively (Helsel and Hirsch, 2002). The dependent relationship of C_{SS} on Q is then described through either a parametric empirical model, most often a log-linear (i.e. power law) relationship, although many other linear to polynomial equations have been utilized, as have non-parametric methods, such as the localized regression technique LOESS (Horowitz, 2003).

Recall that washload abundance (the majority of suspended sediment in many cases) is primarily a supply- rather transport-limited phenomenon, which suggests that the practice of estimating C_{SS} through Q would be rather unsuccessful. However, C_{SS} is measured as the solid mass of suspended sediment per unit volume of the water-sediment mixture, and as such is inherently dependent upon water supply to the channel from the simple perspective of concentration or dilution. Moreover, the internal and external factors that collude to produce runoff in a watershed also control the generation of both the water and sediments present in channelized flow (Walling, 1983). Part of the suspended sediment load is detached from soil surfaces through the delivery of precipitation itself by direct impingement of rainfall, particularly on bare ground (Harisine and Rose, 1991; Gabet and Dunne, 2003). The generation of runoff and its conveyance to the channel through sheet wash (shallow overland flow), rill and gully transport, etc. also entrain sediment particles (Tucker and Bras, 1998; Valentin *et al.*, 2005). Secondary control of Q on C_{SS} arises from the entrainment of deposited sediments in channel beds (particularly those at the coarser end of the suspended particle size range for a given flow) and the erosive action of channelized flow on channel banks (Collins *et al.*, 1998; Walling *et al.*, 1998), which can liberate large quantities of mud and sand. Thus, the exercise of producing a C_{SS}-Q rating curve is primarily the use of Q as a proxy to describe the integrated signal of shared basin scale forcing factors that ultimately control much of the delivery of sediment to the channelized system (Gray *et al.*, 2014).

There often remains a large amount of variance in observed C_{SS} values around a C_{SS}-Q rating curve fitted for a given station on a given river (Walling, 1977). Increased standard errors and lower coefficients of determination are generally associated with larger disparities between the processes controlling the delivery of sediment and water to the channel, as well as changes in these processes over the period of observation and shorter time scales (Asselman, 2000). Watersheds that are very episodic in terms of precipitation, runoff and sediment fluxes often produce C_{SS}-Q relationships with high residual variance (Sadeghi *et al.*, 2008). Such systems, particularly small, mountainous watersheds with a highly variable precipitation and temperature regimes highlight the importance of antecedent conditions (Gray *et al.*, 2014). Short and long term effects of highly variable external factors lead to a wider range of internal watershed conditions, which then interact with precipitation events to produce highly variable runoff and sediment supply responses.

The residual variability in C_{SS} not explained by its relationship with Q provides the basis for further inquiry into changes in the controls of sediment and water production and transport over time (Warrick and Rubin, 2007). Computation of C_{SS}-Q residuals simply involves the subtraction of C_{SS} values predicted by the rating curve from the observed values (Helsel and Hirsch, 2002). These residual values can then be examined for patterns in their fluctuations at different time scales. For example, a suspended sediment record can be examined for monotonic increases or decreases in C_{SS} independent of instantaneous discharge fluctuations, which can be conceptualized as departures from the normal sediment and water supply regime (Warrick and Rubin, 2007; Warrick *et al.*, 2013). Furthermore, C_{SS}-Q residuals can also be tested for correlation with the state of other factors in the watershed that may exert control on suspended sediment production over time, including episodic and legacy disturbances such as wildfire and earthquakes, changes in vegetation, climatic cycles and climate change, and changes in human land use operations such as agriculture, forestry, urbanization and hydrologic modifications (Gray *et al.*, 2014; 2015a).

It should be noted that examination of C_{SS}-Q residuals is an analytical approach to investigating net change in the production of sediment and water supply to the channel and the routing of these constituents through the channelized system. Indeed, if sediment and water supply characteristics change in magnitude and direction (decreasing or increasing) the net effect on the C_{SS}-Q relationship can be null (Warrick, 2015). For this reason, independent analysis of changes in the relationship between precipitation and Q generation should also be examined over time to investigate the role of hydrologic changes on C_{SS} dynamics. For example, large increases in impervious land surface area due to widespread urbanization have been found to increase the proportion of effective precipitation that becomes runoff (Warrick and Rubin, 2007). After the initial wave of sediment generation through construction processes, these urban surfaces often generate less erosion (Wolman, 1967). Therefore the net effect of urbanized land surface area increase can be a dilution of the existing sediment supply, which may be compounded by decreases in sediment supply as well.

As sediment supply and its relationship to water supply exert the dominant control of C_{SS} dynamics, the relative sources of suspended sediments are a topic of great interest. Many analytical approaches have been employed to encounter the origins of suspended sediment at the watershed scale, including subbasin monitoring (Tanji *et al.*, 1978), and natural and artificial tracer studies (Richie and McHenry, 1990; Sommerfield *et al.*, 1999). This problem can also be approached through simulation models, whereby the interaction of internal and external factors that affect water and sediment generation and their interactions are described and related through mathematical functions to generate predictions of sediment and water flux (e.g. Jones *et al.*, 2001, Zhu *et al.*, 2007). Both analytical and simulation modeling approaches generally suffer from a lack of data, both for more detailed analytical inquiry, and for proper validation and calibration of the hydrologic model. However, technological advances in the use of natural tracers, including stable isotope and cosmogenic radio-nuclides have led to recent advances in sediment provenance analysis, while increases in computing power and the sophistication of distributed watershed scale models continue to advance the ability of modeling to incorporate sediment dynamics.

3.4 Estimating Suspended Sediment Flux (Q_{SS})

Estimation of suspended sediment flux (Q_{SS}) is central to the study of fluvial sediments and their role in the environment. Sediments in suspension play a large role in the biological and geophysical processes operating in terrestrial, aquatic and coastal ecosystems, and represent the majority of solid material flux from the terrestrial to oceanic spheres (see Section 3.1). Monitoring ambient C_{SS} is useful for initial water quality characterization, which can be used to evaluate suspended sediment impacts on aquatic ecosystems and the beneficial uses of surface waters (see Section 5). Investigation of suspended sediment dynamics through the consideration of C_{SS} in terms of time, Q, and the temporal patterns of internal and external forcing factors can provide valuable insights into the processes controlling suspended sediment production (see Section 3.3). Understanding controls on suspended sediment dynamics can then be leveraged to better characterize the environmental impacts of fluvial sediments and develop plans for sediment impact abatement. The association of C_{SS} and Q data from a given station on a river or stream also allows for the estimation of Q_{SS}. Characterizing the geographic and temporal distribution of fluvial sediment fluxes is perhaps the most comprehensive approach to determining the processes controlling sediment production and transport. Estimation of sediment flux from a given subbasin also provides the basis for estimating the mass flux of sediment associated fluvial constituents, including pollutants, and characterizing their impacts on receiving water bodies downstream.

Approaches to estimating suspended sediment flux mirror the scale of complexity incorporated into analyses of suspended sediment dynamics. The simplest analytical method for estimating suspended sediment flux is to monitor both C_{SS} and Q, which are then multiplied to obtain Q_{SS}. The most accurate method of monitoring Q_{SS} would be one where measurements are distributed through the channel cross section (see Section 3.1), with C_{SS} and Q measurement frequencies equal to or higher than the temporal scale change for either parameter. The term for this is 'near-census' suspended sediment sampling, which is a very intensive approach, but still leaves some amount of meaningful variation unsampled. As the USGS monitors stage and estimates Q on a 15-minute interval at stream gauge stations throughout the US – this establishes what would typically constitute 'high-resolution' sampling, even though turbidity usually fluctuates more frequently than that interval. Fifteen-minute suspended sediment monitoring is also possible, but also usually relies on turbidity meters, which are used to estimate C_{SS} through a C_{SS}-turbidity rating relationship (see Section 3.2), and generally not employed with explicit acknowledgment of C_{SS} depth stratification.

In many early studies C_{SS} was measured, or averaged from a set of measurements collected over a period of time, and then multiplied by the entire volume of water discharged over that time period, despite variation in Q and C_{SS}. There are many drawbacks to this approach. Employing a convolution of averaged C_{SS} and summed Q values requires either invariance in Q over time, or the assumption that the relationship between C_{SS} and Q is linear. Widespread analyses of suspended sediment dynamics have generally found that the C_{SS}-Q relationship is not linear in most rivers and streams (Walling, 1977), which renders the approach of applying averaged parameters applied over longer time scales relative to the scale of parameter change as fundamentally flawed. Furthermore, even in the rare cases where the C_{SS}-Q relationship is found to be linear, in a scenario of variable Q over the summation period, the distribution of samples would have to be equally representative across the Q domain. For these reasons, lumped estimates of Q_{SS} on the basis of averaged C_{SS} and summed Q_{SS} over long periods relative to the variability of these two parameters is no longer generally practiced in the field of hydrology.

More common is the use of a smaller pool of C_{SS} measurements to develop empirical models of the C_{SS}-Q relationship (see Section 3.3), which are then applied to a Q time series to compute suspended sediment flux. The simplest empirical models are those that fit a single rating curve to an entire {Q, C_{SS}} data set using a single mathematical formula, such as a log-linear/power law, or a polynomial equation (Cohen *et al.*, 1989). Rating-curve-based estimates of suspended sediment load must modify rating curve estimations of C_{SS} to account for systematic biases through bias correction factors (BCF), which are then multiplied by water yield values of a resolution determined by that of the Q time series. For the common scenario of instantaneous Q data used to construct a log-linear C_{SS}-Q rating curve, and daily Q (Q_d) data used for load estimation, Q_{SS} is estimated as per Warrick and Mertes (2009):

$$C_{SS} = BCF_d \cdot BCF_l \cdot C_{SS\ rating\ curve(Q)} \tag{3.4.1}$$

$$Q_{SS} = Q_d \cdot C_{SS} \tag{3.4.2}$$

where BCF_d corrects for bias introduced by using daily rather than instantaneous Q, BCF_l corrects for the logarithmic transformation consequence of calculating regression parameters using geometric rather than arithmetic mean, and $C_{SS\ rating\ curve(Q)}$ is the suspended sediment concentration value estimated from the rating curve applied to the discharge record.

The parameter BCF_d can be estimated by comparing sediment loads estimated from Q_d values to sediment loads estimated with higher resolution data, if available (Warrick and Mertes, 2009). The calculation of BCF_l can be use the parametric methods of Ferguson (1986), or the nonparametric 'smearing' method of Duan (1983). The Ferguson correction for log-transform bias (BCF_{lf}) is calculated as:

$$BCF_{lf} = 10^{\frac{s^2}{2}} \tag{3.4.3}$$

where s^2 is the mean squared error of the residuals. Use of BCF_{lf} is contingent upon the assumption of normality in the distribution of rating curve residuals. However, if the distributions of residuals for the given rating curves are found to differ significantly from normal, then a nonparametric log-correction factor should be investigated (Cohn *et al.*, 1989; Hicks *et al.*, 2000). Testing for normality can be pursued through the Shapiro-Wilk test, where the null hypothesis is that a distribution is normal, and *p*-values below 0.05 are considered to indicate significant departures from normal (Helsel and Hirsch, 2002). The Duan smearing correction factor (BCF_{ld}) does not require residual distribution normality as is calculated as:

$$BCF_{ld} = \frac{\sum_{i=1}^{n} 10^{e_i}}{n} \tag{3.4.4}$$

where e_i is each residual value generated by subtracting the log of the observed C_{SS} values from the log of the $C_{SS\ rating\ curve(Q)}$ estimates and n is the number of samples (Rasmussen *et al.*, 2009). The suitability of these factors in correcting log transformation bias can be further examined by computing the arithmetic mean C_{SS} for each sample set using uncorrected rating curve estimations of C_{SS}, and those corrected by either BCF_{lf}, BCF_{ld} or the arithmetic mean of the two ($BCF_{l(f+d)/2}$), and then comparing these values to the observed sample arithmetic mean C_{SS} (Gray *et al.*, 2015b). The BCF (or lack thereof) that resulted in a mean C_{SS} closest to the observed may then be chosen for inclusion in the estimation of Q_{SS}.

One must also bear in mind that as the calculation of any BCF_l is based on the variance of residuals about the rating curve, it should only be applied uniformly across the entire Q domain under conditions of homoscedasticity. Thus, residuals for all rating curves should be tested for homoscedasticity before BCF_l application. This can be done using the nonparametric Filgner-Killeen test of homogeneity of variances (Helsel and Hirsch, 2002). If the rating curves are found to be heteroscedastic, then efforts should be taken to apply localized BCF_l's, or another method should be used to fit the rating curves in the first place, such as LOESS (Warrick and Mertes, 2009).

Five principle assumptions are implied with the use of parametric C_{SS}-Q rating curves: (i) that the modeled bivariate relationship fits sampled relationship, (ii) normality, (iii) homoscedasticity, (iv) no autocorrelation, and (v) stationarity (Helsel and Hirsch, 2002). Although these assumptions are fundamental to statistical regression, they bear repeating here as they are commonly ignored in practice, with the result of poorly chosen models and misrepresentation of model error. Most importantly, the relationship between the dependent and independent variables (in this case C_{SS} and Q, respectively) of the sample data must follow that of the parametric formula over the independent variable (Q)

domain. If this is not the case, non-parametric methods are available, such as localized regression techniques including LOESS, which do not impose a single formula but curves on a localized or weighted proximity basis. When parametric rating curves are fit to data that do not display the modeled relationship, it commonly leads to the violation of the following two assumptions: that sample C_{SS} values must be normally distribute around the fitted curve with residual variance that does not systematically fluctuate with Q (i.e. homoscedasticity). Often both Q and C_{SS} must be log-transformed in order to achieve normality, which has further ramifications for Q_{SS} estimation that were detailed above. No autocorrelation (aka serial correlation) should be present in the C_{SS} and Q data sets, which by extension implies that the relationship between C_{SS} and Q should be stationary (i.e. time independent) within the period of sampled data.

Application of a single rating curve to a Q record outside of the base period of suspended sediment sampling to estimate Q_{SS} also carries the assumption that the C_{SS}-Q relationship is stationary (i.e. remains the same) over the non-sampled period (Gray *et al.*, 2014). However, it is readily apparent that Q in a stream at any given time is always dependent to some degree on previous Q states and transient depletions of upstream sediment sources. The amount of water flowing through a channel rises and falls over time periods that are determined in part by the lasting effects of internal and external drivers of surface water flow. Similarly, C_{SS} also displays serial correlation patterns, with C_{SS} at a given time often closely related to previous values at event (storm-discharge) and even seasonal time scales. This can be driven by the sudden unlocking of a new sediment source, which eventually depletes (e.g., bank collapse, stripping of riverbed armor layer, or upland mass movement). Annual to interdecadal trends or patterns can also be present in C_{SS} and Q values, particularly with long term changes in internal and external factors influencing sediment and water delivery to, and routing through, the channelized system (e.g. Hestir *et al.*, 2013; Warrick *et al.*, 2013; Gray *et al.*, 2015a).

The issues of autocorrelation and non-stationarity in C_{SS} and Q are tacitly ignored when using a single rating curve, but the explicit incorporation of such dynamics is a step toward more thorough methods of estimating Q_{SS}. For example, suspended sediment hysteresis (i.e., path dependence) is an event scale non-stationary behavior that manifests as different C_{SS}-Q relationships on the rising vs. falling limb of the hydrograph (Hudson, 2003). Consistent hysteretic behavior results in higher variance about a single C_{SS}-Q rating curve fitted to both rising and falling limb sample data.

More complex empirical models include factors that influence C_{SS} beyond instantaneous Q, such as the aforementioned hysteretic behavior, as well as antecedent watershed conditions, seasonality, and time (e.g. Warrick and Mertes, 2009; Gray *et al.*, 2015b). Such additional components can be applied to the estimation of suspended sediment flux through a variety of techniques including multiple regression rating curves and stratified or nested simple regression rating curves. The multiple regression approach uses Q in concert with additional independent variables to estimate C_{SS} values. Multiple regression rating curves require the same assumptions as simple C_{SS}-Q rating curves, with the additional assumption that there is little or no collinearity between independent variables. Stratified simple regression approaches utilize different C_{SS}-Q rating curves depending on the value or state of a given factor or time period (Gray *et al.*, 2015b). For example, if consistent event scale suspended sediment hysteresis is found, two separate rating curves may be employed: one for discharges on the rising limb of the hydrograph, and another for falling limb discharges. Similarly, nested rating curve approaches employ multiple decision tree structures that use the state or value of multiple factors to arrive at a given C_{SS}-Q rating curve (Syvitski *et al.*, 2000).

The purpose of going beyond single C_{SS}-Q rating curves is to produce better estimates of Q_{SS}, whether the proximal motivation is to increase the amount of observed variability that is accounted for by the model or to merely construct a model were the basic assumptions inherent to statistical regression are met. However, the price for increased model complexity is two-fold: (i) increased data demands and (ii) the potential for increased error estimates, which will be discussed at the end of this section. Higher resolution and longer sampling periods are required to elucidate C_{SS}-Q dynamics to inform more complex empirical models for Q_{SS} estimation. Returning to the hysteresis example, if C_{SS} has been measured 20 times at a station on a river over the course of a year, a single rating curve approach will have 20 points with which to fit the regression. However, if about half of the samples were collected on the rising and half on the falling limb of various hydrographs, and one chose to use a stratified rating curve approach, there would only be 10 points for each stratified (i.e. rising and falling) rating curve. The lower number of samples per stratified curve may preclude the ability to determine if suspended sediment hysteresis occurs through statistical techniques such as analysis of covariance (ANCOVA). The ability to determine if a given dynamic is at play is more difficult in systems with high variance in C_{SS} around a simple C_{SS}-Q rating curve, which is typical of rivers draining smaller, steeper and more arid watersheds (Gray *et al.*, 2014). Anthropogenic disturbances can also increase C_{SS} variance (Warrick and Rubin, 2007). Although multiple regression techniques do not result in multiple rating curves fitted to lower populations of data, this technique does require data for each of the additional variables.

Error estimation is often ignored when computing environmental fluxes, and fluvial sediments are no exception. In the modern age of estimating Q_{SS}, attempting to calculate honest and thorough estimates of error is essential to subsequent considerations and analyses that may rely on interpreting these numbers. Sediment load uncertainty is estimated on the basis of measurement errors, rating curve uncertainty, and additional uncertainty associated with extrapolation beyond rating curve Q domains (Helsel and Hirsch, 2002; Harmel *et al.*, 2006; Farnsworth and Warick, 2007). The original C_{SS} and Q measurements used to construct a rating curve have associated error, which is often approximated as a total of approximately 10% (Guy and Norman, 1970; Wass and Leeks, 1999; Yu, 2000; Farnsworth and Warrick, 2007). Rating curve uncertainty for log-linear and multiple linear regressions can be calculated as per Helsel and Hirsch (2002). Error associated with LOESS rating curve uncertainties are generally calculated using the standard error of estimate for discreet Q domains due to the localized regression techniques associated with this method (Farnsworth and Warrick, 2007; Gray *et al.*, 2015b). The application of any rating curve to estimate C_{SS} beyond sampled Q domain incurs additional error as per Helsel and Hirsch (2002). To arrive at total error for a given Q_{SS} estimate, error terms should be propagated through each component of the load estimation formula to arrive at a 1 or 2 sigma error interval.

Moving from single bivariate rating curves to both multiple regression and stratified rating curve techniques has implications for error estimation. Although rating curve uncertainty is generally lowered by these techniques, additional error penalties may outstrip these gains (Gray *et al.*, 2015b). For example, uncertainty can be introduced by additional variables in multiple regression. Stratified rating curves may reduce the Q domain of each individual curve and entail additional error. However, it should be noted that more complex rating curve approaches are often employed to remedy the fact that a single rating curve approach would violate fundamental assumptions such as no autocorrelation and stationarity. As traditional methods of error estimation are predicated on these assumptions having been met, methods that entail their violation produce error estimates that are artificially low. The way forward for reduced Q_{SS} error is to employ estimation approaches that explicitly acknowledge the complexity of sediment production dynamics and the presence of autocorrelation/non-stationarity in C_{SS}-Q relationships, on the basis of data obtained from intensive monitoring over longer periods of time (Downing-Kunz and Schoellhamer, 2013).

4. Suspended Sediment Production in the Colusa Basin Watershed

This section provides an overview of issues related to fluvial sediment production in the Colusa Basin Watershed. Section 4.1 serves as a summary of all previous studies on this topic. The authors and CVRWQCB personnel visited sites within the study region that corresponded to important sampling and observational locations from previous studies along the CBD and tributaries, which is reported in Section 4.2. Suspended sediment data was extracted from these previous studies and analyzed to produce new assessments of ambient C_{SS} and turbidity conditions (Section 4.3.1) and suspended sediment dynamics, particularly in terms of changes C_{SS}-Q relationships over time (Section 4.3.2). Most of the publications associated with these previous studies are available in electronic format in Section 10.1.

4.1 Summary of Findings from Previous Studies

The CBD has been identified as the largest point source of sediment and agricultural waters discharged to the Sacramento River during the latter half of the 20th century (DWR, 1964; Tanji *et al.*, 1978). This observation serves as the primary motivation for the present and previous studies of Colusa Basin sediments by state and federal agencies concerned with water quality, namely the California Department of Water Resources (DWR), the Central Valley Regional Water Quality Control Board (CVRWQCB), the US Bureau of Reclamation (USBR), and the US Environmental Protection Agency (US EPA) (Table 4.1.1). These studies approached the issue of Colusa Basin watershed sediment production through evaluation of ambient suspended sediment characteristics, (USBR, 1973a; 1973b; 1973c; 1974; CVRWQCB, 2011), analysis of suspended sediment dynamics and flux at the field to watershed scale (Low *et al.*, 1974; Tanji *et al.*, 1976; 1980a; 1981a; 1981b; Tanji, 1981; Springborn *et al.*, 2011; Linquist, 2014), watershed scale geomorphic surveys (H.T. Harvey and Associates, 2008; Geomorph *et al.*, 2010), watershed scale erosion and sediment transport modeling (Gatzke, 2010), or through a comprehensive combination of all of these approaches, in addition to 1-D sediment transport modeling in the CBD (Tanji *et al.*, 1978; 1980b; 1981c; 1983; Mirbagheri, 1981; 1988a,b).

The earliest and latest work in the Colusa Basin focused on ambient fluvial sediment characterization (Section 4.1.1). These programs of data collection and analysis amassed sediment concentration and turbidity data, with or without attendant Q data, including the initiation of some interdecadal monitoring by DWR (Section 4.1.1.1). An early turbidity characterization indicated that CBD suspended sediments were probably not a problem for the environmental health of the Sacramento River, but could pose threats to fishes within the Colusa Basin drainage area (Table 4.1.1; Section 4.1.1.2; USBR, 1974). The analytical methods of this work call into question the utility of simple ambient techniques that sampled infrequently over a short period of time.

The CVRWQCB are also generating ambient sediment data through monitoring programs under the Irrigated Lands Regulatory Program (ILRP) and Surface Water Ambient Monitoring Program (SWAMP) (Table 4.1.1; Section 4.1.1.3). The ILRP is a SWB program for regulation of irrigated agricultural return flows in California, with provisions for monitoring and environmental impact assessment (SWB, 2004). The SWAMP is a broader SWB program for the monitoring of water quality parameters and associated biotic and geomorphic data in the surface water bodies of California. The utility of these data for process elucidation is often limited due to the lack of associated Q data, and the lack of C_{SS} data to calibrate turbidity data sets; however they do provide a valuable extension of the fluvial sediment data set for the region (see Section 4.3). These programs have also generated data on sediment-mediated pollutants that are valuable for sediment impact assessment (see Section 6).

Several studies conducted in the Colusa Basin watershed over the last 50+ years have produced important insights into the processes of sediment erosion, transport and deposition in the watershed. Studies incorporating suspended sediment flux analysis have found the bi-modal nature of CBD hydrology (i.e., differences in irrigation season and non-irrigation season hydrology) extends to the seasonal dynamics of sediment flux from the basin, with differential sediment loading and C_{SS}-Q relationship characteristics expressed in the CBD during the non-irrigation and irrigation seasons (Table 4.1.1; Section 4.1.2 and 4.1.4). This results in average sediment flux through the CBD that is larger during the non-irrigation season than during the irrigation season.

Non-irrigation season sediment supply and transport dynamics are driven by the runoff of storm waters. Higher rainfall rates and higher relief were found to result in higher hillslope sediment yield from the foothills than basin and valley lands during the non-irrigation season (Table 4.1.1; Section 4.1.4). However, fallow agricultural fields for row and field crops produced much more sediment during the non-irrigation season than would be expected if natural land cover was in place (Section 4.1.4). Increases in storm driven sediment production was probably due to lower infiltration rates and lack of vegetation on fallow fields leading to increases in sheet and runnel flow, which cause increases in sediment detachment and transport, and erosion/resuspension of sediments in drainage channels (Section 4.1.2.2 and 4.1.4).

Irrigation season sediment dynamics are controlled by the interaction of irrigation waters with cultivated land surfaces, and the delivery of these waters to drainage systems, where erosion, deposition and resuspension also play important roles. Irrigation waters are almost exclusively applied to valley and basin lands, with the majority used by very low gradient rice ponds that generally serve as a sink for supply water sediments (Sections 4.1.2.2, 4.1.2.4, and 4.1.4). Sediment produced during the irrigation season mostly resulted from erosion of furrow and boarder irrigation surfaces, particularly from steeper sloped furrows, and the drainage canal infrastructure (Sections 4.1.2.2 and 4.1.4). The importance of agricultural practices on managing sediment production has also been highlighted by watershed-scale sediment erosion and transport modeling (Section 4.1.5).

Deposition and resuspension of sediment in tributary channels, agricultural drains, and the lower CBD also appeared to play a significant role in the watershed-scale suspended sediment dynamics of the Colusa Basin over event to interannual time scales (Sections 4.1.2.2 and 4.1.4). Flashy storm and irrigation drainage driven flows in tributary channels can result in the deposition of suspended sediment in the channel on the falling limb of tributary hydrographs. Changes in the transport characteristics in drainage canals can also lead to sediments falling out of suspension and deposited in the channel of both smaller drains and the CBD. Furthermore, peak sediment loads develop during intense and/or prolonged non-irrigation season storm events, which generally coincide with higher stages in the Sacramento River. Operation of the CBD outfall gates to prevent the incursion of Sacramento River waters into the CBD results in a backwater effect that slows flow velocities and further favors the deposition of sediments transported to the lower CBD in suspension (4.1.4).

Fluvial sediment is also deposited on alluvial fan, valley and basin lands during non-irrigation season overbank flooding, and in the lower Colusa Basin during the irrigation season, generally as a result of rice field water releases (Section 4.1.4). Although several preliminary studies and reports on potential flood control projects in the Colusa Basin have been developed in support of local interests to decrease the incidence of these events (see Section 2.3.4), no quantitative work has been done to estimate the amounts of sediment deposited during overbank flooding. The importance of hillslope and channel bed/bank sediment source has been further explored through geomorphic surveying and analysis for the CCRCD Colusa Basin Watershed Management Program, which found that many of the tributary foothill channel banks appear to be unstable and relatively susceptible to erosion (Section 4.1.3). Also, a recent modeling study has further supported the general finding that the higher relief foothill portion of the watershed produces most of the sediment supply, while changes in orchard management could decrease sediment supply from almond orchards (Section 4.1.5).

Table 4.1.1. Fluvial sediment studies in the Colusa Basin watershed.

Section	Study Organization	Study Name	Publications	Data Period	Results	Results/Conclusions
4.1.1.1	DWR	Surface water monitoring	DWR database; DWR 1964	1952-1970	C_{SS}, Turbidity	First published observation of CBD outfall plume in the Sacramento River.
4.1.1.2	USBR	Colusa Basin Study	USBR 1973a; 1973b; 1973c	1962-1972*	C_{SS}, Turbidity, Q_{SS}	CBD had small effect on Sacramento turbidity, but possible sediment impacts on fishes in the CBD itself. Field crop irrigation return flows caused irrigation season increases in turbidity in the lower CBD.
4.1.1.3	CVRWQCB	ILRP, SWAMP	CDEC database; Merrill 1977	Apr-Sept, 1976	C_{SS}, Q_{SS}, Water Yield	CBD as the largest single contributor of sediment and agricultural waste water to the Sacramento River.
4.1.2.1	UCD/GCID	Return Flow Water Quality Appraisal	Low *et al.*, 1974	1973	C_{SS}, turbidity, Water Yield	GCID supply water ambient C_{SS} and turbidity about 1/3 of Irrigation season drainage and 1/9 of non-irrigation season drainage.
4.1.2.2	UCD/ USEPA	Irrigation Tailwater Management	Tanji 1981; Tanji *et al.* 1976; 1980a; 1981a; 1981b;	1974-1976	C_{SS}, Turbidity, Q_{SS}, Water Yield	Rice fields act as sediment sinks during the irrigation season, and sediment sources during the non-irrigation season. Lateral drains from rice fields may be significant sediment sources during both seasons.
4.1.2.3	USGS	Yolo Bypass Flux Studies	Domagalski 2001; Smalling *et al.* 2005; Springborn *et al.* 2011	1996-2003	C_{SS}, Turbidity, Q_{SS}, Water Yield, mercury, pesticides	The Colusa Basin watershed is a minor contributor of total sediment and mercury to the Yolo Bypass, but is a major source of sediment associated pesticides.
4.1.2.4	NRCS	Ridge Cut Farms Pilot Study	NRCS 1978;	1976?	C_{SS}, Q_{SS}	Cited in Tanji *et al.*, 1981 as a study of row crop sediment production in the Colusa Basin, but was not located.
4.1.2.4	UCD	Nutrient and Sediment Flux from Rice Fields	Linquist *et al*. 2014	2006-2008	C_{SS}, Q_{SS}	Rice fields acted as sediment sinks during the irrigation season, and sediment sources during the non-irrigation season, with a net annual sediment flux.
4.1.3	CCRCD	Colusa Basin Watershed Management Plan	H.T. Harvey and Associates *et al.* 2008; Geomorph *et al.* 2010; CCRCD 2012	2006-2009	Geomorphic observations	Sediment flux from foothills likely increased due to rangeland use. Streambank and unpaved roadway erosion likely a large source of sediment. Streambank instablility likely exacerbated by human land use and development. Reopperation of roadways, channel sytem restoration activities including channel belt widening and revegetation of riparia recommended on case by case basis.
4.1.4	UCD/ USEPA	NSP CBD	Tanji *et al.* 1978; 1980b; 1981c; 1983; Mirbagheri 1981; Mirbagheri *et al.* 1988a; 1988b; Mirbagheri and Tanji 2007	1977-1981	C_{SS}, Turbidity, Q_{SS}, Water Yield, PSD, organics, clay mineralogy, sediment mediated pollutants, sediment source and transport analysis	Physical, organic, biotic and mineralogical characterization of suspended sediments. Comprehensive monitoring and modeling of sediment dynamics, particularly in the CBD showed that more sediment was generally produced during the non-irrigation season. Geographically, the foothills produced the most sediment, while unpaved roadways and agricultural operations had increased sediment production from the lowlands. Recommended BMPs included erosion control through changes to livestock husbandry, cultivation, road management and channel management practices.
4.1.5	UCD	Orchard Sediment Production Modeling	Gatzke 2010	1985-2008**	Modeled sediment production.	Agricultural BMPs were predicted to be more effective than channel modifications. Strip cropping was predicted to be the most effective for reducing sediment flux during years with high annual precipation rates.

*Based on DWR samples. **Based on DWR and USGS samples

4.1.1 Ambient Suspended Sediment Characterization Studies

The following programs and studies have collected and interpreted suspended sediment data largely on the basis of C_{SS} and/or turbidity without associated Q data. These include some of the earlies sediment observations in Colusa Basin waterways performed by DWR (Section 4.1.1.1) and USBR (Section 4.1.1.2) while conducting studies with interests primarily in flood control, followed by monitoring programs aimed at water quality characterization under CVRWQCP oversight during the early 21st century (Section 4.1.1.3).

4.1.1.1 California Department of Water Resources (DWR): Long Term Suspended Sediment Monitoring.

The DWR collected data on many water quality parameters in the lower CBD between 1952 and 1970 from stations near the Highway 20 crossing of the CBD to Knights Landing. In reviewing the results of the DWR monitoring effort, H.T. Harvey and Associates *et al.* (2008) noted that only 2 of 63 collected samples exceeded the USDA Agricultural Handbook #60 standards for Class I water. Class I waters are generally usable for irrigation, with total dissolved solids (TDS) less than approximately 175 mg/L (H.T. Harvey and Associates, 2008). Notably, DWR Bulletin 109, a report focused on flooding and drainage problems in the basin, contains the first published visual observation of a sediment plume extending from the CBD outfall into the Sacramento River (DWR, 1964). Although the DWR never launched any studies with a particular focus on suspended sediment in the Colusa Basin drainage area, samples collected by this agency have been assessed by others (see Section 4.1.1.2), and are utilized in the present study as well (see Section 4.3).

4.1.1.2 U.S. Bureau of Reclamation (USBR): Colusa Basin Study (1972-1974)

The USBR conducted the Colusa Basin Study between 1972 and 1974 to assess current and potential flood control, drainage, water quality and water supply issues in the region (USBR, 1973 a,b,c). The water quality portion of this study presented a review of primarily DWR data collected between 1962-1971 from sites on the CBD, a few lateral drains, irrigation supply waters, and the Sacramento River above and below the CBD outfall near Knights Landing (USBR, 1973b). Of interest to the present study is the inclusion of turbidity data from 1968-1972 at sites on the CBD, and from 1967-1972 on the Sacramento River just upstream and downstream of the CBD outfall. Unfortunately no C_{SS} data were collected or reported.

The conclusion of this study in terms of suspended sediment was that CBD water had only a limited effect on Sacramento River water quality, but may have had harmful effects on fisheries in the drain. This conclusion was supported by data showing that average annual turbidities in the Sacramento River below the CBD outfall at Knights Landing were lower than those above the CBD outfall during this period (approximately 34 JTU vs. 40 JTU, respectively). Less emphasized was the observation that average irrigation season turbidities were higher below the CBD outfall than above (39 JTU vs. 21 JTU, respectively). Both of these results were based on unweighted averages of monthly turbidity samples, an approach that is unlikely to provide an accurate assessment of sediment flux from one body of water to another, particularly in systems that experience large variability in Q and C_{SS} (or turbidity) over sub-seasonal time scales. This report also included the observation that turbidity levels at the CBD Hwy 20 site decreased between 1969 and 1971 from 181 to 121 NTU, with average turbidities of 129 and 160 JTU during the irrigation seasons and year round respectively (USBR, 1973). However, trends in water quality were not reliably determined due to the short temporal base of the data set (3 years), the fact that average annual turbidities did not display a monotonic trend (the 1970 average turbidity was higher than 1969), in addition to the use of unweighted averaging of monthly samples.

Of note is an addendum section (USBR, 1973c, p. 33), which states that a recent CVRWQCB study found that agricultural practices may be the primary cause of summer turbidity problems in the CBD, as evidenced by increases in turbidity from near Maxwell to Knights Landing from 21 to 64 JTU, respectively. Mismanagement of field crop irrigation and tailwaters are cited as the probable culprit, as sugar beet and corn fields were found to discharge waters with turbidity from 36 to 58 JTU, in comparison to supply water turbidity of ~ 8 JTU. In contrast rice tailwater was lower than supply at 2 JTU. However, drainage laterals from rice and field crops have steep slopes and an absence of drop structures for energy dissipation, which not only allowed off field sediment to remain in suspension, but could also have led to bottom and bank erosion and even higher turbidities of 75 JTU in the drainage laterals feeding the main canal.

4.1.1.3 CVRWQCB ILRP and SWAMP (2002 – Present)

The CVRWQCB developed a Conditional Waiver for the ILRP that required monitoring of discharge from irrigated agricultural fields. These requirements amount to a basin-wide monitoring program to assess impacts of irrigation water discharge implemented by regional or local coalitions of agricultural entities, with annual reports required from each coalition. The Sacramento Valley Water Quality Coalition (Coalition) was formed in 2002 as an agricultural industry alliance to comply with the CVRWQCB Conditional Waiver for the ILRP. The Coalition has conducted a monitoring and reporting program in the Colusa Basin since 2005 at the following locations: CBD above Knights Landing, Freshwater Creek at Gibson Road, Logan Creek at 4 Mile-Excelsior Road, Lurline Creek at Interstate 5, Walker Creek at County Road 48, CBD near Maxwell Road. Monitored fluvial constituents are pesticides, metals, nutrients, toxicity, pathogens, general chemistry, and physical parameters, including turbidity, total suspended solids, and total organic carbon. Unfortunately, Q data are not generally recorded. Water quality monitoring has been conducted at a monthly frequency during the irrigation season, and twice during the entirety of the non-irrigation season.

No definitive conclusions on the role of agriculture in contributing to fluvial sediment in the CBD and its receiving bodies have been advanced directly by the CVRWQCB ILRP. Numerous turbidity measurements were recorded by these studies and monitoring programs, however the utility of much of these data in terms of the goals of this project are limited. Turbidity measurements collected for the purpose of estimating sediment concentrations must be accompanied by pairwise C_{SS} measurements collected over a range of discharges and a time period sufficient to capture temporally dependent changes in sediment composition (see Section 3.4). Despite such shortfalls, ILRP data are considered further in the synthesis of sediment data (Section 4.3), and in the assessment of environmental impacts of suspended sediments (Section 6).

4.1.2 Suspended Sediment Flux Studies

The following studies employed flux-based approaches to investigating fluvial sediment generation and transport in the Colusa Basin region at a number of scales, from individual agricultural fields to the entirety of the watershed. The UCD/GCID Return Flow Water Quality Appraisal focused on water, chemical and particulate fluxes through the GCID for one year, with ambient CSS averaged determined through flow weighting (Section 4.1.2.1). The UCD/US EPA Irrigation Tailwater Management study focused on rice fields and their impacts on lower CBD sediment levels (Section 4.1.2.2). Scientists at the USGS led a number of studies concerned with accounting for the fluxes water, sediment, nutrients and contaminants into the Yolo Bypass, including those originating from the Colusa Basin watershed (Section 4.1.2.3). Finally, two other field scale studies concerned with row and rice cropping are summarized in Section 4.1.2.4.

4.1.2.1 UCD/GCID Return Flow Water Quality Appraisal (1973)

The UCD/GCID Return Flow Water Quality Appraisal (RFWQA) project was a mass balance analysis of ity, which was used produce flow weighted averages of ambient salinity and suspended sediment conditions during the irrigation and non-irrigation seasons of the 1973 water year (Low *et al.*, 1974). During this time period the 163,700 ac. of land serviced by the GCID contained 120,060 ac. of irrigated agricultural and wildlife refuge areas, which received a total of 803,400 ac-ft of water supplied by the GCID during the irrigation season – mostly for rice production. Most of this irrigation supply water left the system as evapotranspiration (559,700 ac-ft), while 172,500 ac-ft exited as surface flow through the CBD. Flow weighted average C_{SS} values were 12 mg/L, 36 mg/L and 109 mg/L for irrigation supply waters, CBD irrigation season and non-irrigation season drainage respectively.

4.1.2.2 UCD/US EPA Irrigation Tailwater Management (1974-1976)

The UCD/US EPA Irrigation Tailwater Management (ITM) project was an in-depth study on irrigation and storm water seasonal flows and water quality conducted between 1975 and 1977 with a focus on canals draining 3,200 to 164,000 acres of irrigated agricultural lands in both the Colusa Basin and a subbasin of the San Joaquin River (Tanji 1981; Tanji *et al.*, 1976, 1980a, 1981a,b). The main goal of this study was to investigate the practicability of irrigation tailwater management as motivated by the PL-92-500, an amendment to the Federal Water Quality Control Act in October, 1972 that mandated specific goals toward reduction of point source pollution. Under this law and attendant permitting programs such as the National Pollutant Discharge Elimination System (NPDES), irrigation tailwater was identified as a potentially effective target for management measures toward the reduction of agricultural pollution discharges into navigable waters. The main products were a scientific determination of whether irrigation tailwater management was a practical and cost-effective approach toward reducing water pollution, and if so, recommendations of appropriate methods. The conclusions of this study were that rice fields in the Colusa Basin were acting as sediment sinks during the irrigation season and sediment sources during the non-irrigation season. Lateral drainage systems from these fields were also found to be potential sources of sediment during both seasons.

The Colusa Basin component of this study focused on the 164,000 acre Glenn-Colusa Irrigation District at spatial scales ranging from field to the entire district, and the entire Colusa Basin watershed. Land use in the GCID at this time, and the present, was primarily flooded rice paddy cultivation, with smaller proportions of land cultivated through border irrigation for pastures, hay and orchards, and furrow irrigation for row crops such as corn, tomatoes and sugar beets. Monitoring of *Q* and the following water quality parameters: electrical conductivity (*EC*), total dissolved solids (*TDS*), turbidity, and C_{SS} was conducted on irrigation supply water, four rice fields (from 61-153 acres), 11 drain laterals and five locations on the CBD between 1975 and 1977. The sampling effort for this study was supplemented by NPDES required water quality monitoring performed by DWR at two CBD sites and Reclamation District 787's drain (Tanji *et al.*, 1981a). Water quality samples were collected at weekly intervals from CBD-1 (the most downstream site on the CBD sampled for the UCD/US USEPA study) and at monthly intervals for the other CBD, drain lateral and supply sites (Tanji *et al.*, 1980a). Seasonal and annual averages of all water quality characteristics were estimated by flow-weighted averaging. Water fluxes were estimated through linear interpolation of monthly and weekly values, which were multiplied by C_{SS} to obtain sediment fluxes for those time periods.

Irrigation district scale results showed that the sediment balance index (ratio of tailwater suspended sediment load to supply suspended sediment load) for the GCID was 0.39 in 1975 (Tanji *et al.*, 1980a). This means that more than half of the suspended load introduced by irrigation supply water settled out in rice fields or was deposited in drainage systems during the irrigation season. Sediment load analysis on the four rice fields examined by this study in 1976 supported this contention, with most tailwater releases bearing both lower concentrations and loads than supply waters (Tanji *et al.*, 1981a). However, it should be noted that the lateral drains generally bore higher C_{SS} than both GCID supply and rice irrigation return flows, presumably due to resuspension of material deposited during previous irrigation and storm season flows. Variations in C_{SS} and sediment load at CBD stations were determined to be the result of differences in local sediment supply and differences in deposition and resuspension dynamics between distinct reaches of the CBD (Tanji *et al.*, 1980a). Values of C_{SS} in the lateral drains and the CBD were generally greater during the non-irrigation season than the irrigation season.

As this study was conducted during the drought of 1975-1977, flux of water and sediment from the Colusa Basin watershed was lower during the non-irrigation season in comparison to the irrigation season due to lower than average annual runoff for multiple years (Tanji *et al.*, 1980a). It was noted that this is the reverse of the case for a normal water year. The average storm runoff from the watershed during this period, assuming contribution of the complete watershed surface area, was estimated as 0.05 ac-ft/ac (16 m^3/km^2) of water, which, at approximately 1/10 of mean annual storm runoff, is clearly a drought condition. Thus the very low storm flow (non-irrigation season) sediment yield of 8 lbs/ac (0.9 tons/km^2) is the result of very low precipitation and runoff during the 1975 to 1979 sampling period. In comparison the mean sediment yield for watersheds of this size in US has been found to be 2 to 3 orders of magnitude higher than this rate (Dendy and Bolton, 1976), and indeed non-drought water years in the Colusa Basin fall closer to this level of sediment yield (see Section 4.1.4).

Problems with this study range from minor typological issues, such as occasional confusion of DWR and UCD site names in Tanji *et al.* (1981a); to more substantive issues regarding sample frequency. In this case C_{SS} and Q were sampled primarily at monthly intervals. However, fluctuations in both C_{SS} and Q in drain laterals and the CBD occurred over shorter time scales (days to weeks). The generally log-linear relationship between C_{SS} and Q in systems such as the CBD result in much high C_{SS} with higher Q ranges. Consequently, collecting infrequent samples relative to the frequency of change and applying those values across the entire interval can lead to vastly erroneous estimates of sediment flux depending on whether or not high Q events are captured. Of course, frequent sampling is time consuming and expensive, with the greatest need occurring during unpredictable events (often through the night), so it is very difficult to achieve.

4.1.2.3 USGS Studies of Fluvial Sediment and Contaminant Flux to the Yolo Bypass

The USGS and collaborators have conducted a number of studies addressing the flux of fluvial sediment and sediment associated contaminants to the Yolo Bypass, including contributions from the Colusa Basin drainage area through the Knights Landing Ridge Cut (Domagalski, 2001; Smalling *et al.*, 2005; Springborn *et al.*, 2011). As noted in Section 2.3.1, the Yolo Bypass is a portion of the lower Sacramento River floodplain that was developed beginning in the 1930s as an out-of-channel flood control structure designed to divert up to approximately 500,000 cfs (14,000 m^3/s) during winter floods. There are six major sources of discharge to the Yolo Bypass: (i) the Sacramento River and (ii) the Feather River at Fremont Weir, (iii) Colusa Basin drainage area discharge from the lower CBD via the Knights Landing Ridge Cut, (iv) Cache Creek, (v) Willow Slough, and (vi) Putah Creek (Figure 4.1.1). These studies found that the Colusa Basin watershed contributed a minor amount of the total sediment and mercury flux into Yolo Bypass, but was one of the major sources of sediment-associated pesticides.

On average the Colusa Basin drainage area has been estimated to contribute approximately 5% of the sediment flux and 3% of the total mercury flux to the Yolo Bypass, both of which were dominated by contributions from Cache Creek and the Sacramento (including Feather tributary) River (Springborn *et al.*, 2011). Colusa Basin drainage area estimates were based on seasonal (discreet irrigation and non-irrigations season) log-linear rating curves developed from 56 pairs of Q and C_{SS} data collected by the USGS between 1996 and 2003 from the lower CBD at Road 99E (CBD-1, also known as CBD near Knights Landing). A lack of interdecadal Q data collection from this station required the construction of an estimated Q time series based on the CBD gauge at Hwy 20 (CBD5), some 30 miles upstream. Routing of discharges and sediment through the KLRC to the Yolo Bypass were then estimated as the difference between discharge to the Sacramento River at the CBD outfall and the estimation for CBD-1.

In contrast to relatively minor contributions of total sediment and mercury flux to the Yolo Bypass, the Colusa Basin drainage area Colusa Basin drainage area is likely be the largest or second largest contributor of pesticides, following only the contributions of the greater Sacramento River watershed (Smalling *et al.*, 2005). Smalling *et al.* (2005) attempted to detect 27 pesticides in water, suspended sediment and bed sediment samples, including the following 16 that were then related to subbasin application rates: bifenthrin, carbaryl, chlorpyrifos, DCPA, diazinon, EPTC, haxazinone, methidathion, metolachlor, molinate, napropamide, oxyfluorfen, pendimethalin, simazine, tau-fluvalinate, and thiobencarb. Samples were collected on four occasions from the KLRC, and on 4 to 10 occasions from the other water bodies contributing to the Yolo Bypass. Pesticide concentrations in suspended sediments were found to correlate with application rates by watershed. Although the Colusa Basin drainage area is much smaller than the upper Sacramento watershed (and its Feather River subbasin), the high proportion of irrigated agriculture in the basin led to high application rates of certain pesticides relative to basin area, including the highest rates for metolachlor and oxyfluorfen, and nearly the same applications as the much larger Sacramento River watershed for napropamide, pendimethalin, tau-fluvalinate, and thiobencarb (Smalling *et al.*, 2005 on the basis of 2003 application rates). The small amount of samples and ambient characterization approach of this study did not result in actual flux estimates. Much more sampling would be required to develop pesticide flux rate estimations from the Colusa Basin drainage area and the Yolo Bypass as a whole.

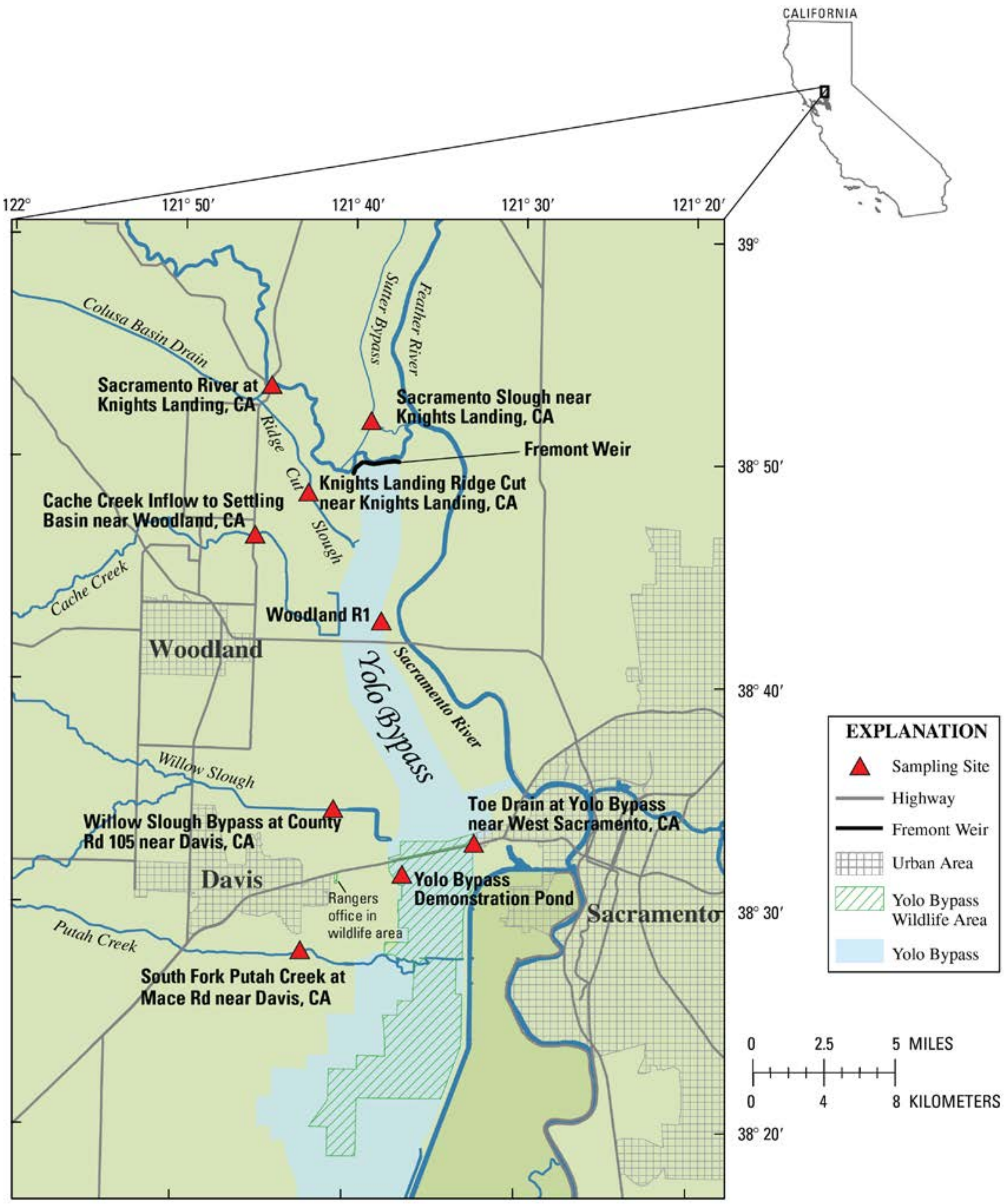

Figure 4.1.1. Hydrologic contributors to the Yolo Bypass (from Smalling *et al.*, 2005).

4.1.2.4 Other Field-Scale Studies

In addition to the larger-scale integrated studies discussed above, and the comprehensive, cross-scale study conducted by UCD/USEPA (see Section 4.1.4), a couple of smaller field-scale studies addressing sediment flux were conducted in the Colusa Basin watershed over the years. These field-scale studies were conducted by researchers with the NRCS and UCD. The NRCS conducted a pilot study on row crops at Ridge Cut Farms in the late 1970s, which could not be located during the present study. A research group headed by Bruce Linquist at UC Davis studied nutrient and sediment flux from rice fields at a number of locations around the Central Valley, including a field in the Colusa Basin near Willows (Linquist *et al.*, 2014). The Linquist *et al.* (2014) study found that on average rice fields acted as sinks for supply water sediments during the irrigation season and sediment sources during the non-irrigation season. Average area deposition rate was 52 lbs/ac (58 kg/ha) during the irrigation season. Average sediment flux during the non-irrigation season was 137 lbs/ac (154 kg/ha). Thus the annual average sediment balance for rice fields was found to be a net sediment flux of 85 lbs/ac (96 kg/ha), which corresponds to 16.6 tons/mi^2 (4.8 tons/km^2). It should be noted that this study was of a number of individual rice fields, and did not incorporate deposition or resuspension or erosion of drainage canals.

4.1.3 Geomorphic Studies Commissioned by the CCRCD (2006–2012)

During the process of developing the Colusa Basin Watershed Management Plan (CCRCD, 2012), the Colusa County Reclamation District commissioned a two-phase study of the region by H.T. Harvey and Associates, Geomorph Inc., and Professor Matthew Kondolf of the University of California, Berkeley (H.T. Harvey and Associates, *et al.*, 2008; Geomorph *et al.*, 2010). The first product of these studies was the 'Colusa Basin Watershed Assessment' (H.T. Harvey and Associates *et al.*, 2008), followed by the 'Colusa Basin Watershed Limited Streambank Analysis' (Geomorph *et al.*, 2010) a survey of the geomorphic and ecological state of tributary channel banks in the Colusa Basin watershed. The H.T. Harvey and Associates *et al.* (2008) report identified watershed stakeholder concerns, characterized historic and current watershed conditions, including changes in key ecosystem features and processes, and identified data gaps necessary for system characterization. They also broadly characterized the basin in terms of historical development, land use, geology, geomorphology, soils, biology, climate, and hydrology/water quality. The Geomorph *et al.* (2010) report includes detailed geomorphic and ecological mapping of 32 foothill streams in the Colusa Basin watershed. The streams were mapped for erosion potential, invasive species, and riparian habitat, providing information to help identify future restoration projects, and address data gaps as identified in H.T. Harvey and Associates *et al.* (2008). It should be noted that the entirety of this work is based on expert opinion packaged as qualitative rating systems with little to no quantitative analysis. This can be useful for hypothesis generation, but is not recommended for making conclusions.

The highest bank erosion potential was found generally in channels on steep alluvial fan/foothill front, as well as steep, channelized sections of lower gradient downstream reaches, and wide upper Inner Coast Ranges valleys with well-developed alluvium (Geomorph *et al.*, 2010). Many of the reaches with high bank erosion potential were likely related to natural geomorphic characteristics. Many reaches with high erosion potential probably also had this character before human intervention, particularly in the uplands and on the alluvial fans. Human-induced channel bank instability was most notable in the lowland channelized reaches where straight, over-deepened channels constructed with deep flows often possess very steep un-vegetated banks, which may be topped with roads. Sediment addition to levee top road grading operations essentially function as a sediment conveyor system, with these sediments eventually lost to the channel, degrading the road, which subsequently has more sediment added.

Broad recommendations for channel bank erosion management were made with the explicit realization that all foothill streams pass through a patchwork of privately held land of primarily agricultural use (Geomorph *et al.*, 2010).

Channel bank management strategies were recommended to focus on reaches with high erosion potential, and in consideration of bank material, geomorphic setting, and human influences. It was suggested that erosion management concentrate on reaches with high potential erosion of channel banks with particle size characteristics that were of most concern for water quality purposes (i.e., fines). Subbasins draining cretaceous marine rock were identified as having greater fine sediment content in bank materials. Reaches with unstable banks that were highly impacted by human land use were identified as potential targets for 'passive restoration', whereby relaxing or discontinuing certain land use practices, such as livestock grazing, could result in significant reductions in erosion without the large monetary investment necessary for active projects. Active projects, such as channel belt/floodplain widening, bank slope relaxation and re-vegetation, etc. were recognized as requiring stream-wide planning, which could be implemented by the range of land owners during times of crises or as part of system wide periodic maintenance. Re-vegetation in the riparian zone was recommended only in areas where flood risk would not be increased, and where physical conditions (channel bank slope, substrate, etc.) were amenable.

4.1.4 A Comprehensive Study of Sediment Production and Transport Dynamics: The UC Davis/USEPA Nonpoint Sediment Production in the Colusa Basin Drainage Area (1977-1981)

Following the UCD/US EPA ITM (see Section 4.1.2.2 above) most of the same UC Davis scientists conducted another large study in the Colusa Basin watershed for the US EPA from 1977-1981, again headed by Professor Ken Tanji (Tanji *et al.*, 1978, 1980b, 1981c, 1983; Mirbagheri, 1981; Mirbagheri and Tanji, 1988a,b). This period was much wetter than that of the UCD/US EPA ITM study (1975-1977, see Section 4.1.2.2), which resulted in higher non-irrigation season water and sediment yields (details below). The UC Davis/ US EPA Study on Nonpoint Sediment Production in the Colusa Basin Drainage Area (referred to hereafter as the UCD NSP CBD) was explicitly focused on the processes controlling non-point source sediment production, composition and transport dynamics over the entire Colusa Basin drainage area. A major component of this study was the delivery of sediment best management practice (BMP) suggestions for rangelands, cultivated lands and unpaved roads aimed at lowering the amount of sediment discharged from the CBD. The reports produced by this study are of particular interest as they present the most complete examination to date of the Colusa Basin watershed in terms of fluvial sediment production and transport dynamics and the identification of plausible controls on sediment erosion, transportation, deposition and resuspension.

Sediment sources were approached through an assessment of the spatial distribution of erosion across the landscape and channelized system. This was conducted through a combination of field observations, plot-scale tests, rain simulations, and a watershed-scale sediment production model based on the modified Wischmeier and Smith Universal Soil Loss Equation (USLE). Geographic information was gathered to inform this model, which included the spatial distribution of soil types and characteristics, topographic relief, vegetation cover and land use. Elucidation of watershed-scale suspended sediment dynamics was approached through the (i) examination of C_{SS}–Q relationships in terms of seasonality and location, (ii) computation of spatially and temporally explicit sediment budgets, and (iii) development of a 1-D sediment transport model. The spatial pattern of sediment fluxes was then used to assess the accuracy of the watershed-scale erosion model.

Field-scale monitoring occurred near Dunnigan, where tail water and sediments sampled from furrow irrigated corn and tomato fields in lands operated by Ridge Cut Farms (Tanji *et al.*, 1978). Surface water monitoring of drains and creeks was conducted between 1977 and 1981 at 13 sites in the Colusa Basin watershed (Tanji *et al.*, 1978; Mirbagheri, 1981). Upland subbasin sampling was conducted at stations along Buckeye Creek, Stone Corral Creek and Funks Creek. Basin-scale sampling was conducted at seven sites along the CBD, including those from the UCD/US EPA ITM study (CBD-1 through CBD-5) and two additional sites upstream (CBD-6 and CBD-7). Note that CBD-1 is the terminal station near Knights Landing (located about 3.5 miles upstream from the outfall gates to the Sacramento River) and is used to measure total outflow from the Colusa Basin drainage area for this study. Weekly Q and water quality measurements were collected year round at multiple sites on Stone Corral and Funks Creeks and the CBD stations. Intensive daily to weekly sampling in a three mile reach of Stone Corral Creek and at the CBD stations was conducted during the irrigation season.

Water quality measurements included C_{SS} (which involved the collection of suspended sediment samples), turbidity, TDS, total carbon, total organic carbon, algae, EC, and major cation and anion concentrations. Stream Q was measured directly using the velocity-area method, which involved sectional channel morphology mapping and the collection of flow velocities at up to 7 or 8 intervals across a given channel. Samples of bed sediments were collected from the CBD and the Sacramento River upstream and downstream of the Knights Landing outfall. Both bed and suspended sediment samples were analyzed for particle size distribution using dry and wet sieving for particles of sand size or coarser, and the hydrometer method for clays and silts. Eight particle size classes were reported: one gravel class, three sand classes, three silt classes, and one clay class. However, actual particle size data collection involved measuring at least 30 particle size classes over this range. Bed sediments were also analyzed for critical shear strength. A pesticide survey of selected chemicals was also conducted on selected suspended and bed sediment samples in 1980 and 1981.

The mineral fraction of suspended sediment ranged from 30-90% during non-irrigation season (Avg. 70%), 10-80% during the irrigation season (average 50%). Greater than 50% of suspended mineral sediment was clay during the non-irrigation season and 80% during the irrigation season. Clay mineralogy analysis through X-ray diffraction showed that chlorite and kaolin were the dominant phyllosilicates in coarse clay (2-0.2 μm) suspended sediment fractions, while cation adsorption specificity decreased in the following order: Ca, Mg, Na. Bedload sediment in the CBD was on average approximately 60% sand, 10-30% POM, and smaller amounts of clay, silt, and gravel.

Algal biomass was lowest in the CBD, decreasing downstream, and highest in the GCID and tributaries such as Stone Corral Creek. Stone Corral creek receives water from rice fields, which are depleted if mineral sediments due to settling, while serving as algal incubators due to high light, temperature and nutrient conditions. The algal contribution to C_{SS} ranged from 3-43%, with an average C_{SS} composition of 10% algae biomass. Algal growth rate was found to be controlled primarily by phosphorous, and secondarily by nitrate and temperature. Suspended organic matter represented from 16-81% of C_{SS} across the entire study area (Avg. 30%). SOM was further characterized as either biodegradable (labile) or non-biodegradable (refractory). This difference was established using the BOD_5 test, which uses the biological oxygen demand of sediment incubated for 5 days to estimate the amount of organic material consumed through microbial decay. The composition of SOM was on average 60% labile and 40% refractory.

Irrigation and non-irrigation hydrologic regimes for the 3-year period of weekly to monthly sampling at CBD-1 were described by two nearly parallel, offset C_{SS}–Q rating curves. The non-irrigation season rating curve was offset from the irrigation season rating curve by a factor of approximately 2. In other words, C_{SS} was about twice as high during the non-irrigation season than during the irrigation season for a given Q. Higher irrigation season discharges were diluted by return flows from ponded rice fields, which contribute water with very low C_{SS} values. Higher variance was observed around the non-irrigation season rating curve, presumably due to higher variation in the spatial distribution and intensity of rain fall events in comparison to the more uniformed erosion and sediment transport characteristics of irrigation application and return flows. An example was given of two measurements from September, 1978 when increased Q due to rice field draining led to a concomitant decrease in C_{SS} (Mirbagheri, 1981, p. 102).

Antecedent basin conditions were also found to have played an important role in the timing of sediment transport. High-intensity runoff events in Stone Corral Creek at Sites Road were found to attain a maximum concentration at the start of runoff, which was inferred to have resulted from the weathering of soils and stream beds during the preceding dry periods, which produced a large and readily transportable load of fine material (Mirbagheri 1981, p. 161). Indeed, the C_{SS} and sediment flux from the Colusa Basin watershed was much higher during the 1979 water year than the subsequent water year, despite the fact that more water was discharged from the basin in 1980. This was attributed to the preceding years of drought from 1975-1978, which allowed sediment supply to accumulate.

The CBD suspended and bed sediment characterization studies indicated that there were also intermediate deposition/entrainment processes at play in the channelized system. Changes over time in channel bed surface particle size distributions for a given site were used to infer deposition or entrainment. Resuspension and transport of tributary sediment to the CBD were found to have occurred in association with high discharges during winter storms. For example, high rainfall-runoff events were observed to cause accelerated stream bed erosion, as evidenced by bed material coarsening and bank-undercutting along Buckeye Creek during the 1978/1979 winter runoff season. In fact, in-channel erosion was found to have occurred in almost all of the streams in the Buckeye and Stone Corral Creek study areas. Conversely, deposition took place in tributaries and the CBD when stream water flow characteristics were insufficient for transport. The channel bed at CBD-3 and CBD-1 both experienced fining over the same period, which was interpreted as deposition of fine sediments.

As noted above, initial stream bed erosion or deposition was mostly inferred indirectly through sequential channel bed particle size characterization, with coarsening indicating erosion due preferential removal of finer fractions. This is in contrast to the sequential surveying method, which would require relatively precise vertical measurement methods. In one case, a three-mile reach of Stone Corral Creek was also monitored for in-channel erosion using a mass balance approach:

$$MID = M_o - M_R - M_i + M_d \tag{4.1.4.1}$$

where *MID* is channel erosion mass, M_o is sediment discharged from the system by outflow of water, M_R and M_i are the mass of sediment entering the system from flooded rice fields and upstream waters, respectively, and M_d is the mass of sediment deposited in the channel. The result was that approximately 60 % of suspended sediments came from in-channel erosion and resuspension of bed material.

Investigation of physical characteristics of flow in relation to bed material and channel cross section surveys over time revealed a number of key insights into the dynamics of sediment transport, deposition and resuspension in the CBD. Shear velocity, bed shear stress and flow velocity all generally decreased downstream until CBD-1A, with a slight increase to CBD-1 (see Section 10.3 for these data). This was determined in part through downstream hydraulic geometry metrics:

$$D = K_d Q^{\alpha} \tag{4.1.4.2}$$

$$U = K_{\mathrm{u}} Q^{\beta} \tag{4.1.4.2}$$

where D = depth, U = average flow velocity, K_d and K_u are the depth and velocity coefficients, α and β are the depth and velocity exponents that describe how the geometric variable change in the downstream direction with increased flow. Depth increased for a given *Q* downstream, but this was counteracted by flow velocity decreases, which led to a net reduction in bed shear stress downstream. However, critical shear stress (i.e., the minimum required to entrain sediment off the bed) was actually higher downstream due to the cohesiveness of the finer particles deposited in the lower reaches of the CBD. With the exception of winter storms, the bed shear stress in the CBD was below critical, leading to net deposition of sediment in the CBD. Net deposition was maximum between CBD-1B and CBD-1A where bed shear stress was minimum. The 1980 Channel survey showed aggradation in the lower CBD on the order of approximately 0.25 and 0.75 ft at CBD-3 and CBD-1A, respectively (Mirbagheri, 1981). Of note is an apparent discrepancy between decreased bed shear stress from station CBD-2 to CBD-1, while C_{SS} was observed to increase between these stations despite a lack of any significant new sediment sources outside of the channel. This increase in C_{SS} was attributed to resuspension by aquatic organisms, namely carp (Mirbagheri 1981, p 168-170).

To further understand suspended sediment transport, deposition and entrainment dynamics, a 1-D sediment transport model was applied to the 20-mile lower reach of the CBD (Tanji *et al.*, 1981c, Mirbagheri, 1981). This model was sensitive to (i) flow rate, (ii) current velocity, (iii) bed shear stress, and (iv) the settling velocities of particles, which incorporated chemical controls on flocculation. The following physical factors controlling in-channel sediment transport were identified through this model: (i) longitudinal flow pattern, (ii) flow rate, (iii) bed configuration and roughness, (iv) current velocities, (v) fluid shear stress, (vi) critical shear stress of the bed material, and (vii) water depth. Additional chemical factors affecting sediment transport were those that affect dispersion, flocculation, and sedimentation of cohesive suspended sediment particles. These factors include the concentration of soluble ions either measured as total dissolved solids (TDS) or electrical conductivity (EC), (ii) sodium adsorption ratio (SAR), and (iii) pH of the water. However, TDS and SAR were found to be negligible factors, while the alkaline character of the CBD drainwater (pH approximately 8) played an important role in maintaining dispersion through negative pH dependent surface charge maintenance, particularly of the organic fraction. Lower pH would result in protonation of exchange surfaces and increased flocculation/deposition.

A number of key conclusions related to sediment production and management in the Colusa Basin watershed were advanced by this study. In terms of sediment sources, four main erosion modalities were considered: (i) sheet and rill, (ii) channel, (iii) gully, and (iv) roadway. The main sources of soil loss were found to be sheet and rill erosion from upland and dry-farmed areas caused by raindrop impact and surface water flow over the soil. The USLE model underestimated soil losses by approximately 20% on the basis of comparisons to watershed scale sediment flux estimations. Slope steepness was an important component in estimating soil loss in western foothills, but rainfall-simulation studies showed that increasing slope effect became less important beyond 40%. Underestimation by the model may have been related to the fact that it did not incorporate gully and roadway erosion. Field observations led investigators to believe that unpaved roadways were also significant source of sediment entering the CBD.

Mirbagheri (1981) noted that sediment exported from a given basin is commonly approximately ¼ of that estimated to have eroded from the basin over a given time interval. The bulk of sediments are deposited in intermediate locations whenever flow characteristics are insufficient to maintain transport. These intermediately stored sediments are transported during episodes of accelerated streambed erosion during more hydrologically active winter storm seasons. This observation also calls into question the underestimation of short term sediment load estimates produced by the USLE approach applied in this study. It should also be noted that this study did not directly address bedload, although it was inferred to be significant during the non-irrigation season, but “may not be significant” during the irrigation season (Mirbagheri, 1981). Not accounting for bedload would be expected to cause an underestimation of basin scale sediment load estimated from suspended sediment concentrations alone, in comparison to basin scale erosion estimates. This also highlights the apparent discrepancy in the underestimation of basin scale sediment loads by the USLE approach of this study.

The UCD NSP CBD study recommended a number of sediment management BMPs. A major consideration in the development of recommended BMPs was that they must be economical and not impede continued agricultural productivity. Furthermore, the authors specified that the most productive BMP is one designed specifically for a particular area. Two main BMP approaches were identified: reduction of on-site erosion and prevention of sediment from reaching a given waterway. Five major areas of interest for reducing on-site erosion were identified: (i) livestock management was highlighted as potentially the most cost-effective method of erosion control, followed by (ii) cultivation practices, (iii) irrigation land management, (iv) road management, and (v) channel management. The three types of potential livestock management explored were vegetation management (i.e. accelerating vegetation growth), facilitating practices such as increased animal yield, and reduction practices (i.e. decreasing the amount of livestock on given areas). Five cultivation practices were recommended to reduce on-site erosion: (i) sloping cultivated land management through contour cropping, (ii) increased infiltration through chemical application, organic matter incorporation, or reducing compaction, (iii) zero or minimum tillage agriculture, (iv) conservation cropping systems such as rotation of grasses and legumes, and (v) plant growth during critical erosion periods. The major recommendation for irrigated land management was technical and operation modifications to minimize surface runoff. Road management recommendations included certain dirt road closures in areas with erosion problems during wet weather, and permanent closures of non-essential roads. Channel erosion management focused on active channel engineering such as: (i) grade stabilization, (ii) construction of inlet structures, (iii) reshaping channels including the erection of rock structures or riprap at creek bends and installation of large boulders with wire fences and revetments to reduce land erosion, (iv) planting suitable ground covers, and (v) the installation of sedimentation basins. Prevention of sediment from reaching waterways was recommended for roads through the installation of water bars, culverts and water spreaders. The other major sediment transport prevention approach was the development of vegetative stream buffer strips.

It should be noted that there was no design phase for this study. However, a general two phase approach with initial education followed by implementation was suggested for employing the recommended BMPs. Education of landowners, farmers, and ranchers on the benefits possible with effective land management was viewed as critical for the successful implementation of these practices.

Also, the UCD NSP CBD study was conducted just as the USBR was finishing construction on the 111-mile long Tehama-Colusa Canal (TCC). At this time it was estimated that the TCC would deliver an additional 400,000 ac-ft of water from the Sacramento River at Red Bluff Diversion Dam to ~ 200,000 acres of previously dry-farmed and locally (groundwater) irrigated agriculture. This project was predicted to generate approximately 100,000 ac-ft of return flow, half of which would be reused, and the other half (approximately50,000 ac-ft) would be discharged through the CBD. The UCD/USEPA NPS CBD scientists expected that initial application of these waters would destabilize the sediment system for some time before the newly irrigated lands, drainage channels and banks became stabilized and began to behave more like those that had been irrigated for decades by Glenn-Colusa Canal water at the time of this study. However, a lack of sediment monitoring in terms of sample quality, and spatial and temporal distribution over the intervening decades does not allow for a rigorous assessment of their predictions regarding temporary acceleration of sediment production following the full activation of the TCC (see Section 4.3.2).

4.1.5 A Watershed Scale Sediment Production Model Focused on Almond Orchard Management

Two previous studies in the Colusa Basin watershed examined the role of hillslope sediment contribution to CBD suspended sediment loads using approaches based on the Universal Soil Loss Equation: the UCD/USEPA NSP CBD (see Section 4.1.4), and a Masters project by S.E. Gatzke from Professor Minhua Zhang’s laboratory in the Department of

Land, Air and Water Resources at the University of California, Davis (Gatzke, 2010). The Gatzke (2010) study is summarized here and compared to the results of the UCD/USEPA NSP CBD study.

The Soil Water Assessment Tool (SWAT) was used to model the effectiveness of five 'best management practices 'BMPs' on reducing sediment flux from almond orchards in the Colusa Basin. The BMPs tested included two channel modifications: grassed waterways and channel stabilization structures, and three upland practices: strip crops, cover crops and vegetative filter strips. The effects of BMPs on sediment flux were tested for above median, median, and below median precipitation scenarios. Increased storm intensity was also investigated through distributed precipitation and single large storm tests on BMP effectiveness.

Study results indicated that upland BMPs were more effective than channel modifications, which is in general agreement with the findings of the UCD/USEPA NSP CBD study (Section 4.1.4). Upland BMPs resulted in 15 to 100% reduction in sediment load for various scenarios, while channel modifications resulted in reductions of only 8 to 14%. Of the channel modifications, grassed waterways were more effective than channel stabilization structures. Of the upland BMPs, strip crops were the most effective for years with above median and median precipitation, with estimated sediment reductions of 63% in both cases, while cover crops resulted in 54 and 15% reductions for each scenario, respectively. Cover crops were estimated to reduce sediment load completely during the below average precipitation simulation, while strip crops and vegetative filter strips led to 64 and 59% reductions, respectively.

The following issues call into question the validity of this study's findings:

(i) Model estimates of sediment loads were the product of simulations driven by precipitation inputs, and hence rainfall, runoff, erosion and sediment transport process are assumed. However, the model was calibrated and validated on the basis of only the June through November period from 1985- 2008. Very little to no precipitation falls during this period for any given year.

(ii) The SWAT model uses a questionable empirical approach to estimating channel bed degradation and aggradation by relating maximum sediment carrying capacity to peak channel velocity through the power law equation: $S_{ch} = av^b$, where S_{ch} (ton m^{-3}) is the maximum concentration of sediment transported by streamflow, a and b are user-defined coefficients, and v (m s^{-1}) is peak channel velocity calculated from Manning's equation.

(iii) Particle size of suspended and bed sediments are not considered in this modeling approach, nor are the complexities of cohesive sediment transport.

4.2 Study Region Visit

A number of UCD personnel and CVRWQCB staff visited the Colusa Basin watershed on Thursday October 23, 2014 (Table 4.2.1). The purpose of the site visit was to provide the participants with a physical experience of the Colusa Basin watershed and some of its key hydrological features. The field excursion progressed from the outfall, to several historical sampling sites along the CBD and its major tributary, Stone Corral Creek, and then finished with a brief visit to the interior Coast Range Foothills and two major irrigation canals (Table 4.2.2). Photographs were taken at each site and particular attention was given to hydrologic, geomorphic and vegetation characteristics of the Colusa Basin Drain, Stone Corral Creek and Antelope Creek, and are presented in the following sections. Original image files are found in Section 10.2

Table 4.2.1. Participants of the 10.23.2014 study region visit.

Name	Organization	Affiliation
Greg Pasternack	UCD	Professor
Andrew Gray	UCD, UCR	Postdoctoral Scholar, Assistant Professor
John Childs	UCD, USACE	PhD. Student, Research Engineer
Sooyoun Nam	UCD, TUAT*	Visiting Student, PhD. Student
Alisha Wenzel	CVRWQCB, SWAMP	Staff
Brett Stevens	CVRWQCB, ILRP	Staff
Dana Kuleszra	CVRWQCB, ILRP	Staff
Lynn Coster	CVRWQCB, ILRP	Staff

*TUAT = Tokyo University of Agriculture and Technology.

Table 4.2.2. Ittinerary of 10.26.2014 site visit.

Stop	Location	Report Section
1	The CBD outfall into the Sacramento River	4.2.1.1
2	CBD Outfall Gates	4.2.1.1
3	CBD-1 at Roads 99E and 108	4.2.1.2
4	CBD-2 at County Line Road	4.2.1.3
5	CBD-3 at Tule Road	4.2.1.4
6	CBD-3A at Hahn Rd*	n/a
7	CBD-4 at Davis Weir	4.2.1.5
8	Colusa*	n/a
9	Colusa National Wildlife Refuge	4.2.1.6
10	CBD-5	4.2.1.6
11	Stone Corral Creek at Four Mile Rd	4.2.2
12	SC-4*	n/a
13	Stone Corral Creek at Cemetery Road*	n/a
14	Stone Corral Creek at McDermott Road*	n/a
15	Stone Corral Creek at Sites Road in Sites, CA*	n/a
16	Coast Range foothills and Antelope Creek	4.2.3
17	Tehama-Colusa Canal	4.2.4
18	Glenn-Colusa Canal	4.2.4

CBD 1-5 and Stone Corral Creek station nomenclature corresponds to sampling sites employed in the UCD/US EPA ITM and/or NPS CBD studies. Stops marked with (*) were not visited due to time constraints.

4.2.1 The CBD

The main points of interest on the CBD were the CBD outfall region, including the outfall, outfall gates and the Knights Landing Ridge Cut (Section 4.2.1.1), historical CBD sampling sites (Sections 4.2.1.2-4.2.1.6), and the Colusa National Wildlife Refuge (Section 4.2.1.6). Travel between points of interest passed rice fields and orchards on small to medium sized dirt, gravel and paved county roads. Discharge through the CBD was relatively low as the site visit took place near the end of the irrigation season, but not during the peak end of season rice field draw-down and before the onset of winter rains. Outfall gate operations were typical of irrigation season head management, with backwater effects extending at least as far upstream as CBD-2 (Section 4.2.1.3). Sampling sites CBD-1 and CBD-2 are located on lower gradient reaches in the outfall gate backwater zone and were found to have channel beds with a shallow fine sediment mantle over coarse sediments at (Sections 4.2.1.2, 4.2.1.3) indicative of backwater conditions leading to deposition of fine sediments during low flow periods. Sampling sites CBD-3 and CBD-4 on higher gradient reaches above the low flow backwater zone were found to have coarser channel beds without the fine sediment mantel (Sections 4.2.1.4, 4.2.1.5). Sediment trapping structures were observed, such as large woody debris snags behind bridge supports at CBD-2 and CBD 3 (Sections 4.2.1.3 and 4.2.1.4). Channel bank erosional structures were also found, including bare earth and gullies at CBD-3 (Section 4.2.1.4). Some components of the Colusa National Wildlife Refuge were inundated and waterfowl were present (4.2.1.6).

4.2.1.1 The CBD Outfall Region

The CBD outfall region was visited including the CBD outfall and the CBD outfall gates (Figure 4.2.1). This portion of the CBD was found in a hydrologic state typical of that described by previous observers (see Section 4.1) for low flow irrigation season conditions. Sacramento River stage was low and low flows emanating from the CBD produced no visible sediment plume (Figure 4.2.2 and Figure 4.2.3). The CBD outfall gates were found operating to maintain lower CBD head for irrigation withdrawal with very little water released (Figure 4.2.4 and Figure 4.2.5). This results in backwater conditions (i.e. standing or very low velocity water) present behind the CBD outfall gates (Figure 4.2.5).

Figure 4.2.1. Stop 1: The CBD outfall into the Sacramento River near Knights Landing. Stop 2: The CBD outfall gates.

Figure 4.2.2. Sacramento River at the CBD outfall, as viewed from the western levee of the Sacramento River. Note recreational fisherman at bottom center of frame.

Figure 4.2.3. The CBD outfall into the Sacramento River as viewed looking East from the Knights Landing Fishing Access boat launch.

Figure 4.2.4. The CBD outfall gates looking west from the Knights Landing Fishing Access boat launch during Stop 1.

Figure 4.2.5. Stagnant water behind the CBD outfall gates viewed the east levee.

4.2.1.2 CBD-1 at Roads 99E and 108

The group traveled northwest on Road 108 to stop 3 of the site visit: the historic sampling station CBD-1 at Roads 99E and 108 (Figure 4.2.6). The Road 99E Bridge over the CBD had been employed by the UCD/USEPA studies, as well as previous DWR and USGS sampling efforts (see Section 4.1) (Figure 4.2.7 and Figure 4.2.8). This reach of the CBD was found to be within the backwater zone behind the CBD outfall gates (Figure 4.2.9). Channel bed sediments were found to have a surficial layer of unconsolidated fines (clays and fine silts) mantling an underlying layer incorporating coarser materials including gravel (Figure 4.2.10). Channel bed sediments appear to reflect irrigation season low-flow backwater conditions superimposed upon more energetic conditions of past irrigation or non-irrigation season higher flow conditions consistent with the observations of the UCD/US EPA NPS CBD (see Section 4.1.4).

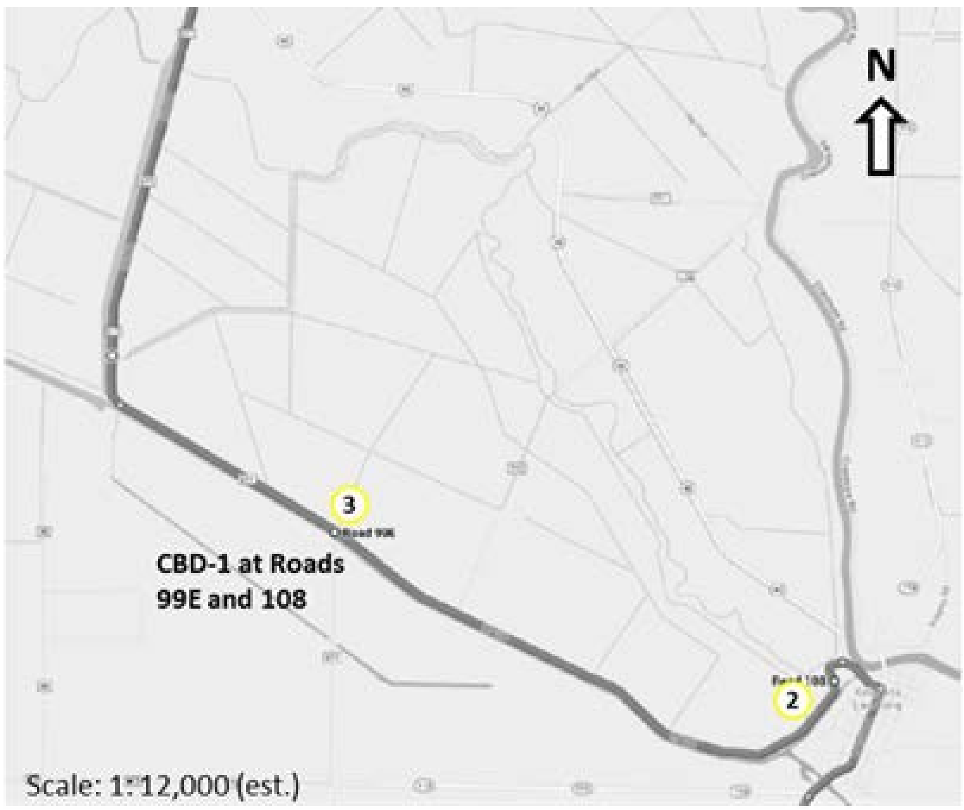

Figure 4.2.6. Stop 3: CBD-1 at Roads 99E and 108.

Figure 4.2.7. The Road 99E Bridge over the CBD as seen from Road 108 on the East levee of the CBD. This bridge was the location of the UCD/US EPA NPS CBD sampling station CBD-1, as well as previous hydrologic gauging/sampling efforts by the DWR and the USGS (stations A0294710 and 11390890, respectively).

Figure 4.2.8. The Road 99E Bridge as viewed from the base of the west levee of the CBD.

Figure 4.2.9. Still waters of the CBD as viewed in the downstream direction from the Road 99E Bridge.

Figure 4.2.10. Western channel margin at CBD-1 illustrating the range of particle sizes, from clays to coarse gravel with shoe for scale. Note fine sediment mantel on channel bottom.

4.2.1.3 CBD-2 at County Line Road

Stop 4 of the site visit was CBD-2 at County Line Road – another bridge crossing employed by the UCD/USEPA NPS CBD study for water and suspended sediment (see Section 4.1.4) (Figure 4.2.11). The County Line Road Bridge had amassed a pile of woody debris on its upstream side, which would increase sediment trapping in this area (Figure 4.2.12 and Figure 4.2.13). Like CBD-1, the reach containing CBD-2 was also found to be within the backwater zone of the CBD outfall gates, with very still water conditions (Figure 4.2.14). Channel bed sediments also exhibited a mantle of fine clay and silt above a coarser mixture incorporating fine gravels, and a high organic content was clearly present (Figure 4.2.15).

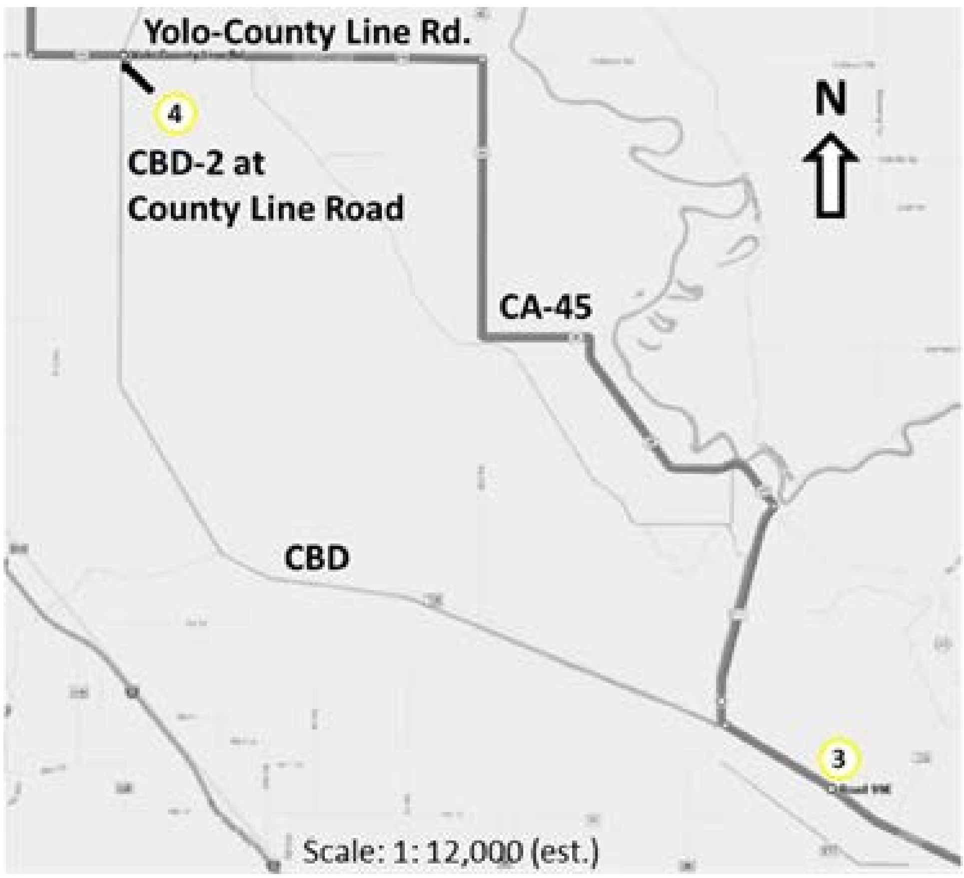

Figure 4.2.11. Stop 4: CBD-2 at County Line Road.

Figure 4.2.12. The County Line Road Bridge over the CBD, which was the location of the UCD/US EPA NPS CBD sampling station CBD-2 as viewed from Road 108 on the east levee of the CBD. Note the deposit of woody debris and sediment against the bridge supports in mid-channel.

Figure 4.2.13. The County Line Bridge and woody debris as viewed from the concrete abutment at the base of the east levee of the CBD.

Figure 4.2.14. The CBD channel exhibiting still water conditions as viewed from the County Road Bridge in the downstream direction.

Figure 4.2.15. CBD channel sediment collected near the base of the east levee illustrating fine top layer over an organic rich mix of fine gravel to clay sediments.

4.2.1.4 CBD-3 at Tule Road

Travel continued onto College City Road, with Stop 5 of the site visit at the historical sampling site of CBD-3 at Tule Road, which was also employed by the UCD/US EPA NPS CBD study (see Section 4.1.4) (Figure 4.2.16). The location has a stilling well installation for stage monitoring (Figure 4.2.17 and Figure 4.2.18). Another woody debris jam was found against the supports on the upstream side of the Tule Road Bridge (Figure 4.2.19). Gullies were found in the bare earth of the eastern banks of the CBD near this bridge, indicating channel bank sediment sources (Figure 4.2.20). Flowing water indicated that this reach of the CBD was likely above the current backwater effects of the outfall gates (Figure 4.2.21). Channel bed sediment and bedforms were indicative of higher stream energy conditions in this region of the CBD (Figure 4.2.22, Figure 4.2.23, Figure 4.2.24), which is consistent with the results of channel geomorphic and sediment transport analyses carried out by the UCD/US EPA NPS CBD (Section 4.1.4). Channel bed sediments in currently inundated portions of the channel were found to be composed of silt to fine gravel without the mantle of fine clay and silt found in the backwater regions downstream (Figure 4.2.22). Emergent sand bars near the bridge and downstream were evidence of higher energy sediment transport and deposition regimes at times of higher discharge (Figure 4.2.23 and Figure 4.2.24). The CBD is this region is narrower than downstream, and riparian vegetation in more prevalent (Figure 4.2.25).

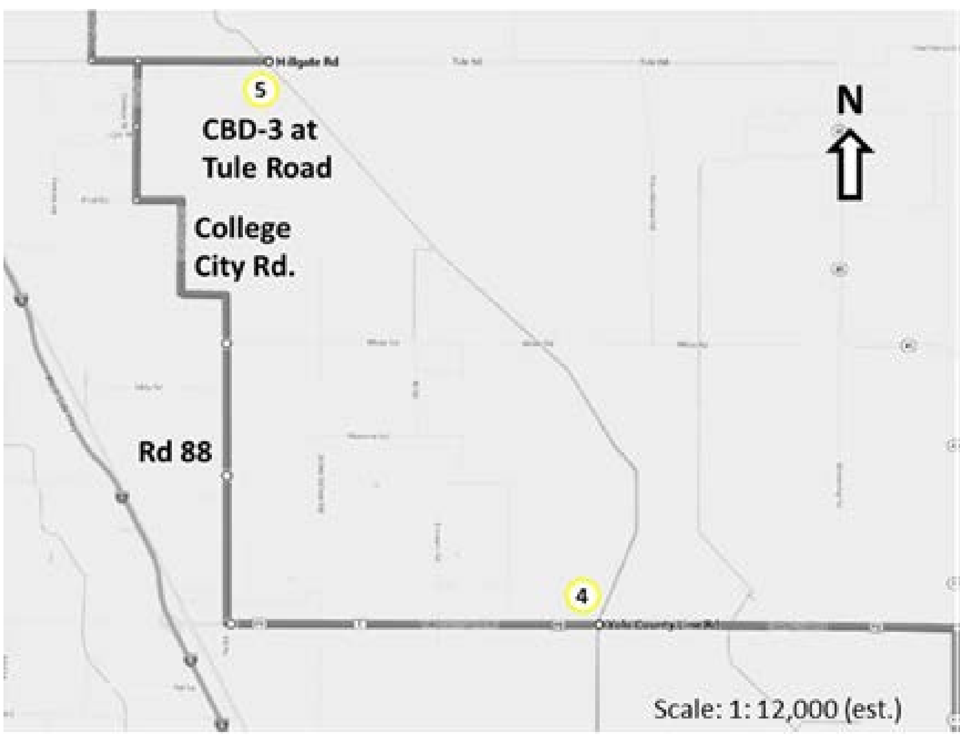

Figure 4.2.16. Stop 5: CBD-3 at Tule Road.

Figure 4.2.17. The Tule Road Bridge over the CBD, which was the location for the UCD/US EPA NPS CBD project's sample site CBD-3 as viewed from the eastern bank (river left) of the CBD. Note apparent stilling well installation for discharge monitoring.

Figure 4.2.18. Gauging station at CBD-3.

Figure 4.2.19. View of underside of Tule Rd. Bridge from east bank (river left) illustrating woody debris jam.

Figure 4.2.20. Evidence of gully erosion on the east bank (river left) of the CBD under the Tule Rd. Bridge.


Figure 4.2.21. The CBD waters exhibiting flowing conditions at the Tule Rd. Bridge.


Figure 4.2.22. CBD channel bed material collected near the east bank illustrating silt to fine gravel composition.

Figure 4.2.23. The CBD channel as viewed from the Tule Road Bridge looking in the downstream direction and illustrating the mid-channel sand bar vegetation.

Figure 4.2.24. The CBD channel extending downstream as viewed from the Tule Road Bridge. Note the sand bar extending into the channel from the right (west) bank.

Figure 4.2.25. The CBD channel extending upstream as viewed from the Tule Rd. Bridge. Note riparian vegetation extending over mid-channel from each bank.

4.2.1.5 CBD-4 at Davis Weir

Planned stops 5 and 6 were not performed due to time considerations. The next stop that was observed on the site visit was CBD-4 at Davis Weir, another UCD/USEPA sampling site (Section 4.1.4) (Figure 4.2.26 and Figure 4.2.27). The Davis Weir is operated by the GCID, who continue to maintain stage monitoring at this site (Figure 4.2.28). Directly downstream of the Davis Weir is an enlargement of the CBD that involves parallel rather than single channels (Figure 4.2.29).

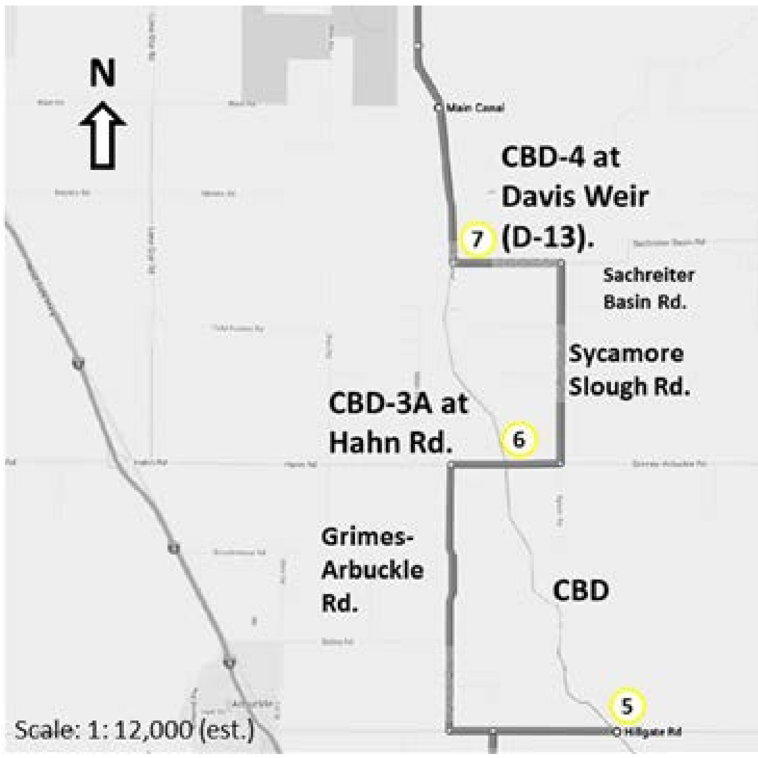

Figure 4.2.26. Stops 6: CBD-3A at Hahn was not performed due to time considerations. Stop 7: CBD-4 at Davis Weir.

Figure 4.2.27. Davis Weir on the CBD, also the location of CBD-4, an historical UCD/USEPA NPS CBD sampling station, as viewed from river left.

Figure 4.2.28. GCID gauges (A) directely upstream and (B) downstream of the Davis Weir.

Figure 4.2.29. View of CBD downstream from Davis Weir. Note dual channel reach in upper left quadrant of frame.

4.2.1.6 The Colusa National Wildlife Refuge and CBD-5 at Highway 20

The site visit progressed on to Colusa, CA, the Colusa National Wildlife Refuge and CBD-5 at Highway 20 (Figure 4.2.30). The CBD runs through the Colusa National Wildlife Refuge and is involved in its flooding and drainage (Figure 4.2.31 and Figure 4.2.32). Portions of the Colusa National Wildlife Refuge were flooded at this time and waterfowl were present (Figure 4.2.33). The Highway 20 Bridge is the CBD-5 sampling site utilized by the UCD/US EPA NPS CBD study (Section 4.1.4). This is also the location of long term hydrologic monitoring by DWR (station A02876), and more recent sample collection by CVRWQCB ILRP and SWAMP (station 520COL006) (see Section 4.1.1). Flowing water conditions were observed here, well upstream of CBD outfall gate backwater effects.

Figure 4.2.30. Stop 8: Colusa, CA. Stop 9: Colusa National Wildlife Refuge.
Stop 10: CBD-5 at Hwy. 20.


Figure 4.2.31. The CBD running through the Colusa National Wildlife Refuge.


Figure 4.2.32. Water control structures in the Colusa Basin Wildlife Refuge.


Figure 4.2.33. Inundated wetlands at the Colusa Basin Wildlife Refuge with waterfowl in mid frame.

Figure 4.2.34. The Highway 20 Bridge over the CBD, which was the location of the CBD-5 sampling site during the UCD/US EPA NPS CBD project, and continues to be the location of the DWR hydrologic gauging station A02876, as viewed from river right. Samples have also been collected here under CVRWQCB programs (station 520COL006). Note the presence of surface currents visible downstream from the central bridge supports.

4.2.2 Stone Corral Creek

This leg of the trip shifted from the CBD to Stone Corral Creek, which was then followed out of the lowlands and into the foothills (Section 4.2.3). Travel progressed from the rice fields of the basin lands, on to row crops and orchard. Stone Corral Creek at Four Mile Road, a sampling site during the UCD/US EPA studies, was visited (Figure 4.2.35). A large partially vegetated gully draining a nearby orchard was observed near the Four Mile Road Bridge over Stone Corral Creek (Figure 4.2.36). Channel banks with a mosaic of vegetation and bare earth were also observed on Stone Corral creek in the vicinity, which appeared to be over-steepened and unstable in agreement with the large set of channel bank observations performed by Geomorph *et al.* 2010) (see Section 4.1.3) (Figure 4.2.37)

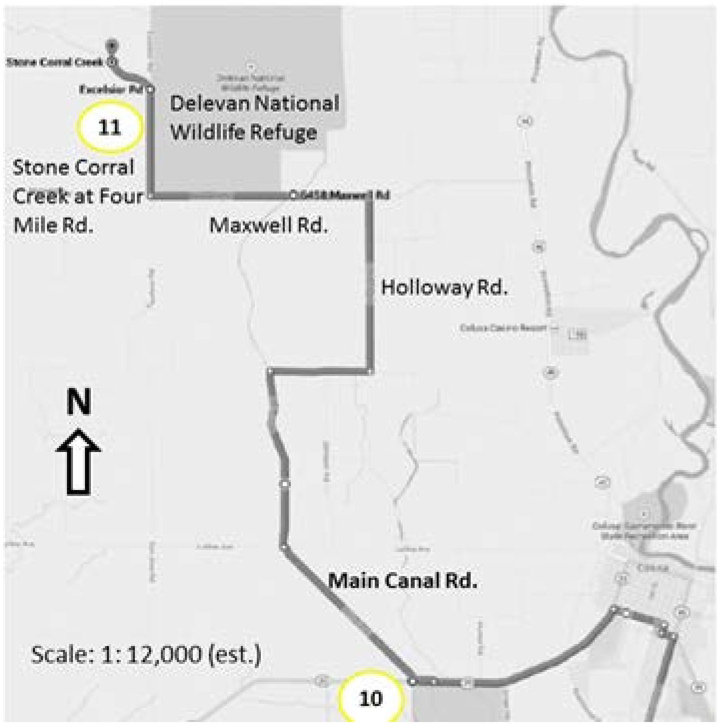

Figure 4.2.35. Stop 11. Stone Corral Creek at Four Mile Road.

Figure 4.2.36. Stone Corral Creek at the Four Mile Road Bridge. Note large vegetated gully on far bank.

Figure 4.2.37. Stone Corral Creek in the vicinity of the Four Mile Road Bridge. Note steep channel banks with a mosaic of vegetated cover and bare earth.

4.2.3 The Coast Range Foothills

This portion of the site visit progressed out of the valley and basin lands, up the rise of the eastern front of the Coast Ranges foothills (Section 4.2.3.1) and into Antelope Valley, one of the linear valleys of the interior foothills (Section 4.2.3.2). Of particular interest in these regions were channel and hillslope erosional features.

4.2.3.1 Eastern Rise of the Coast Range Foothills

The Maxwell/Sites Road was followed up the remnant alluvial fan of Stone Corral Creek and into the eastern rise of the Coast Ranges foothills (Figures 4.2.38 and 4.2.39). Steeply plunging exposures of the Tehama formation were visible along the eastern front near the Stone Corral Creek drainage gap, including rock cliff faces (Figure 4.2.40).

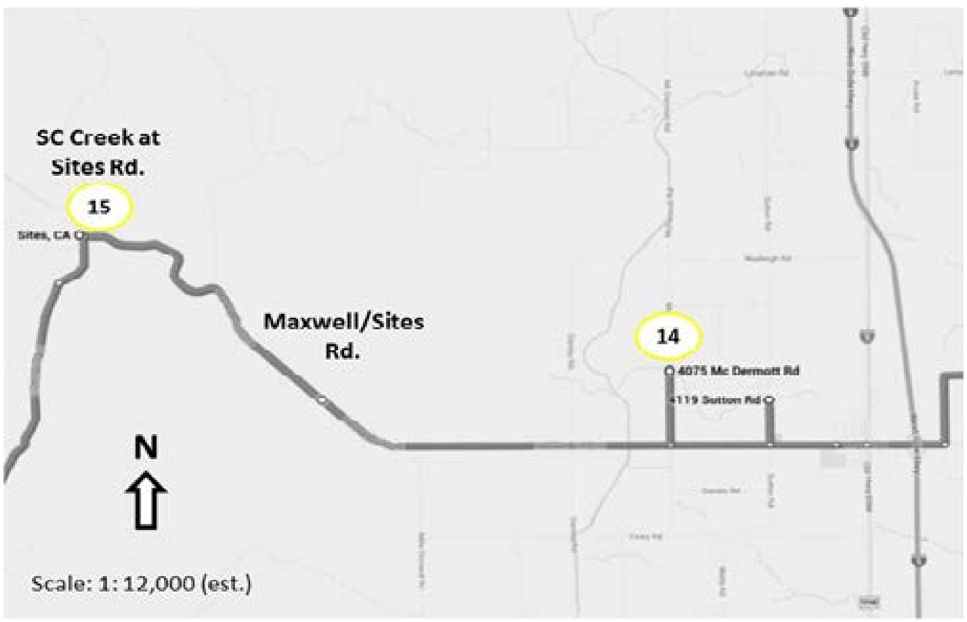

Figure 4.2.38. The path driven up the eastern rise of the Coast Ranges Foothills. These stops were not visited due to time constraints.

Figure 4.2.39. The Coast Range foothills eastern front as viewed from the Maxwell/Sites Road. The Stone Corral Creek drainage gap is visible in the mid-right field of the frame.

Figure 4.2.40. Cliff exposure of steeply plunging bedrock of the Tehama formation near the Stone Corral Creek drainage gap in the eastern front of the Coast Range Foothills.

4.2.3.2 Antelope Creek and the Coast Range Foothills

Antelope Creek Valley, which is the potential location of the largest reservoir in the proposed NODOS facility for additional Sacramento River Water Storage (see Section 2.3.4), was followed via Antelope Creek Road (Figure 4.2.41). As the foothill region of the Colusa Basin watershed have been found to be the largest contributors of to the production of sediment from the watershed (see Section 4.1), particular attention was paid to erosional features. Diverse stops were made along Antelope Creek to view erosional features of the surrounding hillsides, tributaries and the channel of Antelope Creek itself (Figure 4.2.42 to Figure 4.2.46). Active, steep debris slides were observed (Figure 4.2.42), as well as horizontal, linear erosional features conforming to the steeply plunging strata of the deformed bedrock (Figure 4.2.43), and intermittently active channel head cuts high on hillslope convergence zones (Figure 4.2.44). The channel banks of a tributary and those of Antelope Creek itself were also observed to have many visible slumps and mosaics of grasses and bare vegetation, indicating a high likelihood of channel instability, in agreement with the broader findings of Geomorph *et al.* (2010) for this region (Section 4.1.3) (Figure 4.2.45 and Figure 4.2.46).

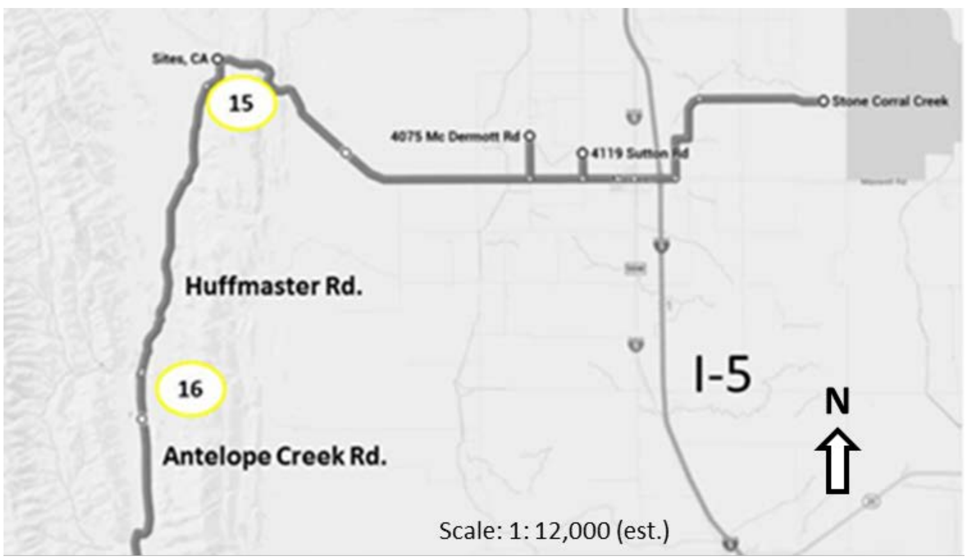

Figure 4.2.41. Diverse stops were made along Antelope Creek accessed via Antelope Creek Road (Stop 16).

Figure 4.2.42. Steep debris slide near the floor on the north side of Antelope Valley.

Figure 4.2.43. Steep slopes vegetated with grass and oak on the south side of Antelope Valley. Note linear erosional features running normal to the slope (horizontally across the frame) illustrating the control of steeply folded bedrock strata on the geomorphic development of the Coast Range foothills.

Figure 4.2.44. Grass covered slopes on the southern side of Antelope Valley with headwater channel initiation visible in the top center field of the frame.

Figure 4.2.45. Ephemeral tributary of Antelope Creek on the south side of the valley, with steep banks with grassy cover and bare soil.

Figure 4.2.46. The dry bed of Antelope Creek as viewed from river right with incised thalweg, and steep right bank with grass cover and bare earth.

4.2.4 The Tehama and GCID Main Canals

The final stage of the site visit focused on the two main conveyances of irrigation waters in the Colusa Basin: the Tehama Colusa Canal and the GCID Main Canal in the vicinity of Williams, CA (see Section 2.3.1) (Figure 4.2.47). The more modern Tehama Colusa Canal is a trapezoidal concrete structure in this region (Figure 4.2.48). The older GCID Main Canal still has an earthen construction (Figure 4.2.49 and Figure 4.2.50).

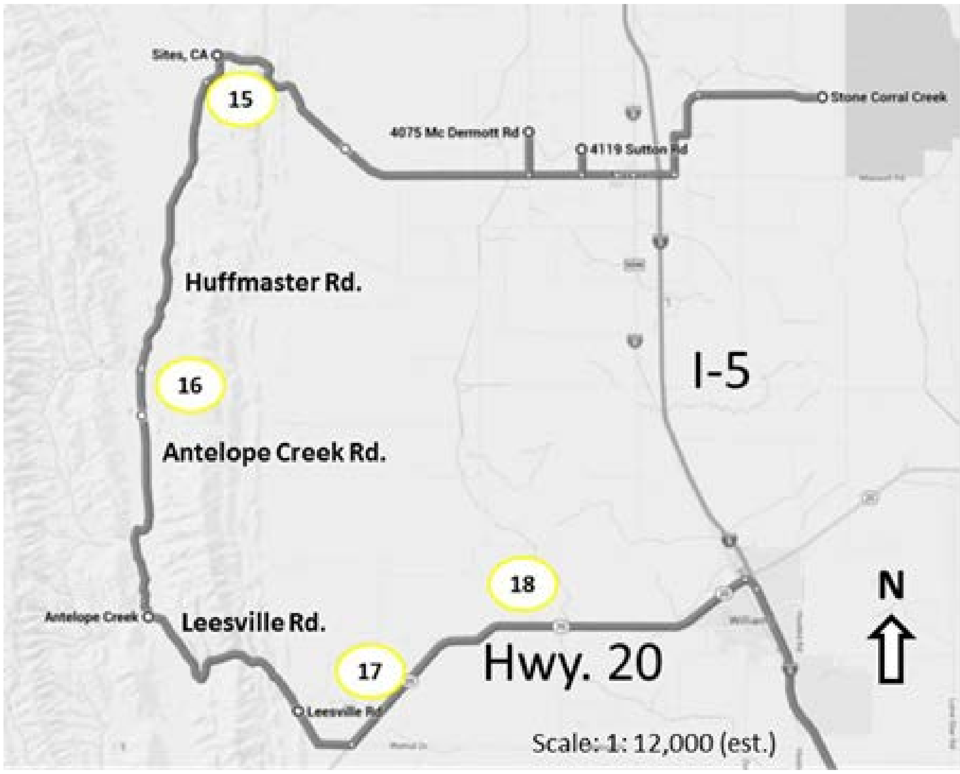

Figure 4.2.47. Stops 17 and 18, the Tehama Colusa and the GCID Main Canals, respectively were accessed via Highways I-5 and 20 as Leesville Road was inaccessible (i.e. private).

Figure 4.2.48. The Tehama Colusa Canal with view of the Coast Range foothills to the northwest. Note its concrete construction.

Figure 4.2.49. The GCID Main Canal as viewed from its east bank. Note its earthen construction.

Figure 4.2.50. The earthen channel bank and bottom of the GCID Main Canal.

4.3 Synthesis of Suspended Sediment Ambient Characteristics and Dynamics

Suspended sediment data collected for previous studies on sediment dynamics and ongoing monitoring programs (see Section 4.1) was pooled to inform a new analysis of the suspended sediment dynamics of the Colusa Basin watershed. The objectives of this analysis were to evaluate whether sediment conditions and dynamics had changed significantly since in-depth studies of the late 1970s by assessing ambient suspended sediment concentrations and turbidities (Section 4.3.1), and examine temporal and spatial patterns of suspended sediment concentration regimes (Section 4.3.2). Data files are available in Section 10.3.

4.3.1 Ambient Suspended Sediment Concentrations and Turbidity Values

All available data for the suspended sediment metrics C_{SS} and turbidity in the Colusa Basin drainage area and sites of interest on its two main receiving water bodies, the Sacramento River and the Knights Landing Ridge Cut, were collated. The basic dimensions of the suspended sediment data set were then described in terms of geographic and temporal coverage, and the sampling agencies and programs responsible for data collection and reporting. The following statistical descriptors of the suspended sediment metrics were computed for each sampling station in aggregate and by season: mean, maximum, minimum and standard deviation.

The highest mean and maximum C_{SS} and turbidity values were generally found during the non-irrigation season. Ranges of turbidity and C_{SS} values observed at each station generally varied by one to two orders of magnitude, with generally higher variability during the non-irrigation season. Magnitudes of C_{SS} and turbidity generally increased downstream in the CBD, with notable exceptions as observed reported in the UCD/USEPA NSP CBD study (see Section 4.1.4). The highest C_{SS} values in the entire Colusa Basin drainage area were found in foothill streams during high rainfall/runoff events in the non-irrigation season.

The high spatial and temporal variability of fluvial suspended sediment abundance in the Colusa Basin drainage area highlights the fact that water quality conditions in terms of fluvial sediments is also variable, and that sediment impact assessments must incorporate considerations of the duration of high ambient C_{SS}/Turbidity magnitudes (see Section 5).

Data on C_{SS} and turbidity in the Colusa Basin drainage area and receiving water bodies were collected by DWR and the USGS, UC Davis scientists during the UCD/USEPA ITM and NSP CBD projects, and by multiple entities for the CVRWQCB programs: ILRP and SWAMP (Table 4.3.1). Although the base period of sampling extended from 1957 through 2014, more than 80% of the 4497 C_{SS} samples and 1432 turbidity measurements collected in the Colusa Basin drainage area were produced by the UCD/USEPA studies conducted between 1975 and 1981. Some 1477 and 638 C_{SS} and turbidity samples were collected from the sampling stations on the Sacramento located immediately upstream and downstream of the CBD outfall, respectively. Most of the sampling at sites of interest on the Sacramento River was conducted by the DWR and the USGS between 1960 and 1980, although sampling has continued into 2014 through efforts by the DWR and under the ILRP and SWAMP programs. A small amount of suspended sediment characterization took place in the Knights Landing Ridge Cut during the 2007 water year under the CVRWQCB ILRP, which produced 15 and 13 C_{SS} and turbidity measurements, respectively.

Table 4.3.1. Suspended sediment samples by water body.

Colusa Basin drainage area

Agency/ Program	Samples (n)		Period of Sampling*	
	C_{SS}	Turbidity	Beginning	End
DWR	305	305	7/30/1957	5/7/2014
ILRP	255	343	4/8/2003	6/25/2013
SWAMP	13	28	6/18/2009	6/29/2011
UCD/USEPA	3738	3456	4/7/1975	9/28/1981
USGS	186	0	2/7/1996	4/15/1998
Total	*4497*	*4132*	*7/30/1957*	*5/7/2014*

Sacramento River

Agency/ Program	Samples (n)		Period of Sampling*	
	C_{SS}	Turbidity	Beginning	End
DWR	519	519	7/20/1960	5/7/2014
ILRP	8	8	4/8/2003	10/2/2003
SWAMP	0	31	-	-
UCD/USEPA	0	80	5/12/1981	9/15/1981
USGS	950	0	12/18/1972	5/31/1980
Total	*1477*	*638*	*7/20/1960*	*5/7/2014*

Knights Landing Ridge Cut

Agency/ Program	Samples (n)		Period of Sampling*	
	C_{SS}	Turbidity	Beginning	End
ILRP	15	13	12/11/2006	8/7/2007

*Period of sampling encompassing all samples (both C_{SS} and Turbidity) collected by each agency/program.

Several methods were utilized to collect and analyze C_{SS} or total suspended solids (*TSS*) samples. Despite differences in processing methods between C_{SS} and *TSS* samples, all were pooled and will be referred to as C_{SS} samples in this study (see Gray *et al.*, 2000). Differences in these laboratory procedures, and others such as the precise pore size of filters or aspects of centrifuge technique likely had a small impact on systematic bias by collection agency/program. Differences in sample collection techniques, particularly between surface/subsurface grab samples and depth or flow (depth/width) integrated sampling techniques may have resulted more significant systematic bias between agencies/programs. These issues are examined in Section 4.3.2 through testing for differences in the C_{SS}-Q relationship on the basis of a number of factors, including the agency/program of collection. Most turbidity data was collected and reported in NTU or JTU, however a small number of early samples collected by DWR from the lower CBD and the Sacramento River in 1960s were reported in 'turbidity as SiO_2 (mg/L) units. Turbidities measured in NTU and JTU were pooled by station due to the general equivalence of these units, while those reported in SiO_2 units were not utilized in the study due to a lack of equivalence and standard conversion (see Section 3.2).

Suspended sediment data collection in the Colusa Basin drainage area was conducted by previous studies and sampling programs at locations along the CBD, in irrigation drainage lateral canals, foothill tributaries of the CBD, and irrigation supply waters from the Glenn Colusa Irrigation District (GCID) supply canal. Some 1747 and 1722 turbidity and C_{SS} samples were collected from 11 stations along the CBD between 1957 and 2014 by the DWR, UCD/USEPA, USGS, and the CVRWQCB SWAMP (Table 4.3.2, Figure 4.3.1). Most (> 90%) of the samples from the CBD were collected during the UCD/USEPA NSP CBD studies from 1977 to 1981. Additional sampling by the DWR, the UCD/USEPA ITM project, the USGS and the CVRWQCB resulted in an expansion of the CBD-1 data set base period (1957–2014). The CBD-5 sample set was also extended through CVRWQCB efforts including ILRP turbidity measurements and SWAMP C_{SS} samples collected between 2005 and 2012. The three sampling stations lowest in the CBD (CBD Outfall, CBD at Knights Landing downstream , and CBD at Knights Landing upstream) were considered as a single location labeled as 'CBD Outfall' due to their spatial proximity and location below the CBD outfall gates (see Figure 4.3.1).

4.3.1.1 CBD Ambient Suspended Sediment Conditions

Between the years 1957 and 2014 some 1747 and 722 turbidity and C_{SS} measurements, respectively, were collected at 11 stations along the CBD. Mean turbidity values recorded at the CBD stations ranged from 10 NTU/JTU at CBD-7, the uppermost station, during the irrigation season, to 127 NTU/JTU at CBD-2 during the non-irrigation season (Table 4.3.3). Likewise, mean C_{SS} values ranged from 23 to 171 mg/L for CBD-7 during the irrigation season and the CBD-2 during the non-irrigation season, respectively (Table 4.3.4). In general, the uppermost reaches of the CBD displayed lower mean, minimum, and maximum turbidity and C_{SS} values than middle and lower reaches of the CBD, with the exception of the CBD Outfall. This may be influenced by the trapping of sediment behind the outfall gates and deposition of sediment in the low slope reaches of the lower CBD. However the CBD Outfall sample set is very small and bears low ambient values in part due to sampling conducted during low discharges (more on this topic in Section 4.3.2). Values of all statistical descriptors of C_{SS} and Turbidity magnitudes were generally higher during the non-irrigation season than during the irrigation season for all stations on the CBD, with the exception of CBD-2B. As thoroughly examined in the UCD/USEPA NSP CBD studies, the higher sediment concentrations found at CBD-2B appear to be caused in part by entrainment of bed material in the steeper region of the CBD directly upstream during irrigation return flows (see Section 4.1.4).

Table 4.3.2. CBD suspended sediment data.

CBD Stations	SS Data (n)		Programs						Seasonal Coverage		Sample Period	
	Turb.	C_{SS}	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
				ITM	NSP CBD		ILRP	SWAMP				
CBD Outfall	10	-	-	-	x	-	-	-	x	-	5/12/1981	9/15/1981
CBD.a.KnLnd.dnstr	5	-	-	-	-	-	-	x	x	x	5/18/2009	12/14/2009
CBD.a.KnLnd.upstr	10	-	-	-	-	-	-	x	x	x	2/25/2009	5/4/2011
CBD-1	712	712	x	x	x	x	x	-	x	x	7/30/1957	5/7/2014
CBD-2	203	203	-	-	x	-	-	-	x	x	12/22/1977	9/28/1981
CBD-2b	76	76	-	-	x	-	-	-	x	x	5/2/1978	9/29/1980
CBD-3	222	222	-	-	x	-	-	-	x	x	1/17/1978	9/28/1981
CBD-4	160	160	-	-	x	-	-	-	x	x	10/3/1977	9/15/1981
CBD-5	75	75	-	-	x	-	x	x	x	x	10/3/1977	9/18/2012
CBD-6	90	90	-	-	x	-	-	-	x	x	10/3/1977	9/15/1981
CBD-7	184	184	-	x	x	-	-	-	x	x	4/7/1975	9/15/1981
Total	*1747*	*1722*	*x*	*x*	*x*	*x*	-	*x*	*x*	*x*	*7/30/1957*	*5/7/2014*

CBD Outfall is located at the outfall of the CBD into the Sacramento River. CBD.a.KnLnd.dnstr = CBD at Knights Landing downstream, which is approximately 300 meters upstream from the CBD Outfall. CBD.a.KnLnd.upstr = CBD at Knights Landing upstream, which is approximately 400 meters upstream from the CBD Outfall. The following UCD/USEPA stations corrospond to existing bridges/road crossings of the CBD: CBD-1 at Road 99E and Road 109, CBD-2 at County Line Road, CBD-2b at White Road, CBD-3 at Tule Rd., CBD-4 at Davis Weir, CBD-5 at Highway 20, CBD-6 at Princeton Road, CBD-7 at Sidds Road.

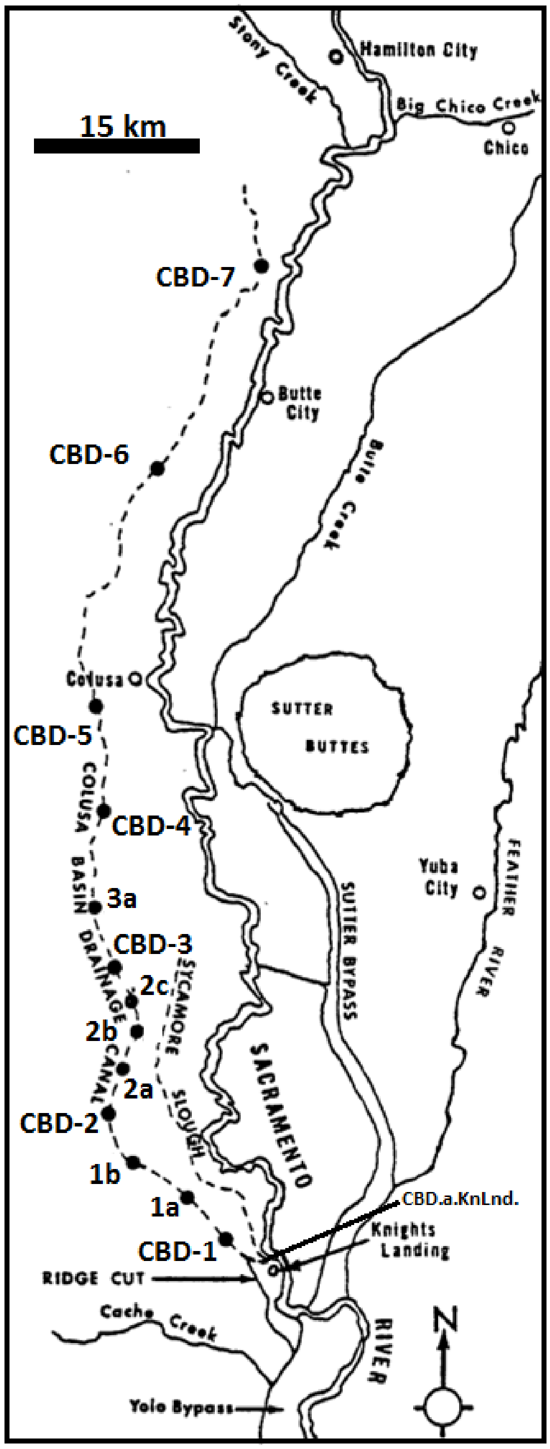

Figure 4.3.1. Suspended sediment sampling stations on the CBD. Stations labeled with an alpha-numeric pair are also 'CBD' prefix stations. 'CBD.a.KnLnd.' indicates the lowest three stations in the CBD (CBD Outfall, CBD at Knights Landing downstream , and CBD at Knights Landing upstream) are all downstream of the CBD outfall gates and are located at the outfall of the CBD into the Sacramento River, and 300 and 400 meters upstream, respectively. (Adapted from Tanji *et al.*, 1978).

Table 4.3.3. CBD turbidity descriptive statistics by station and season

CBD Station	Season	n	Beginning	End	Turbidity			
					Mean	Min	Max	Stdev
CBD Outfall	All	25	5/12/1981	5/4/2011	55	15	113	22
CBD Outfall	Irrigation	18	5/12/1981	5/4/2011	51	15	82	20
CBD Outfall	Non-Irrigation	7	2/25/2009	2/2/2011	64	40	113	25
CBD-1	All	712	7/30/1957	5/7/2014	72	1	1700	139
CBD-1	Irrigation	335	7/30/1957	5/7/2014	57	1	1700	116
CBD-1	Non-Irrigation	377	10/14/1957	11/6/2013	85	5	1250	156
CBD-2	All	203	12/22/1977	9/28/1981	82	0	1750	159
CBD-2	Irrigation	106	4/2/1978	9/28/1981	41	0	321	36
CBD-2	Non-Irrigation	97	12/22/1977	3/30/1981	127	4	1750	219
CBD-2B	All	76	5/2/1978	9/29/1980	34	11	120	22
CBD-2B	Irrigation	65	5/2/1978	9/29/1980	35	11	120	23
CBD-2B	Non-Irrigation	11	10/3/1978	11/5/1979	32	22	46	8
CBD-3	All	222	1/17/1978	9/28/1981	70	0	975	114
CBD-3	Irrigation	131	4/2/1978	9/28/1981	41	0	120	22
CBD-3	Non-Irrigation	91	1/17/1978	3/30/1981	111	7	975	168
CBD-4	All	160	10/3/1977	9/15/1981	45	1	720	97
CBD-4	Irrigation	105	4/3/1978	9/15/1981	26	1	115	19
CBD-4	Non-Irrigation	55	10/3/1977	3/17/1981	82	4	720	158
CBD-5	All	75	10/3/1977	9/18/2012	62	12	675	115
CBD-5	Irrigation	47	4/3/1978	9/18/2012	36	12	81	16
CBD-5	Non-Irrigation	28	10/3/1977	2/28/2006	107	17	675	181
CBD-6	All	90	10/3/1977	9/15/1981	29	2	380	62
CBD-6	Irrigation	46	4/3/1978	9/15/1981	11	2	32	7
CBD-6	Non-Irrigation	44	10/3/1977	3/17/1981	47	3	380	85
CBD-7	All	184	4/7/1975	9/15/1981	16	1	335	41
CBD-7	Irrigation	116	4/7/1975	9/15/1981	10	1	82	11
CBD-7	Non-Irrigation	68	10/6/1975	3/17/1981	28	2	335	65

Table 4.3.4. CBD C_{SS} descriptive statistics by station and season.

CBD Station	Season	n	Beginning	End	C_{SS}			
					Mean	Min	Max	Stdev
CBD-1	All	712	7/30/1957	5/7/2014	96	6	1454	126
CBD-1	Irrigation	335	7/30/1957	5/7/2014	84	11	801	68
CBD-1	Non-Irrigation	377	10/14/1957	11/6/2013	106	6	1454	159
CBD-2	All	203	12/22/1977	9/28/1981	120	10	1578	177
CBD-2	Irrigation	106	4/2/1978	9/28/1981	72	10	213	40
CBD-2	Non-Irrigation	97	12/22/1977	3/30/1981	171	12	1578	244
CBD-2B	All	76	5/2/1978	9/29/1980	71	18	198	41
CBD-2B	Irrigation	65	5/2/1978	9/29/1980	73	18	198	43
CBD-2B	Non-Irrigation	11	10/3/1978	11/5/1979	62	38	87	16
CBD-3	All	222	1/17/1978	9/28/1981	120	11	984	160
CBD-3	Irrigation	131	4/2/1978	9/28/1981	88	11	288	50
CBD-3	Non-Irrigation	91	1/17/1978	3/30/1981	166	16	984	236
CBD-4	All	160	10/3/1977	9/15/1981	76	6	1006	107
CBD-4	Irrigation	105	4/3/1978	9/15/1981	57	6	219	37
CBD-4	Non-Irrigation	55	10/3/1977	3/17/1981	112	8	1006	170
CBD-5	All	75	10/3/1977	9/18/2012	91	7	880	132
CBD-5	Irrigation	47	4/3/1978	9/18/2012	60	7	214	38
CBD-5	Non-Irrigation	28	10/3/1977	2/28/2006	129	31	880	187
CBD-6	All	90	10/3/1977	9/15/1981	46	1	324	64
CBD-6	Irrigation	46	4/3/1978	9/15/1981	28	8	79	15
CBD-6	Non-Irrigation	44	10/3/1977	3/17/1981	64	1	324	87
CBD-7	All	184	4/7/1975	9/15/1981	29	1	356	42
CBD-7	Irrigation	116	4/7/1975	9/15/1981	23	1	157	19
CBD-7	Non-Irrigation	68	10/6/1975	3/17/1981	38	2	356	63

4.3.1.2 Lateral Drain Ambient Suspended Sediment Conditions

Some 435 and 422 turbidity and C_{SS} samples, respectively, were collected from 16 sites along lateral drains (including relic sloughs of the Sacramento River) in the Colusa Basin drainage area between 1975 and 2011 (Table 4.3.5, Figure 4.3.2, Figure 4.3.3). The lateral drains were primarily sampled by the UCD/USEPA during the ITM and NSP CBD projects between 1975 and 1981, which together account for over 90% of both turbidity and C_{SS} samples (Table 4.3.5). The remainder of samples was collected under the CVRWQCB ILRP and SWAMP between 2003 and 2011. There was no apparent overlap in sampling stations between the UCD/USEPA and CVRWQCB sampling programs. The highest C_{SS} and turbidity values were sampled during the non-irrigation season at all lateral drain locations where both seasons were sampled, with the exception of a small (n = 6) sample set from Sycamore Slough. Minimum turbidity or C_{SS} values were generally < 10 (NTU or mg/L) during either season at stations with a higher degree of monitoring (n > 20) (Table 4.3.6 and Table 4.3.7). Maximum turbidity values ranged from 53 to 165 NTU during the irrigation season, and 450 to 2900 NTU for stations with a higher degree of monitoring (Table 4.3.6). Similarly, maximum C_{SS} values ranged from 82 to 165 mg/L during the irrigation season and 562 to 1630 mg/L during the non-irrigation season for highly monitored stations (Table 4.3.7).

Table 4.3.5. Later drain suspended sediment data.

Lateral Drain Stations	SS Data (n)		Programs						Seasonal Coverage		Sample Period	
				UCD/USEPA			CVRWQCB					
	Turb.	C_{SS}	DWR	ITM	NSP CBD	USGS	ILRP	SWAMP	Irrigation	Non-irrigation	Beginning	End
LD1. Ag.ditch.nr.Wescott.rd	2	2	-	-	-	-	-	x	x	-	5/25/2011	6/29/2011
LD2. Ag.ditch.nr.WillSGreen.rd	2	2	-	-	-	-	-	x	x	-	5/25/2011	6/29/2011
LD3. Bondurant-slough	116	116	-	x	x	-	-	-	x	x	4/7/1975	9/15/1981
LD4. Dr.S.o.rd.14	-	1	-	-	-	-	x	-	x	-	6/5/2003	6/5/2003
LD5. Dr.t.walker.cr.a.country.rd.F	2	-	-	-	-	-	x	-	x	-	7/11/2005	7/25/2005
LD6. East.drain.a.4mile.rd	9	10	-	-	-	-	x	-	x	-	4/10/2003	9/16/2003
LD7. GCID-Drain-55	91	91	-	x	x	-	-	-	x	x	4/10/2003	10/7/2003
LD8. GCID-section-25	57	57	-	x	x	-	-	-	x	x	4/7/1975	8/31/1981
LD9. Kuhl-Weir	57	57	-	x	x	-	-	-	x	x	4/7/1975	8/31/1981
LD10. Powell.sl.a.hwy20	2	2	-	-	-	-	-	x	x	-	5/25/2011	6/29/2011
LD11. Powell.sl.dnstr.n.Wescott.rd	2	2	-	-	-	-	-	x	x	-	5/25/2011	6/29/2011
LD12. Powell.sl.upstr.n.Wescott.rd	2	2	-	-	-	-	-	x	x	-	5/25/2011	6/29/2011
LD13. Salmon-hole	74	74	-	x	x	-	-	-	x	x	4/7/1975	8/31/1981
LD14. Sycamore.sl.a.hwy45	5	6	-	-	-	-	x	-	x	x	6/24/2003	10/7/2003
LD15. Unn.canal.a.hwy45	5	-	-	-	-	-	x	-	x	-	7/8/2004	9/2/2004
LD16. Unn.dr.walker.cr.crd.28	9	-	-	-	-	-	x	-	x	-	7/12/2004	7/25/2005
Total	*435*	*422*	-	*x*	*x*	-	*x*	*x*	*x*	*x*	*4/7/1975*	*6/29/2011*

LD1. Ag.ditch.nr.Wescott.rd = Agricultural ditch near Wescott Road, LD2. Ag.ditch.nr.WillSGreen.rd = Agricülutural ditch near Will S. Green Road, LD3.Bondurant-slough = Bondurant Slough, LD4. Drain.S.o.rd.14 = Drain south of Road 14, LD5. Drain.t.walker.cr.a.country.rd.F = Drain to Walker Creek at country road F., LD6. East.drain.a.4mile.rd = East drain at Fourmile Road, LD7. GCID-Drain-55 = Glenn Colusa Irrigation District Drain 55, LD8. GCID-section-25 = Glenn Colusa Irrigation District Lateral Drain section 25, L9. Kuhl-Weir = Kuhl Weir, LD10. Powell.sl.a.hwy20 = Powell Slough at Highway 20, LD11. Powell.sl.dnstr.n.Wescott.rd = Powell Slough downstream near Wescott Road, LD12. Powell.sl.upstr.n.Wescott.rd = Powell Slough downstream near Wescott Road, LD14. Sycamore.sl.a.hwy45 = Sycamore Slough at Highway 45, LD15. Unn.canal.a.hwy45 = Unnamed canal at Highway 45, LD 16. Unn.dr.walker.cr.country.rd.28 = Unnamed drain to Walker Creek at Country Road 28.

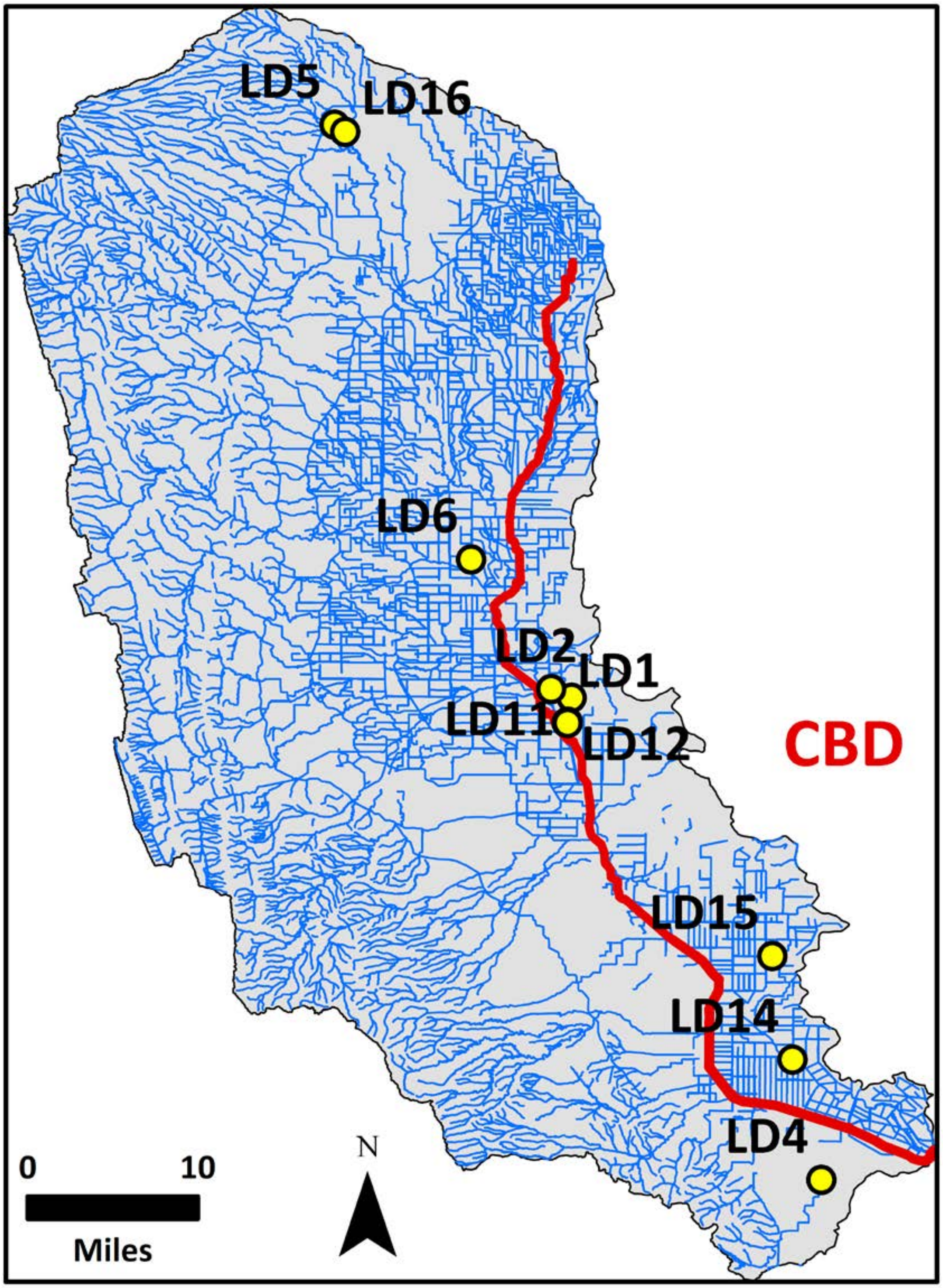

Figure 4.3.2. Lateral drain sampling stations utilized by the CVRWQCB in the Colusa Basin drainage area. LD1 = Agricultural Ditch near Wescott Road, LD2 = Agricultural Ditch near Will S. Green Road, LD4 = Drain south of Road 14, LD5 = Drain to Walker Creek at County Road F, LD6 = East Drain at Fourmile Road, LD11 = Powell Slough downstream near Wescott Road, LD12 = Powell Slough upstream near Wescott Road, LD14 = Sycamore Slough at Highway 45, LD15- Unnamed Canal at Highway 45, LD16 = Unnamed drain to Walker Creek at County Road 28. See Table 4.3.5 for details and Figure 4.3.3 for additional lateral drain stations sampled only under the UCD/USEPA studies.

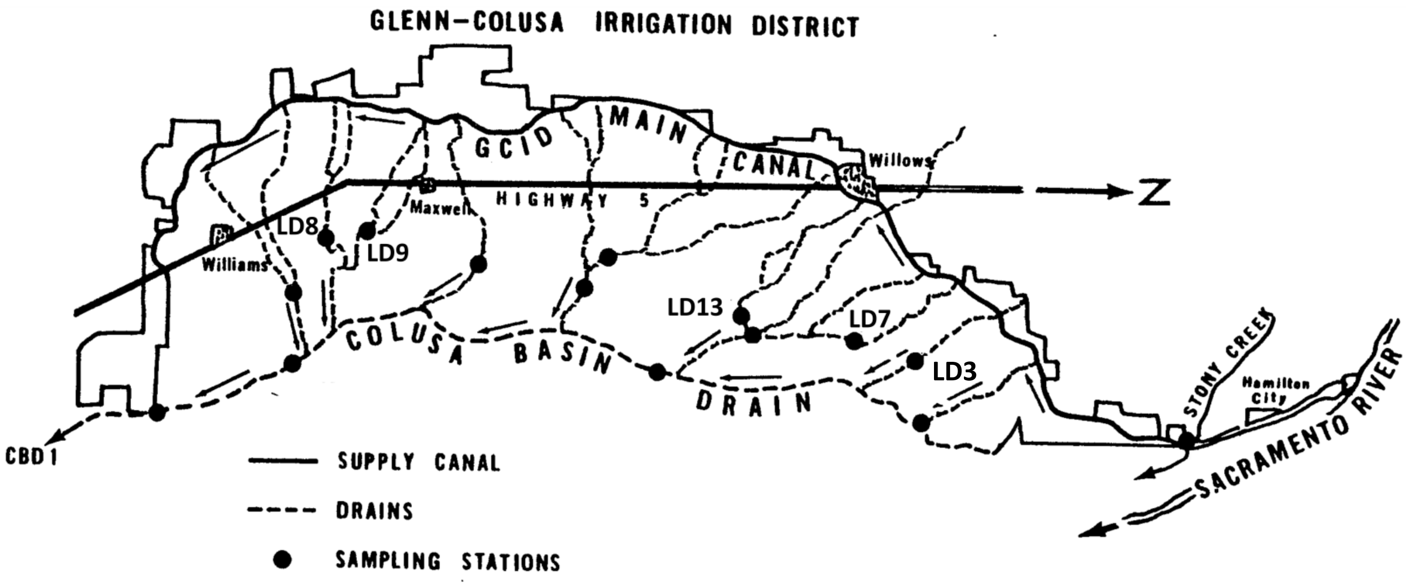

Figure 4.3.3. Lateral drain sampling stations utilized solely by the UCD/USEPA NPS CBD project. LD3 = Bondurant Slough, LD7 = GCID Drain 55, LD8 = GCID Lateral Drain section 25, LD9 = Kuhl Weir, LD13 = Salmon Hole. See Table 4.3.5 for details. (Adapted from Tanji *et al.*, 1978).

Table 4.3.6. Lateral drain turbidity descriptive statistics by station and season.

Station	Season	n	Beginning	End	Turbidity			
					Mean	Min	Max	Stdev
LD1. Ag.ditch.nr.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	49	17	81	45
LD2. Ag.ditch.nr.WillSGreen.rd	Irrigation	2	5/25/2011	6/29/2011	52	30	73	31
LD3. Bondurant-slough	All	116	4/7/1975	9/15/1981	30	0	975	121
LD3. Bondurant-slough	Irrigation	60	4/7/1975	9/15/1981	7	0	77	10
LD3. Bondurant-slough	Non-Irrigation	56	10/6/1975	3/17/1981	55	1	975	171
LD5. Drain.t.walker.cr.a.country.rd.F	Irrigation	2	7/11/2005	7/25/2005	6	4	9	3
LD6. East.drain.a.4mile.rd	Irrigation	9	4/10/2003	9/16/2003	23	19	27	4
LD7. GCID-Drain-55	All	91	4/7/1975	9/23/1980	50	0	2900	308
LD7. GCID-Drain-55	Irrigation	48	4/7/1975	9/23/1980	8	0	165	23
LD7. GCID-Drain-55	Non-Irrigation	43	10/6/1975	3/18/1980	96	1	2900	446
LD8. GCID-section-25	All	57	4/7/1975	8/31/1981	50	2	470	90
LD8. GCID-section-25	Irrigation	32	4/7/1975	8/31/1981	32	2	125	28
LD8. GCID-section-25	Non-Irrigation	25	10/6/1975	3/2/1981	73	3	470	130
LD9. Kuhl-Weir	All	57	4/7/1975	8/31/1981	37	2	450	69
LD9. Kuhl-Weir	Irrigation	32	4/7/1975	8/31/1981	19	2	79	15
LD9. Kuhl-Weir	Non-Irrigation	25	10/6/1975	3/2/1981	60	2	450	98
LD10. Powell.sl.a.hwy20	Irrigation	2	5/25/2011	6/29/2011	36	31	40	7
LD11. Powell.sl.dnstr.n.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	71	60	82	15
LD12. Powell.sl.upstr.n.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	63	28	99	51
LD13. Salmon-hole	All	74	4/7/1975	8/31/1981	46	1	1200	162
LD13. Salmon-hole	Irrigation	38	4/7/1975	8/31/1981	11	1	53	11
LD13. Salmon-hole	Non-Irrigation	36	10/6/1975	3/2/1981	83	6	1200	228
LD14. Sycamore.sl.a.hwy45	Irrigation	5	6/24/2003	9/16/2003	41	29	59	13
LD15. Unn.canal.a.hwy45	Irrigation	5	7/8/2004	9/2/2004	16	8	30	9
LD16. Unn.dr.walker.cr.county.rd.28	Irrigation	9	7/12/2004	7/25/2005	16	2	50	19

Table 4.3.7. Lateral drain C_{SS} descriptive statistics by station and season.

Station	Season	n	Beginning	End	C_{SS}			
					Mean	Min	Max	Stdev
LD1. Ag.ditch.nr.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	91	91	91	NA
LD2. Ag.ditch.nr.WillSGreen.rd	Irrigation	2	5/25/2011	6/29/2011	73	73	73	NA
LD3. Bondurant-slough	All	116	4/7/1975	9/15/1981	34	1	735	98
LD3. Bondurant-slough	Irrigation	60	4/7/1975	9/15/1981	15	1	117	16
LD3. Bondurant-slough	Non-Irrigation	56	10/6/1975	3/17/1981	54	1	735	139
LD4. Drain.S.o.rd.14	Irrigation	1	6/5/2003	6/5/2003	116	116	116	NA
LD6. East.drain.a.4mile.rd	All	10	4/10/2003	10/7/2003	44	36	50	4
LD6. East.drain.a.4mile.rd	Irrigation	9	4/10/2003	9/16/2003	43	36	46	4
LD6. East.drain.a.4mile.rd	Non-Irrigation	1	10/7/2003	10/7/2003	50	50	50	NA
LD7. GCID-Drain-55	All	91	4/7/1975	9/23/1980	45	2	1630	180
LD7. GCID-Drain-55	Irrigation	48	4/7/1975	9/23/1980	17	2	256	36
LD7. GCID-Drain-55	Non-Irrigation	43	10/6/1975	3/18/1980	76	2	1630	257
LD8. GCID-section-25	All	57	4/7/1975	8/31/1981	76	6	562	112
LD8. GCID-section-25	Irrigation	32	4/7/1975	8/31/1981	50	9	200	41
LD8. GCID-section-25	Non-Irrigation	25	10/6/1975	3/2/1981	109	6	562	158
LD9. Kuhl-Weir	All	57	4/7/1975	8/31/1981	64	5	982	137
LD9. Kuhl-Weir	Irrigation	32	4/7/1975	8/31/1981	31	5	106	21
LD9. Kuhl-Weir	Non-Irrigation	25	10/6/1975	3/2/1981	106	9	982	199
LD10. Powell.sl.a.hwy20	Irrigation	2	5/25/2011	6/29/2011	44	44	44	NA
LD11. Powell.sl.dnstr.n.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	127	127	127	NA
LD12. Powell.sl.upstr.n.Wescott.rd	Irrigation	2	5/25/2011	6/29/2011	27	27	27	NA
LD13. Salmon-hole	All	74	4/7/1975	8/31/1981	65	3	1500	209
LD13. Salmon-hole	Irrigation	38	4/7/1975	8/31/1981	20	4	82	18
LD13. Salmon-hole	Non-Irrigation	36	10/6/1975	3/2/1981	112	3	1500	294
LD14. Sycamore.sl.a.hwy45	All	6	6/24/2003	10/7/2003	68	0	117	46
LD14. Sycamore.sl.a.hwy45	Irrigation	5	6/24/2003	9/16/2003	61	0	117	49
LD14. Sycamore.sl.a.hwy45	Non-Irrigation	1	10/7/2003	10/7/2003	99	99	99	NA

4.3.1.3 Foothill Tributary Ambient Suspended Sediment Conditions

Some 1829 and 1827 turbidity and C_{SS} samples, respectively, were collected from 23 stations along 11 foothill tributaries of the CBD between 1965 and 2013 (Table 4.3.8, Figure 4.3.4, Figure 4.3.5, Figure 4.3.6). The foothill tributaries were also primarily sampled by the UCD/USEPA during the ITM and NSP CBD projects between 1975 and 1981, which together account for over 90% of both turbidity and C_{SS} samples (Table 4.3.5). The remainder of samples was collected under the CVRWQCB ILRP and SWAMP between 2003 and 2013. There was overlap in sampling stations between the UCD/USEPA and CVRWQCB sampling programs on Freshwater Creek, Hunter Creek, and Stone Corral Creek (at Fourmile Road). The highest turbidity and C_{SS} values were sampled during the non-irrigation season at all foothill tributary locations where both seasons were sampled, with the exception of a small sample sets collected from Salt Creek at Old Highway 99 (n=9) and Sand Creek at Miller Road (n=8), and a larger sample set from Walker Creek on near 99W and County Road 33 (n = 49) (Table 4.3.9 and Table 4.3.10). Minimum Turbidity or C_{SS} values were generally < 10 (NTU or mg/L) during either season at stations with a higher degree of monitoring (n > 20) (Table 4.3.9 and Table 4.3.10). Maximum turbidity values ranged from 43 to 800 NTU during the irrigation season, and 250 to 7800 NTU for stations with a higher degree of monitoring (Table 4.3.9). Similarly, maximum C_{SS} values ranged from 79 to 16,192 mg/L during the irrigation season and 86 to 1,630 mg/L during the non-irrigation season for highly monitored stations (Table 4.3.10).

Table 4.3.8. Foothill tributary suspended sediment data.

Foothill Tributary Stations	SS Data (n)		Programs						Seasonal Coverage		Sample Period	
				UCD/USEPA			CVRWQCB					
	Turb.	C_{SS}	DWR	ITM	NSP CBD	USGS	ILRP	SWAMP	Irrigation	Non-irrigation	Beginning	End
T1. Buckeye-Rd2	27	27	-	-	x	-	-	-	-	x	1/9/1978	3/3/1980
T2. Freshwater-Creek	131	131	-	x	x	-	x	-	x	x	4/7/1975	6/19/2013
T3. Funks-Lenahan	146	146	-	-	x	-	-	-	x	x	1/12/1978	9/28/1981
T4. Funks-McDermott	175	175	-	-	x	-	-	-	x	x	1/12/1978	9/28/1981
T5. Hunter-Creek	63	59	-	x	x	-	x	-	x	x	4/7/1975	8/7/2007
T6. Logan.cr.W.br.2.6m.bl.I_5	1	1	-	-	-	-	-	x	x	-	6/18/2009	6/18/2009
T7. Logan-Creek	150	150	-	x	x	-	x	-	x	x	4/7/1975	9/18/2007
T8. Lurline.cr.a.99W	12	7	-	-	-	-	x	-	x	x	2/9/2007	9/19/2007
T9. Sand.cr.a.Miller.rd	7	8	-	-	-	-	x	-	-	x	4/10/2003	10/7/2003
T10. SCC-Cemetery	7	7	-	-	x	-	-	-	-	-	1/12/1978	3/28/1978
T11. SCC-Delevan	34	34	-	-	x	-	-	-	x	-	5/2/1978	9/15/1978
T12. SCC-Fourmile	217	217	-	-	x	-	x	-	x	x	4/25/1978	11/28/2007
T13. SCC-GCID	96	96	-	x	x	-	-	-	-	-	4/7/1975	8/31/1981
T14. SCC-Lovelace	34	34	-	-	x	-	-	-	x	-	5/2/1978	9/15/1978
T15. SCC-McDermott	187	187	-	-	x	-	-	-	x	x	1/12/1978	9/28/1981
T16. SCC-Sites	21	177	-	-	x	x	-	-	x	x	11/17/1965	3/26/1981
T17. SCC-Twomile	199	199	-	-	x	-	-	-	x	x	4/25/1978	9/28/1981
T18. SCC-Frontage	173		-	-	x	-	-	-	-	-	4/25/1978	9/28/1981
T19. Spring.cr.a.E.camp.rd	3	-	-	-	-	-	x	-	x	-	6/13/2005	7/12/2005
T20. Spring.cr.a.walnut.dr	36	-	-	-	-	-	x	-	x	x	7/12/2004	10/25/2007
T21. Walker.cr.a.county.rd48	7	6	-	-	-	-	x	-	x	x	2/8/2007	9/18/2007
T22. Walker.cr.nr.99W.CR33	49	49	-	-	-	-	x	-	x	x	2/19/2009	6/19/2013
T23. Willow-Creek	117	117	-	x	x	-	-	-	x	x	4/7/1975	9/15/1981
Total	*1892*	*1827*	-	*x*	*x*	-	-	-	*x*	*x*	*11/17/1965*	*6/19/2013*

T1.Buckeye-Rd2 = Buckeye Creek at Road 2, T2.Freshwater-Creek = Freshwater Creek, T3.Funks-Lenahan = Funks Creek at Lenahan Road, T4.Funks-McDermott = Funks Creek at McDermott Road, T6.Logan.cr.W.br.2.6m.bl.I_5 = Logan Creek, West Branch approximately2.6mi below I-5, T7.Logan-Creek = Logan Creek, T8.Lurline.cr.a.99W = Lurline Creek at Highway 99 west, T9.Sand.cr.a.Miller.rd = Sand Creek at Miller Road, T10.SCC-Cemetery = Stone Corral Creek at Cemetery Road, T11.SCC-Delevan = Stone Corral Creek at Delevan Road, T12.SCC-Fourmile = Stone Corral Creek at Fourmile Road, T13.SCC-GCID = Stone Corral Creek in the GCID area east of I-5, T14.SCC-Lovelace = Stone Corral Creek at Lovelace Weir, T15.SCC-McDermott = Stone Corral Creek at McDermott Road, T16.SCC-Sites = Stone Corral Creek at Sites Road,T17. SCC-Twomile = Stone Corral Creek at Twomile Road, T18.SCC-Frontage = Stone Corral Creek at Frontage Road, T19.Spring.cr.a.E.camp.rd = Spring Creek at East Camp Road, T20.Spring.cr.a.walnut.dr = Spring Creek at Walnut Drive, T21.Walker.cr.a.country.rd48 = Walker Creek at Country Road 48, T22. Walker.cr.nr.99W.CR33 = Walker Creek near 99W County Road 33. T23.Willow-Creek = Willow Creek.

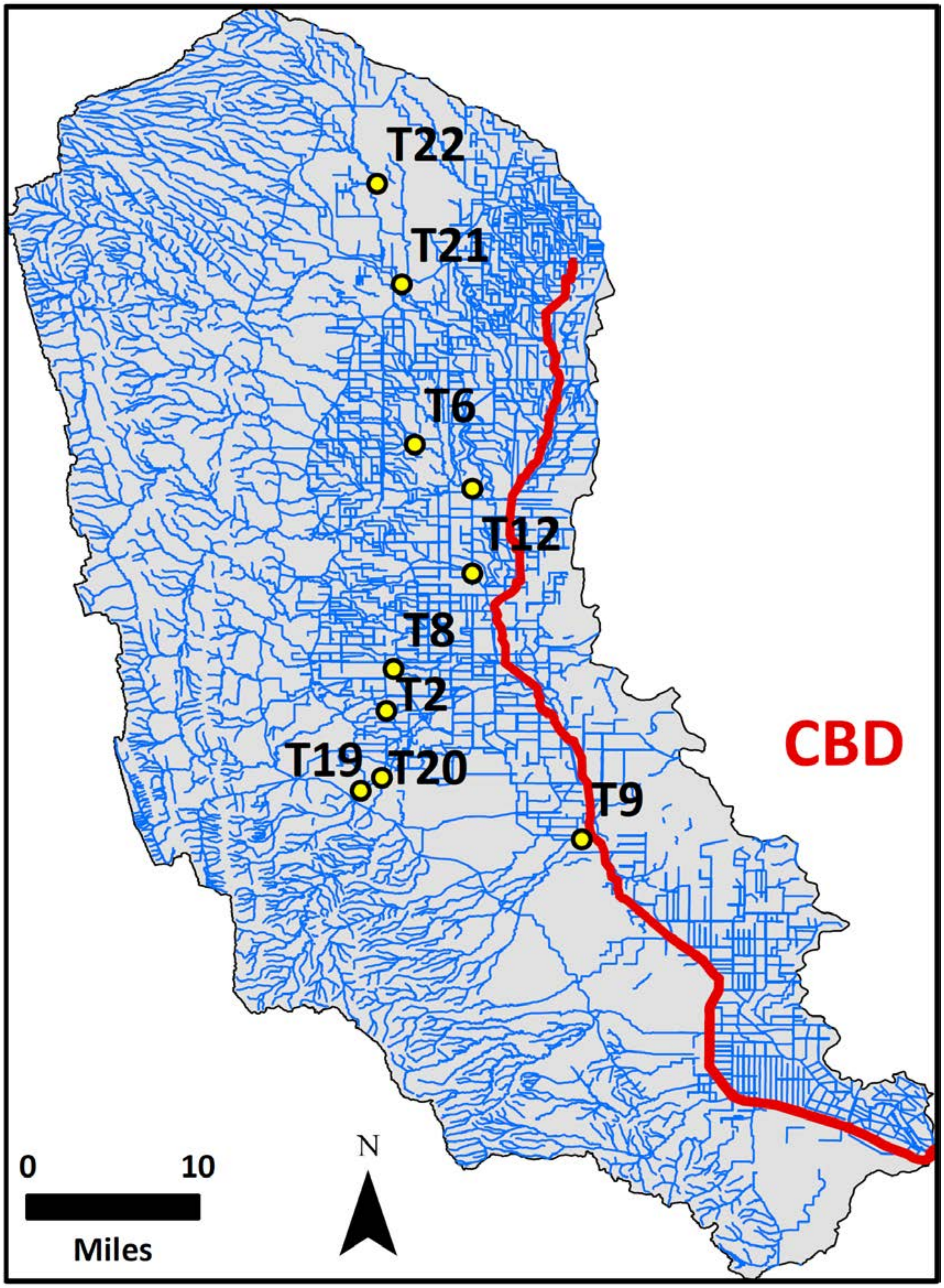

Figure 4.3.4. Foothill tributary sampling stations utilized by the CVRWQCB. T2 = Freshwater Creek, T6 = Logan Creek West Branch approximately2.6 miles below 1-5, T8 = Lurline Creek at Highway 99 West, T9 = Sand Creek at Miller Road, T12 = Stone Corral Creek at Fourmile Road, T19 = Spring Creek at East Camp Road, T20 = Spring Creek at Walnut Drive, T21 = Walker Creek at County Road 48, T22 = Walker Creek near Highway 99 West and County Road 33. See Table 4.3.8 for details and Figure 4.3.5 for additional foothill tributary stations sampled only under the UCD/USEPA studies.

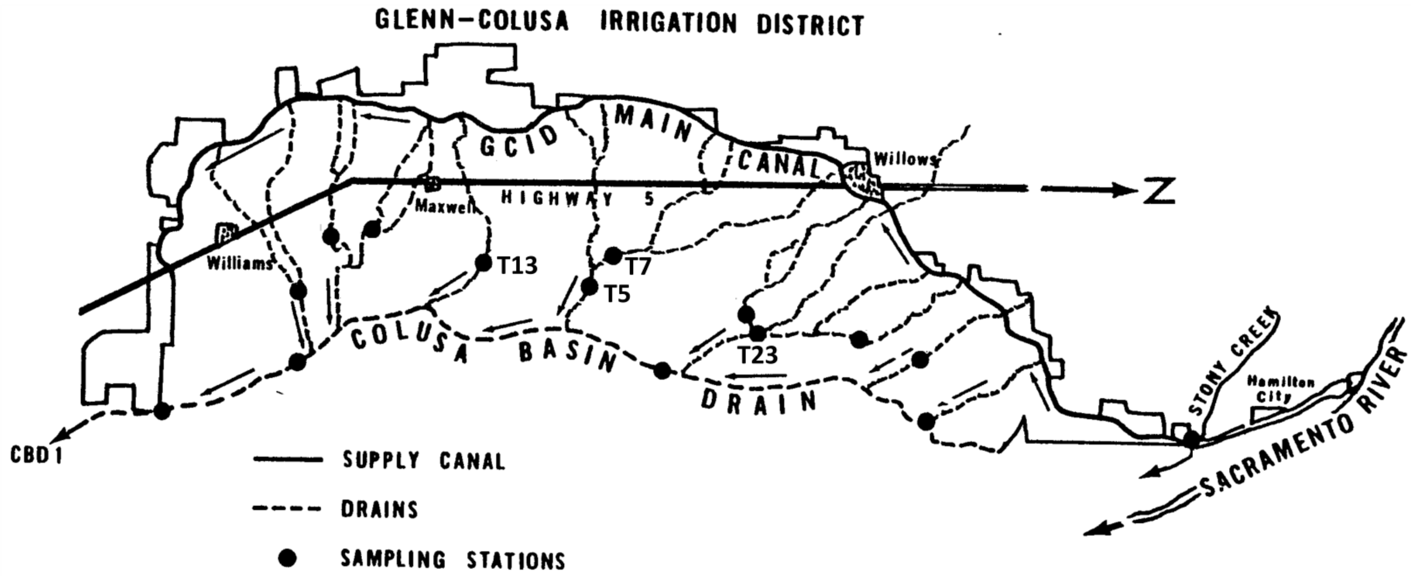

Figure 4.3.5. Foothill tributary stations sampled during the UCD/USEPA NPS CBD project in the GCID. T5 = Hunter Creek, T7 = Logan Creek, T13 = Stone Corral Creek, D6 = Willow Creek. See Table 4.3.8 for details. (Adapted from Tanji *et al.*, 1978).

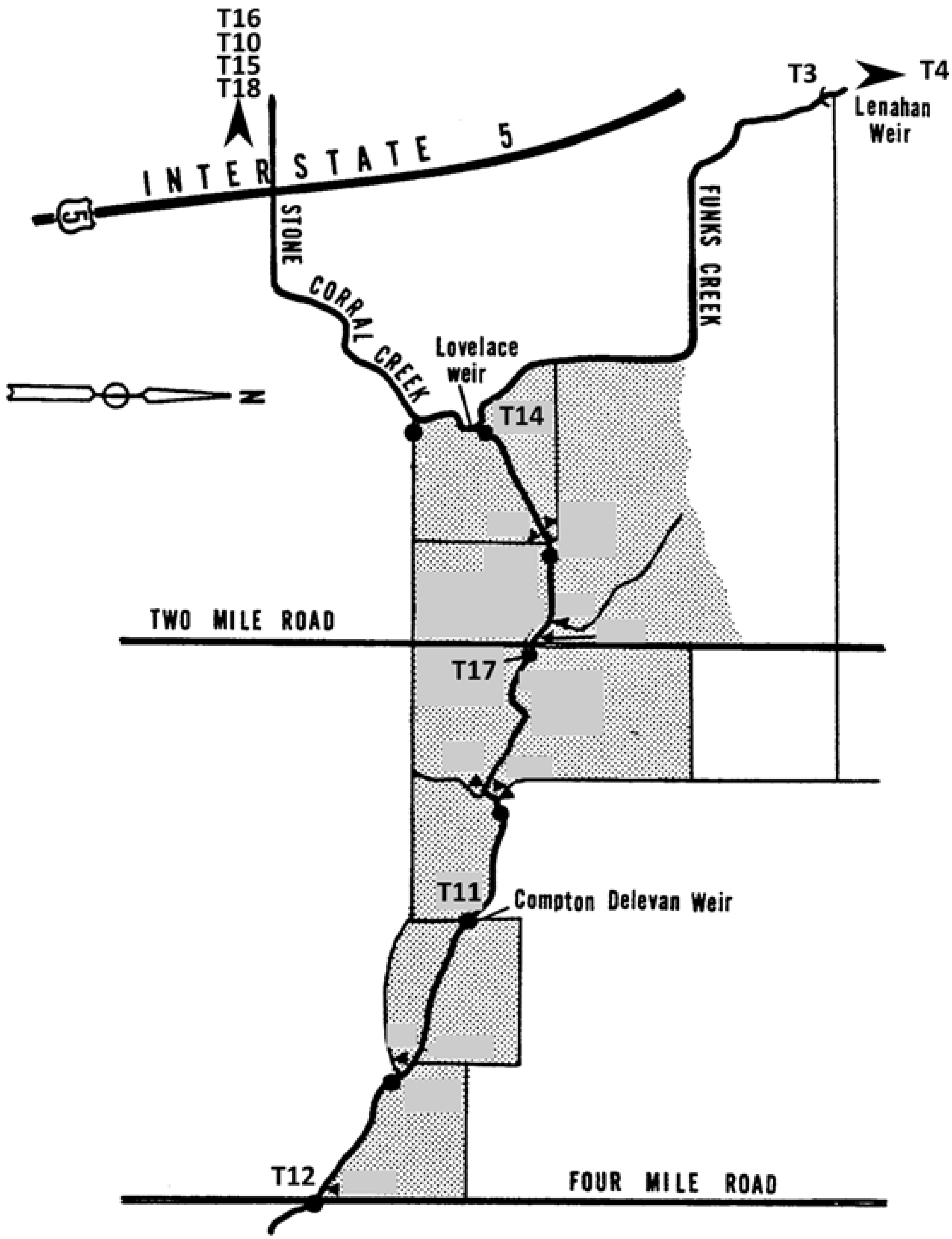

Figure 4.3.6. Stone Corral Creek (continued) and Funks Creek sampling stations utilized by the UCD/USEPA NPS CBD study. Note that T4,T10,T15,T16,T18 are further upstream on Funks and Stone Corral Creeks, placing them out of frame. T3 = Funks Creek at Lenahan Road, T4 = Funks Creek at McDermott Road, T10 = Stone Corral Creek at Cemetery Road, T11 = Stone Corral Creek at Compton Delevan Weir, T12 = Stone Corral Creek at Fourmile Road, T14 = Stone Corral Creek at Lovelace Weir, T15 = Stone Corral Creek at McDermott Road, T16 = Stone Corral Creek at Sites, CA, T17 = Stone Corral Creek at Twomile Road, T18 = Stone Corral Creek at Frontage Road. See Table 4.3.8 for details. (Adapted from Tanji *et al.*, 1978).

Table 4.3.9. Foothill tributary turbidity descriptive statistics by station and season.

Tributary Station	Season	n	Beginning	End	Turbidity			
					Mean	Min	Max	Stdev
T1.Buckeye-Rd2	Non-Irrigation	27	1/9/1978	3/3/1980	1940	18	7800	2215
T2.Freshwater-Creek	All	131	4/7/1975	6/19/2013	48	3	550	76
T2.Freshwater-Creek	Irrigation	69	4/7/1975	6/19/2013	41	7	200	37
T2.Freshwater-Creek	Non-Irrigation	62	10/6/1975	3/21/2013	56	3	550	103
T3.Funks-Lenahan	All	146	1/12/1978	9/28/1981	83	3	2700	311
T3.Funks-Lenahan	Irrigation	77	4/2/1979	9/28/1981	17	5	67	10
T3.Funks-Lenahan	Non-Irrigation	69	1/12/1978	3/30/1981	155	3	2700	443
T4.Funks-McDermott	All	175	1/12/1978	9/28/1981	74	3	2200	261
T4.Funks-McDermott	Irrigation	102	4/18/1978	9/28/1981	29	3	800	80
T4.Funks-McDermott	Non-Irrigation	73	1/12/1978	3/30/1981	138	3	2200	385
T5.Hunter-Creek	All	63	4/7/1975	8/7/2007	93	2	3120	402
T5.Hunter-Creek	Irrigation	36	4/7/1975	8/7/2007	23	2	74	16
T5.Hunter-Creek	Non-Irrigation	27	10/6/1975	3/2/1981	185	2	3120	607
T6.Logan.cr.W.br.2.6m.bl.I_5	Irrigation	1	6/18/2009	6/18/2009	11	11	11	NA
T7.Logan-Creek	All	150	4/7/1975	9/18/2007	79	7	3950	351
T7.Logan-Creek	Irrigation	68	4/7/1975	9/18/2007	29	7	170	24
T7.Logan-Creek	Non-Irrigation	82	10/6/1975	2/8/2007	121	8	3950	472
T8.Lurline.cr.a.99W	All	7	2/9/2007	9/19/2007	87	18	390	135
T8.Lurline.cr.a.99W	Irrigation	6	4/18/2007	9/19/2007	36	18	63	16
T8.Lurline.cr.a.99W	Non-Irrigation	1	2/9/2007	2/9/2007	390	390	390	NA
T9.Sand.cr.a.Miller.rd	Irrigation	7	4/10/2003	9/16/2003	71	34	141	43
T10.SCC-Cemetery	Non-Irrigation	7	1/12/1978	3/28/1978	676	4	2300	962
T11.SCC-Delevan	Irrigation	34	5/2/1978	9/15/1978	34	17	92	14
T12.SCC-Fourmile	All	217	4/25/1978	11/28/2007	66	8	1775	170
T12.SCC-Fourmile	Irrigation	134	4/25/1978	9/18/2007	38	8	150	22
T12.SCC-Fourmile	Non-Irrigation	83	10/3/1978	11/28/2007	112	8	1775	268
T18.SCC-Frontage	All	173	4/25/1978	9/28/1981	56	2	2175	222
T18.SCC-Frontage	Irrigation	95	4/25/1978	9/28/1981	20	3	54	12
T18.SCC-Frontage	Non-Irrigation	78	10/3/1978	3/30/1981	99	2	2175	326
T13.SCC-GCID	All	96	4/7/1975	8/31/1981	59	6	770	118
T13.SCC-GCID	Irrigation	52	4/7/1975	8/31/1981	36	6	125	23
T13.SCC-GCID	Non-Irrigation	44	10/6/1975	3/17/1981	87	8	770	170
T14.SCC-Lovelace	Irrigation	34	5/2/1978	8/1/2014	20	5	54	10
T15.SCC-McDermott	All	187	1/12/1978	9/28/1981	112	1	3100	400
T15.SCC-McDermott	Irrigation	96	4/25/1978	9/28/1981	19	1	77	15
T15.SCC-McDermott	Non-Irrigation	91	1/12/1978	3/30/1981	210	2	3100	559
T16.SCC-Sites	Non-Irrigation	21	1/10/1978	3/26/1981	478	4	2850	730
T17.SCC-Twomile	All	199	4/25/1978	9/28/1981	71	4	2200	236
T17.SCC-Twomile	Irrigation	119	4/25/1978	9/28/1981	27	4	215	22
T17.SCC-Twomile	Non-Irrigation	80	10/3/1978	3/30/1981	136	5	2200	362
T19.Spring.cr.a.E.camp.rd	Irrigation	3	6/13/2005	7/12/2005	207	70	390	165
T20.Spring.cr.a.walnut.dr	All	36	7/12/2004	10/25/2007	82	6	250	63
T20.Spring.cr.a.walnut.dr	Irrigation	14	7/12/2004	9/18/2007	64	9	192	56
T20.Spring.cr.a.walnut.dr	Non-Irrigation	22	1/26/2005	10/25/2007	94	6	250	65

T21.Walker.cr.a.county.rd48	All	6	2/8/2007	9/18/2007	8	6	11	2
T21.Walker.cr.a.county.rd48	Irrigation	5	4/17/2007	9/18/2007	8	6	10	1
T21.Walker.cr.a.county.rd48	Non-Irrigation	1	2/8/2007	2/8/2007	11	11	11	NA
T22.Walker.cr.nr.99W.CR33	All	49	2/19/2009	6/19/2013	21	1	250	40
T22.Walker.cr.nr.99W.CR33	Irrigation	25	4/22/2009	6/19/2013	14	2	58	13
T22.Walker.cr.nr.99W.CR33	Non-Irrigation	24	2/19/2009	3/21/2013	28	1	250	56
T23.Willow-Creek	All	117	4/7/1975	9/15/1981	46	2	870	128
T23.Willow-Creek	Irrigation	60	4/7/1975	9/15/1981	14	2	43	11
T23.Willow-Creek	Non-Irrigation	57	10/6/1975	3/17/1981	79	3	870	178

Table 4.3.10. Foothill tributary C_{SS} descriptive statistics by station and season.

Tributary Station	Season	n	Beginning	End	C_{SS}			
					Mean	Min	Max	Stdev
T1.Buckeye-Rd2	Non-Irrigation	27	1/9/1978	3/3/1980	3675	24	11784	3547
T2.Freshwater-Creek	All	131	4/7/1975	6/19/2013	74	5	820	115
T2.Freshwater-Creek	Irrigation	69	4/7/1975	6/19/2013	69	6	277	65
T2.Freshwater-Creek	Non-Irrigation	62	10/6/1975	3/21/2013	81	5	820	154
T3.Funks-Lenahan	All	146	1/12/1978	9/28/1981	174	2	4196	600
T3.Funks-Lenahan	Irrigation	77	4/2/1979	9/28/1981	38	9	164	27
T3.Funks-Lenahan	Non-Irrigation	69	1/12/1978	3/30/1981	326	2	4196	850
T4.Funks-McDermott	All	175	1/12/1978	9/28/1981	155	1	4922	556
T4.Funks-McDermott	Irrigation	102	4/18/1978	9/28/1981	60	6	1530	152
T4.Funks-McDermott	Non-Irrigation	73	1/12/1978	3/30/1981	287	1	4922	826
T5.Hunter-Creek	All	63	4/7/1975	3/2/1981	68	3	730	131
T5.Hunter-Creek	Irrigation	36	4/7/1975	8/7/2007	40	7	121	26
T5.Hunter-Creek	Non-Irrigation	27	10/6/1975	3/2/1981	101	3	730	189
T6.Logan.cr.W.br.2.6m.bl.I_5	Irrigation	1	6/18/2009	6/18/2009	11	11	11	NA
T7.Logan-Creek	All	150	4/7/1975	9/18/2007	104	8	4699	399
T7.Logan-Creek	Irrigation	68	4/7/1975	9/18/2007	49	13	318	43
T7.Logan-Creek	Non-Irrigation	82	10/6/1975	2/8/2007	149	8	4699	535
T8.Lurline.cr.a.99W	All	7	2/9/2007	9/19/2007	66	7	200	63
T8.Lurline.cr.a.99W	Irrigation	6	4/18/2007	9/19/2007	44	7	66	26
T8.Lurline.cr.a.99W	Non-Irrigation	1	2/9/2007	2/9/2007	200	200	200	NA
T9.Sand.cr.a.Miller.rd	All	8	4/10/2003	10/7/2003	131	63	253	71
T9.Sand.cr.a.Miller.rd	Irrigation	7	4/10/2003	9/16/2003	127	63	253	76
T9.Sand.cr.a.Miller.rd	Non-Irrigation	1	10/7/2003	10/7/2003	162	162	162	NA
T10.SCC-Cemetery	Non-Irrigation	7	1/12/1978	3/28/1978	938	14	3196	1371
T11.SCC-Delevan	Irrigation	34	5/2/1978	9/15/1978	59	19	163	25
T12.SCC-Fourmile	All	217	4/25/1978	11/28/2007	134	8	3691	366
T12.SCC-Fourmile	Irrigation	134	4/25/1978	9/18/2007	75	13	315	47
T12.SCC-Fourmile	Non-Irrigation	83	10/3/1978	11/28/2007	228	8	3691	574
T13.SCC-GCID	All	96	4/7/1975	8/31/1981	96	19	938	144
T13.SCC-GCID	Irrigation	52	4/7/1975	8/31/1981	68	20	313	49
T13.SCC-GCID	Non-Irrigation	44	10/6/1975	3/17/1981	129	19	938	202
T14.SCC-Lovelace	Irrigation	34	5/2/1978	8/1/2014	29	8	147	23
T15.SCC-McDermott	All	187	1/12/1978	9/28/1981	268	1	16192	1368
T15.SCC-McDermott	Irrigation	96	4/25/1978	9/28/1981	46	3	1010	103

T15.SCC-McDermott	Non-Irrigation	91	1/12/1978	3/30/1981	504	1	16192	1942
T16.SCC-Sites	All	177	11/17/1965	3/26/1981	278	4	6024	713
T16.SCC-Sites	Irrigation	38	4/3/1966	6/3/1968	126	4	2590	429
T16.SCC-Sites	Non-Irrigation	139	11/17/1965	3/26/1981	319	4	6024	769
T17.SCC-Twomile	All	199	4/25/1978	9/28/1981	140	6	5148	527
T17.SCC-Twomile	Irrigation	119	4/25/1978	9/28/1981	43	8	231	27
T17.SCC-Twomile	Non-Irrigation	80	10/3/1978	3/30/1981	286	6	5148	813
T21.Walker.cr.a.county.rd48	All	6	2/8/2007	9/18/2007	6	5	7	1
T21.Walker.cr.a.county.rd48	Irrigation	5	4/17/2007	9/18/2007	6	5	7	1
T21.Walker.cr.a.county.rd48	Non-Irrigation	1	2/8/2007	2/8/2007	7	7	7	NA
T22.Walker.cr.nr.99W.CR33	All	49	2/19/2009	6/19/2013	26	2	106	27
T22.Walker.cr.nr.99W.CR33	Irrigation	25	4/22/2009	6/19/2013	27	4	106	25
T22.Walker.cr.nr.99W.CR33	Non-Irrigation	24	2/19/2009	3/21/2013	26	2	86	30
T23.Willow-Creek	All	117	4/7/1975	9/15/1981	60	3	932	137
T23.Willow-Creek	Irrigation	60	4/7/1975	9/15/1981	25	3	79	18
T23.Willow-Creek	Non-Irrigation	57	10/6/1975	3/17/1981	97	8	932	189

4.3.1.4 Irrigation Supply Waters Ambient Suspended Sediment Conditions

Irrigation supply waters from the Glenn Colusa Irrigation District's main canal were sampled for turbidity and C_{SS} during the UCD/USEPA projects between 1975 and 1981 (Table 4.3.11 and Table 4.3.12). Suspended sediment concentrations in supply waters were also generally higher during the non-irrigation season, but were generally lower than those found in drainage waters throughout the region.

Table 4.3.11. Irrigation supply waters suspended sediment data.

Irrigation Supply Waters	SS Data (n)		Programs						Seasonal Coverage		Sample Period	
	Turb.	C_{SS}	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
				ITM	NSP CBD		ILRP	SWAMP				
GCID-Supply	69	69	-	x	x	-	-	-	x	x	4/7/1975	8/31/1981

Table 4.3.12. Irrigation supply water turbidity descriptive statistics by station and season.

Irrigation Supply Waters	Season	n	Beginning	End	Turbidity			
					Mean	Min	Max	Stdev
GCID-supply	All	69	4/7/1975	8/31/1981	29	2	490	81
GCID-supply	Irrigation	39	4/7/1975	8/31/1981	13	2	69	16
GCID-supply	Non-Irrigation	30	10/6/1975	3/2/1981	50	2	490	120

Table 4.3.13. Irrigation supply water C_{SS} descriptive statistics by station and season.

Irrigation Supply Waters	Season	n	Beginning	End	C_{SS}			
					Mean	Min	Max	Stdev
GCID-supply	All	69	4/7/1975	8/31/1981	52	2	697	134
GCID-supply	Irrigation	39	4/7/1975	8/31/1981	21	4	81	18
GCID-supply	Non-Irrigation	30	10/6/1975	3/2/1981	92	2	697	196

4.3.1.5 Knights Landing Ridge Cut and Sacramento River Ambient Suspended Sediment Conditions

The two water bodies receiving discharge from the CBD are the KLRC and the Sacramento River (Table 4.3.14, Table 4.3.15, and Table 4.3.16). Very little sediment sampling has occurred in the KLRC, with a total of 13 and 15 turbidity and C_{SS} samples, respectively, collected from two locations under the CVRWQCB ILRP during 2003 (Table 4.3.14). Turbidity values were only measured in the KLRC during the irrigation season, with values ranging from 11 to 61 NTU and mean values of 31 and 45 at the North and South stations, respectively (Table 4.3.15).

Relevant suspended sediment monitoring occurred on the Sacramento River at three locations: two upstream and one downstream from the CBD outfall (Table 4.3.14). The furthest upstream station under consideration is 'S1', which is located at the USGS gauge #11389500: Sacramento River at Colusa, CA, and was sampled 968 times for turbidity and C_{SS} by the USGS and under the CVRWQCB ILRP between 1972 and 2011 (Table 4.3.14). Turbidity and C_{SS} values ranged from 2 to 140 NTU and 3 to 2,000 mg/L, respectively, with much lower values during the irrigation than non-irrigation season (Table 4.3.15 and Table 4.3.16). The upstream station most proximal to the CBD outfall is 'S2', the DWR gauge: Sacramento River above CBD, which was sampled 313 and 293 times for turbidity and C_{SS}, respectively between 1960 and 2014 by the DWR and under the UCD/USEPA NSP CBD project (Table 4.3.14). Turbidity and C_{SS} values at S2 ranged from 1 to 255 NTU and 3 to 535 mg/L, respectively, and were also higher during the non-irrigation season (Table 4.3.15 and Table 4.3.16).

The most proximal station downstream from the CBD outfall is 'S3', the DWR gauge: Sacramento River below Knights Landing, which was sampled 237 and 226 times for turbidity and C_{SS}, respectively, by the DWR between 1960 and 2014 (Table 4.3.14). Turbidity and C_{SS} values at S3 ranged from 3 to 300 NTU and 4 to 575 mg/L, respectively, again with higher values found during the non-irrigations season (Table 4.3.15 and Table 4.3.16). Mean and maximum values of turbidity increased downstream on the Sacramento River from S1 to S2 and S3 (Table 4.3.15). Trends in C_{SS} consistent with downstream direction were not evident between these Sacramento River stations (Table 4.3.16).

Table 4.3.14. Sacramento River and Knights Landing Ridge Cut suspended sediment data.

Recieiving Water Body Stations	SS Data (n)		Programs						Seasonal Coverage		Sample Period	
				UCD/USEPA			CVRWQCB					
	Turb.	C_{SS}	DWR	ITM	NSP CBD	USGS	ILRP	SWAMP	Irrigation	Non-irrigation	Beginning	End
KL1. KnLnd.RC.a.rd16.N	7	8	-	-	-	-	x	-	x	x	4/8/2003	10/2/2003
KL2. KnLnd.RC.a.rd16.S	6	7	-	-	-	-	x	-	x	x	6/3/2003	10/2/2003
S1. sac.r.a.colusa	968	968	-	-	-	x	x	-	x	x	12/18/1972	5/4/2011
S2. sac.r.ab.cbd	313	293	x	-	x	-	-	-	x	x	7/20/1960	5/7/2014
S3. sac.r.bl.KnLnd	237	226	x	-	-	-	-	-	x	x	7/20/1960	5/7/2014
Total	1531	1502	x	-	x	x	x	-	x	x	7/20/1960	5/7/2014

KL1. KnLnd.RC.a.rd16.N = Knights Landing Ridge Cut at Road 16 North, KL2. KnLnd.RC.a.rd16.S = Knights Landing Ridge Cut at Road 16 South, S1. sac.r.a.colusa = Sacramento River at Colusa, S2. sac.r.ab.cbd = Sacramento River above CBD, S3. sac.r.bl.KnLnd = Sacramento River below CBD.

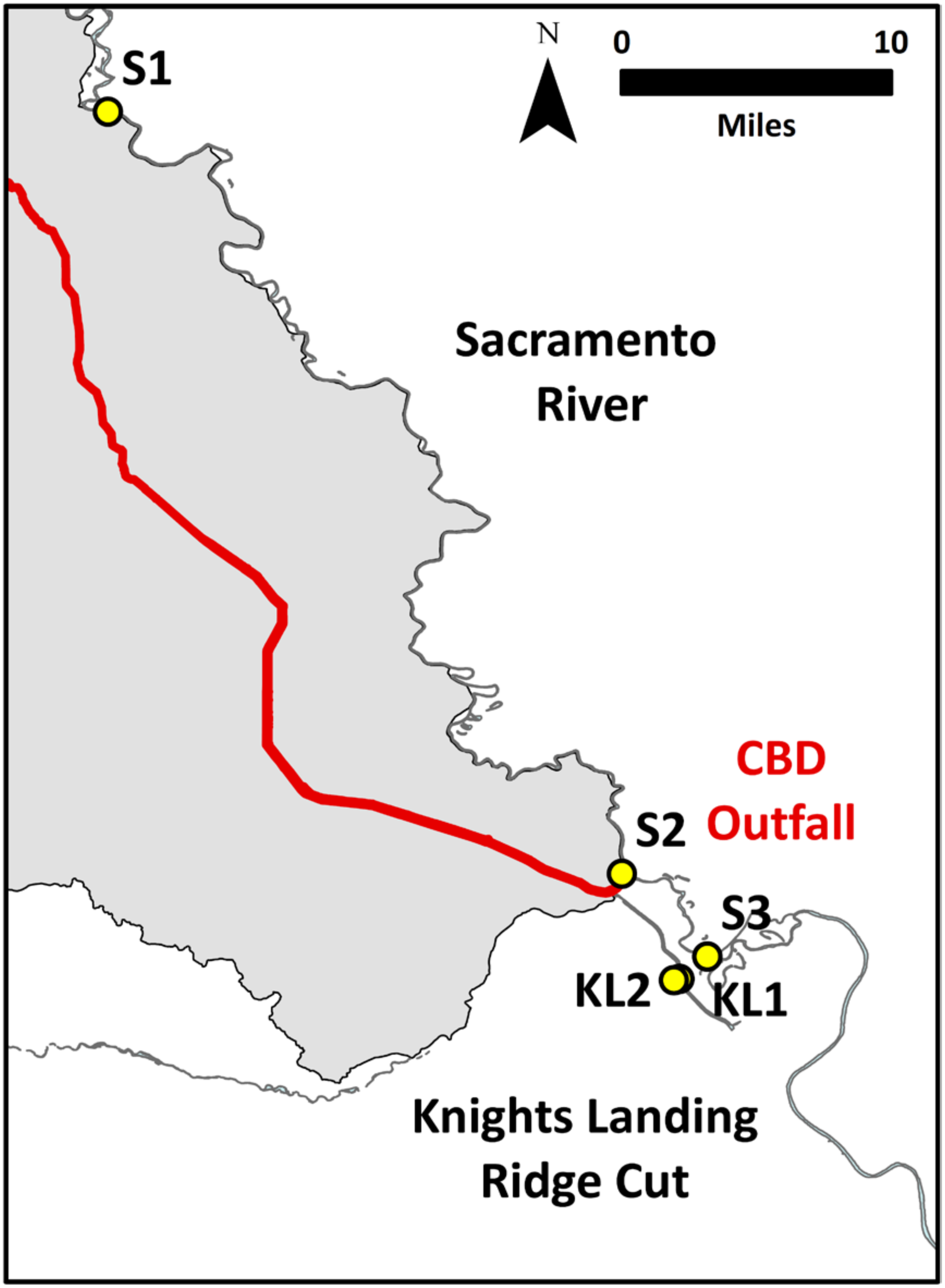

Figure 4.3.7. Sampling stations on the Sacramento River and Knights Landing Ridge Cut. KL1 = DWR gauge: Knights Landing Ridge Cut at Road 16 north, KL2 = DWR gauge: Knights Landing Ridge Cut at Road 16 south, S1 = USGS gauge #11389500: Sacramento River at Colusa CA, S2 = DWR gauge: Sacramento River above CBD, S3 = DWR gauge: Sacramento River below Knights Landing. See Table 4.2.14 for details.

Table 4.3.15. Sacramento River and Knights Landing Ridge Cut suspended sediment data. turbidity descriptive statistics by station and season

Receiving Water Body Stations	Season	n	Beginning	End	Turbidity			
					Mean	Min	Max	Stdev
KL1.KnLnd.RC.a.rd16.N	Irrigation	7	4/8/2003	9/11/2003	31	11	39	12
KL2.KnLnd.RC.a.rd16.S	Irrigation	6	6/3/2003	9/11/2003	45	27	61	15
S1. sac.r.a.colusa	All	968	12/18/1972	5/4/2011	14	2	140	32
S1. sac.r.a.colusa	Irrigation	353	4/1/1977	5/4/2011	6	2	18	6
S1. sac.r.a.colusa	Non-Irrigation	615	12/18/1972	2/2/2011	27	2	140	51
S2. sac.r.ab.cbd	All	283	10/20/1960	5/7/2014	22	1	255	37
S2. sac.r.ab.cbd	Irrigation	147	4/3/1972	5/7/2014	12	1	98	10
S2. sac.r.ab.cbd	Non-irrigation	136	3/15/1972	11/6/2013	32	1	255	51
S3. sac.r.bl.KnLnd	All	237	7/20/1960	5/7/2014	22	2	300	34
S3. sac.r.bl.KnLnd	Irrigation	121	7/20/1960	5/7/2014	14	5	91	10
S3. sac.r.bl.KnLnd	Non-Irrigation	116	10/19/1960	11/6/2013	30	2	300	47

Table 4.3.16. Sacramento River and Knights Landing Ridge Cut C_{SS} descriptive statistics by station and season.

Receiving Water Body Stations	Season	n	Beginning	End	C_{SS}			
					Mean	Min	Max	Stdev
KL1.KnLnd.RC.a.rd16.N	All	8	4/8/2003	10/2/2003	88	23	246	68
KL1.KnLnd.RC.a.rd16.N	Irrigation	7	4/8/2003	9/11/2003	92	23	246	73
KL1.KnLnd.RC.a.rd16.N	Non-Irrigation	1	10/2/2003	10/2/2003	56	56	56	NA
KL2.KnLnd.RC.a.rd16.S	All	7	6/3/2003	10/2/2003	89	36	140	38
KL2.KnLnd.RC.a.rd16.S	Irrigation	6	6/3/2003	9/11/2003	98	62	140	33
KL2.KnLnd.RC.a.rd16.S	Non-Irrigation	1	10/2/2003	10/2/2003	36	36	36	NA
S1. sac.r.a.colusa	All	968	12/18/1972	5/4/2011	157	3	2000	201
S1. sac.r.a.colusa	Irrigation	353	4/1/1977	5/4/2011	95	3	460	58
S1. sac.r.a.colusa	Non-Irrigation	615	12/18/1972	2/2/2011	192	3	2000	241
S2. sac.r.ab.cbd	All	117	10/20/1960	5/7/2014	54	3	535	79
S2. sac.r.ab.cbd	Irrigation	68	9/24/1975	5/7/2014	36	3	146	26
S2. sac.r.ab.cbd	Non-Irrigation	49	10/20/1960	3/30/1983	79	8	535	114
S3. sac.r.bl.KnLnd	All	226	7/20/1960	5/7/2014	49	4	575	73
S3. sac.r.bl.KnLnd	Irrigation	115	7/20/1960	5/7/2014	35	4	116	22
S3. sac.r.bl.KnLnd	Non-Irrigation	111	10/19/1960	11/6/2013	61	7	575	98

4.3.2 Suspended Sediment Dynamics

If any measure of C_{SS}, either direct or though estimation by proxy, is to be of use in the elucidation of sediment dynamics and/or the development of mass flux estimates, associated Q values are required. Without paired Q values, measures of C_{SS} convey information that is only useful in term of incidental water quality composition characterization (see Section 3.3). The collection of paired $\{Q, C_{SS}\}$ data permits the evaluation of the relationship between these two integrated expressions of watershed function. Indeed, across channelized systems representing a wide range of physical, biotic and climatic characteristics and spatial scales, the most useful environmental parameter for the prediction of C_{SS} is Q.

Examining the relationship between C_{SS} and Q is a powerful tool in the process of understanding suspended sediment dynamics at the watershed scale with broader applications than flux estimation alone (see Section 3.3). The C_{SS}-Q relationship is not one to one, or even linear, in most cases, and never completely deterministic (i.e. the variation in Q does not fully describe the variation in C_{SS}). The supply of sediment to the channelized system is intrinsically linked to the supply of water through the entrainment of sediment by water over shared transport pathways such as overland flow. However, additional pathways and processes such as interflow (water), mass wasting (primarily sediment), and aeolian transport (sediment) are not shared. Watershed conditions, from land cover and soil states to antecedent moisture conditions, are integrated expressions of the history of interacting internal and external forcing factors, also differentially affect the delivery of water and sediment to the channel. For example, moderate periods of drought may reduce the hydrologic response of a given storm as more water is lost to interception and soil moisture reservoirs, while sediment supply may increase due to increased erosivity of soils due to vegetation die-backs and preloading of channels due to soil creep aeolian deposition. Furthermore, sediment will only be transported in suspension when the tractive capabilities of the flow field are sufficient to counteract the settling velocity characteristics of the particles in question. Therefore, the differences in the characteristics and processes controlling the supply of water and sediment to the channel, the potentially erosive interaction of channelized flow with channel bank and bed, and the effects of deposition when shear stresses and shear velocities decrease lead to further divergence in the C_{SS} and Q response characteristics of a watershed in general. For these reasons Q never completely describes the variation to fluvial C_{SS}.

Although this fact hampers the accurate estimation of suspended sediment flux from C_{SS}–Q rating curves, the unexplained ‘residuals’ of these models can provide a further stepping stone for inquiry into the patterns and processes of sediment behavior. Changes in these controls on water and sediment supply/transport to/through the channel can cause the $C_{SS} – Q$ relationship to change. When such environmental processes, relationships or expressions do not change over time they are considered ‘stationary,’ which is an important assumption implicit to descriptions of system behavior that rely on short periods of monitoring relative to the period of description (see Section 3.3).

When considered together the suspended sediment data sets collected during of previous studies (see Sections 4.1 and 4.3) provide the basis for an interannual to interdecadal scale investigation into the suspended sediment dynamics in the Colusa Basin drainage area. The following sections present the development of log-linear C_{SS}-Q rating curves for all ambient surface water suspended sediment sampling stations presented in Section 4.3.1 where instantaneous Q data was collected in association with C_{SS} sampling. Rating curve relationships were then used as the basis for examining the temporal dependence of suspended sediment dynamics at Colusa Basin drainage area and the Sacramento River in the vicinity of the CBD outfall: (i) dependence on sampling agency, and (ii) temporal dependence (stationarity) at seasonal to interannual time scales.

4.3.2.1 Conclusions of suspended sediment dynamic analyses

The following were significant results of the suspended sediment dynamic analyses below:

- Many stations displayed seasonally distinct C_{SS}-Q rating relationships, with higher C_{SS} values during the non-irrigation season. This was most consistently the case for stations on the CBD.
- Several stations did not display any differences between irrigation and non-irrigation season (some later drains, foothill tributaries, one CBD station, and S3: Sacramento River below Knights Landing).
- Lack of seasonal differences most likely in part due to high residual variability in C_{SS}-Q rating curves and in-channel deposition/resuspension dynamics that in part subvert the large differences in water application/runoff modalities between seasons.
- No significant long term (interdecadal scale) trends in C_{SS}-Q residuals were found among the few long term records available. This is despite the fact that large-scale changes have occurred in the Colusa Basin drainage area over the period of suspended sediment collection (late 1960s through early 21st century), including the introduction of additional irrigation waters (and concomitant increase in irrigated land area) with the completion of the Tehama-Colusa Canal in the late 1970s/early 1980s. However, records spanning the entire time period were very sparse toward the latter part of the record, and increased monitoring efforts in the near future would provide a more certain picture of how C_{SS}-Q relationships have changed over time in the region.
- Significantly decreasing C_{SS}-Q residuals were found for some stations over shorter (decadal to interannual) time periods, particularly for the late 1970s through early 1980s. As observed by the UCD/USEPA NPS CBD studies, these apparent trends were most likely controlled by changes in C_{SS}-Q relationships due to long-term drought in the region during the mid to late 1970s.
- In general, the high variability in C_{SS} in relation to Q, the propensity for seasonal changes in the C_{SS}-Q relationship due to differences in the non-irrigation and irrigation season hydrologic regimes, and interannual C_{SS} regimes driven by antecedent basin conditions (i.e. drought), indicate that decadal duration, high resolution monitoring (observation spacing of minutes to hours) of both C_{SS} and Q are required to adequately characterize the system to service both suspended sediment impact assessments and suspended sediment flux estimations (see Sections 7 and 8 for further discussion of data gaps and monitoring recommendations, respectively).

4.3.2.2 Paired {Q, C_{SS}} data

A total of 3219 sets of paired {*Q*, C_{SS}} data were available from 36 stations in the Colusa Basin drainage area, including 7 CBD stations (Table 4.3.17), 5 lateral drain stations (Table 4.3.18), 18 tributary stations (Table 4.3.19), 2 irrigation supply water stations (Table 4.3.20), and 2 relevant stations on the Sacramento River (Table 4.3.21). Most sampling in the Colusa Basin drainage area was conducted under the UCD/USEPA NSP CBD project (see Section 4.1.4), with smaller contributions from the DWR, USGS, and CVRWQCB ILRP (Table 4.3.17, Table 4.3.18, Table 4.3.19, Table 4.3.20), while all Sacramento River samples were collected by the DWR (Table 4.3.21). Sampling for most stations took place during the irrigation and non-irrigation season, permitting comparison of seasonal suspended sediment dynamics. As the UCD/USEPA NSP CBD project dominated sample collection, the sampling period for most stations ran from the late 1970s to early 1980 or 1981, which only allows for interannual scale analysis of temporal dependence. However, the following stations were sampled over longer base periods, which allow for analysis of decadal to interdecadal scale temporal dependence: CBD-1, S2 (Sacramento River above CBD) and S3 (Sacramento River below Knights Landing).

Table 4.3.17. CBD stations with C_{SS} and associated *Q* data.

Station	Programs						Seasonal Coverage		Sample Period	
	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
		ITM	NSP CBD		ILRP	SWAMP				
CBD-1	x		x	x			137	143	9/24/1975	4/15/1998
CBD-2			x				105	81	4/11/1978	9/28/1981
CBD-2B			x				65	11	5/2/1978	9/29/1980
CBD-3			x				105	115	1/31/1978	9/28/1981
CBD-4			x				104	43	10/3/1977	9/15/1981
CBD-6			x				46	37	10/3/1977	9/15/1981
CBD-7			x				50	19	10/3/1977	9/15/1981
Total	*x*		*x*	*x*			*612*	*449*	*9/24/1975*	*4/15/1998*

The following UCD/USEPA stations correspond to existing bridges/road crossings of the CBD: CBD-1 at Road 99E and Road 109, CBD-2 at County Line Road, CBD-2b at White Road, CBD-3 at Tule Rd., CBD-4 at Davis Weir, CBD-5 at Highway 20, CBD-6 at Princeton Road, CBD-7 at Sidds Road.

Table 4.3.18. Lateral drain stations with C_{SS} and associated Q data.

Station	Programs						Seasonal Coverage		Sample Period	
	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
		ITM	NSP CBD		ILRP	SWAMP				
LD3.Bondurant-slough			x				25	32	10/3/1977	9/15/1981
LD7.GCID-Drain-55			x				36	31	10/3/1977	9/23/1980
LD9.Kuhl-Weir			x				25	20	10/3/1977	8/31/1981
LD13.Salmon-hole			x				21	14	1/8/1978	8/31/1981
LD8.GCID-section-25			x					4	1/10/1978	2/7/1978
Total			*x*				*107*	*101*	*10/3/1977*	*9/15/1981*

See Table 4.3.5 and Figure 4.3.2, Figure 4.3.3 for details.

Table 4.3.19. Foothill tributaries with C_{SS} and associated Q data.

Station	Programs						Seasonal Coverage		Sample Period	
	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
		ITM	NSP CBD		ILRP	SWAMP				
T1.Buckeye.Rd2			x					17	1/9/1978	3/3/1980
T2.Freshwatercreek			x				26	20	10/3/1977	8/31/1981
T3.Funks-Lenahan			x					6	1/12/1978	3/6/1978
T4.Funks-McDermott			x				96	71	1/12/1978	9/28/1981
T5.Hunter-Creek			x				24	21	10/3/1977	8/31/1981
T6.Logan-Creek			x				25	20	10/3/1977	8/31/1981
T8. Lurline.cr.a.99W							5		4/18/2007	8/22/2007
T10. SCC-Cemetery			x					7	1/12/1978	3/28/1978
T11. SCC-Delevan			x				34		5/2/1978	9/15/1978
T12. SCC-Fourmile			x				115	80	4/25/1978	9/28/1981
T18. SCC-Frontage			x				90	78	4/25/1978	9/28/1981
T13. SCC-GCID			x				46	37	10/3/1977	8/31/1981
T14. SCC-Lovelace			x				34		5/2/1978	8/1/2014
T15. SCC-McDermott			x				91	89	1/12/1978	9/28/1981
T17. SCC-Twomile			x				114	80	4/25/1978	9/28/1981
T16. SCC-Sites			x				26	20	10/3/1977	8/31/1981
T22. Walker.cr.nr.99W.CR33					x		12	14	2/19/2009	1/24/2012
T23. Willow-Creek			x				47	38	10/3/1977	9/15/1981
Total			*x*		*x*		*785*	*598*	*10/3/1977*	*8/1/2014*

See Table 4.3.8, Figure 4.3.4, Figure 4.3.5, and Figure 4.3.6for details.

Table 4.3.20. Irrigation supply stations with C_{SS} and associated Q data.

Station	Programs						Seasonal Coverage		Sample Period	
	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
		ITM	NSP CBD		ILRP	SWAMP				
GCID-Main-Canal			x				26	18	10/3/1977	8/31/1981
GCID-Supply			x				138	117	11/14/1977	9/28/1981
Total			*x*				*164*	*135*	*10/3/1977*	*9/28/1981*

Table 4.3.21. Sacramento River stations with C_{SS} and associated Q data.

Station	Programs						Seasonal Coverage		Sample Period	
	DWR	UCD/USEPA		USGS	CVRWQCB		Irrigation	Non-irrigation	Beginning	End
		ITM	NSP CBD		ILRP	SWAMP				
S2. sac.r.ab.cbd	x						54	57	1/18/1961	7/26/1989
S3. sac.r.bl.KnLnd	x						89	68	7/12/1967	11/24/1981
Total	*x*						*143*	*125*	*1/18/1961*	*7/26/1989*

S1. sac.r.ab.cbd = Sacramento River above CBD, S2. sac.r.bl.KnLnd = Sacramento River below Knights Landing

4.3.2.3 Log-linear C_{SS}-Q rating curves and ANCOVA comparison of seasonal C_{SS}-Q relationships

Available C_{SS} and associated Q data were used to model the dependence of C_{SS} on Q. A log-linear sediment rating curve describes this relationship through a linear regression fitted to log-transformed data in the form

$$log(C_{SS}) = log(a) + b\,log(Q) + \varepsilon \quad (4.3.1)$$

where a and b are intercept and slope constants, respectively and ε is the error term. Log-linear rating curves were constructed for each station with paired $\{Q, C_{SS}\}$ data. Additional log-linear rating curves were constructed for station data sub-grouped by season (irrigation and non-irrigation) when possible. All data sets and subsets were tested for normality, homoscedasticity, and linear fit, the results of which were found to agree with the Global Statistic, a composite test of the applicability of linear regression to a given data set using the 'gvlma' package in the R computing environment (Pena and Slate, 2006).

Seasonal differences in C_{SS}-Q relationships were investigated through ANCOVA comparisons of log linear rating curves constructed for the irrigation and non-irrigation seasons. ANCOVA can be used to compare the bivariate, linear relationships of different subsets of data. First multiple regression models are constructed from data subsets using the following general model for two group comparison as per Larsen (2003):

$$\log(C_{SS}) = \beta_0 + \beta_1 \mathrm{Log}(Q_i) + \beta_2 Z + \beta_3 (\mathrm{Log}Q_i) Z + \varepsilon \quad (4.3.2)$$

where Z is a synthetic variable categorizing the data into any two subsets using a value of 1 or 0, β values are regression fitted coefficients and ε represents random variation not accounted for by the rest of the model. The model for the relationships between log(Q) and log(C_{SS}) for the two groups can then be defined as:

G1 (Z = 1): $$\log(C_{SS}) = (\beta_0 + \beta_2) + (\beta_1 + \beta_3)\mathrm{Log}(Qi) + \varepsilon \qquad (4.3.3)$$

G2 (Z = 0): $$\log(C_{SS}) = \beta_0 + \beta_1 \log(Q_i) + \varepsilon \qquad (4.3.4)$$

These models form the basis for testing the subset rating curves for coincidence, where both subgroups should be described by the same rating curve, parallelism, the condition where rating curve slopes are statistically the same, and offset equivalence, where rating curve intercepts are equal. Coincident subgroups display the exact same relationship between the dependent and independent variables, in this case log(C_{SS}) and log(Q). In testing for coincidence the null hypothesis is:

H_0: $$\beta_2 = \beta_3 = 0. \qquad (4.3.5)$$

If the null hypothesis cannot be discarded, then both groups are considered coincident, and the relationship between log(C_{SS}) and log(Q) is described as equation 4.2.4 for the entire data set. If the null hypothesis is discarded, then further tests for parallelism and equivalence of offset (also known as equality of intercepts or elevation equivalence) are required to determine how the relationship between log(C_{SS}) and log(Q) significantly differ. The null hypothesis of parallelism, the condition in which the slopes of the two subgroup regression lines are equal, is:

H_0: $$\beta_3 = 0. \qquad (4.3.6)$$

Similarly, difference in offset requires only that the intercepts of the two subsets are significantly different, with a null hypothesis of:

H_0: $$\beta_2 = 0. \qquad (4.3.7)$$

Log-linear C_{SS}-Q rating curves for stations on the CBD produced R^2 values of 0.03 to 0.60 with RMSE of 0.12 to 0.41 log (mg/L) (Table 4.3.22). All CBD station aggregate data sets (including both irrigation and non-irrigation season data) were found to not meet linear regression assumptions with the exception of station CBD-2B. Station data sub-grouped by season more often met linear assumptions, but low R^2 values and high RMSE values generally remained. The seasonal subset rating curves differed significantly for all stations in terms of both slope and offset, with the exception of CBD-1, which differed only in terms of slope, and CBD-2B, where the seasonal rating curves were found to be coincident.

For those stations found to differ seasonally, non-irrigation rating curves were all higher in slope, and also higher in offset at CBD-6 and CBD-7 (the most upstream stations on the CBD).

Table 4.3.22. CBD log-linear and rating curves and seasonal ANCOVA.

Sample set information		C_{SS} - Q log-linear regression descriptors						LR Test	LR Seasonal ANCOVA		
Station	Season	log (a)	P-value	log (b)	P-value	R^2	RMSE	Global Statistic	Coincidence	Parallelism	Offset
CBD-1	All	1.31	***	0.43	***	0.33	0.29	N	**	**	Equivalent
CBD-1	Irrigation	1.59	***	0.21	**	0.04	0.29	Y			
CBD-1	Non-Irrigation	1.22	***	0.49	***	0.51	0.28	N			
CBD-2	All	1.29	***	0.40	***	0.20	0.31	N	*	*	**
CBD-2	Irrigation	1.52	***	0.19	ns	0.03	0.26	Y			
CBD-2	Non-Irrigation	1.25	***	0.50	***	0.34	0.35	N			
CBD-2B	All	1.55	***	0.18	ns	0.04	0.23	Y	Coincident	Parallel	Equivalent
CBD-2B	Irrigation	1.44	***	0.25	*	0.05	0.25	Y			
CBD-2B	Non-Irrigation	1.77	***	0.01	ns	0.11	0.12	Y			
CBD-3	All	1.20	***	0.51	***	0.31	0.30	N	***	***	**
CBD-3	Irrigation	1.47	***	0.27	***	0.11	0.25	N			
CBD-3	Non-Irrigation	1.06	***	0.65	***	0.45	0.31	N			
CBD-4	All	1.43	***	0.27	***	0.09	0.30	N	**	**	***
CBD-4	Irrigation	1.40	***	0.24	**	0.05	0.27	N			
CBD-4	Non-Irrigation	1.32	***	0.63	***	0.47	0.28	Y			
CBD-6	All	1.34	***	0.44	***	0.21	0.36	N	***	***	***
CBD-6	Irrigation	1.32	***	0.19	*	0.09	0.21	Y			
CBD-6	Non-Irrigation	1.45	***	0.93	***	0.51	0.39	Y			
CBD-7	All	1.19	***	0.54	***	0.24	0.41	N	**	**	***
CBD-7	Irrigation	1.09	***	0.59	***	0.30	0.33	N			
CBD-7	Non-Irrigation	1.71	***	1.50	***	0.60	0.39	Y			

P-value and ANCOVA results: ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001, note that significant ANCOVA test results indicate that seasonal regression subset rating curves differ significantly as a whole (Coincidence test), in terms of slope (Parallelism test) or intercept (Offset test). Global Statistic: Y = linear assumptions satisfied, N = linear assumptions not satisfied.

Log-linear C_{SS}-Q rating curves for stations on lateral drains produced R^2 values of 0.01 to 0.69 with very high RMSE values of 0.25 to 0.67 log (mg/L) (Table 4.3.23). The lateral drain station aggregate data sets (including both irrigation and non-irrigation season data) were found to not meet linear regression assumptions with the exception of GCID Drain 2047 at Bondurant Slough and GCID section 25. Station data sub-grouped by season more often met linear assumptions, but low R^2 values and high RMSE values generally remained, with the exception of non-irrigation season rating curves for stations Bondurant Slough, Kuhl Weir, and GCID Lateral Drain section 25. The seasonal subset rating curves differed significantly for the aforementioned three stations, and were coincident for GCID Drain 55, and Salmon Hole. For those stations found to differ seasonally, non-irrigation rating curves were all higher in slope and offset.

Table 4.3.23. Lateral drain station log-linear and rating curves and seasonal ANCOVA.

Sample set information		C_{SS} - Q log-linear regression descriptors						LR Test	LR Seasonal ANCOVA		
Station	Season	log (*a*)	P-value	log (*b*)	P-value	R^2	RMSE	Global Statistic	Coincidence	Parallelism	Offset
LD3. Bondurant-slough	All	1.48	***	0.63	***	0.25	0.49	Y	**	**	**
LD3. Bondurant-slough	Irrigation	1.09	***	0.24	ns	0.05	0.32	Y			
LD3. Bondurant-slough	Non-Irrigation	1.90	***	0.99	***	0.46	0.51	Y			
LD7. GCID-Drain-55	All	1.09	***	0.08	ns	0.01	0.47	N	Coincident	Parallel	*
LD7. GCID-Drain-55	Irrigation	0.98	***	0.07	ns	0.02	0.36	N			
LD7. GCID-Drain-55	Non-Irrigation	1.43	***	0.54	*	0.12	0.52	N			
LD9. Kuhl-Weir	All	1.63	***	0.32	*	0.11	0.41	N	***	***	***
LD9. Kuhl-Weir	Irrigation	1.42	***	0.23	*	0.15	0.25	N			
LD9. Kuhl-Weir	Non-Irrigation	2.18	***	1.02	***	0.62	0.32	Y			
LD13. Salmon-hole	All	1.70	***	0.42	*	0.12	0.57	N	Coincident	Parallel	**
LD13. Salmon-hole	Irrigation	1.15	***	0.02	ns	0.05	0.32	Y			
LD13. Salmon-hole	Non-Irrigation	2.11	***	0.59	ns	0.17	0.67	Y			
LD8. GCID-section-25	All	1.70	***	0.32	*	0.07	0.46	Y	***	***	*
LD8. GCID-section-25	Irrigation	1.57	***	-0.05	ns	0.04	0.35	Y			
LD8. GCID-section-25	Non-Irrigation	2.19	***	1.28	***	0.69	0.34	Y			

P-value and ANCOVA results: ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001, note that significant ANCOVA test results indicate that seasonal regression subset rating curves differ significantly as a whole (Coincidence test), in terms of slope (Parallelism test) or intercept (Offset test). Global Statistic: Y = linear assumptions satisfied, N = linear assumptions not satisfied.

Log-linear C_{SS}-Q rating curves for stations on foothill tributaries produced R^2 values of 0.01 to 0.73 with high RMSE values of 0.15 to 0.67 log (mg/L) (Table 4.3.24). The foothill tributary station aggregate data sets (including both irrigation and non-irrigation season data) were found to not meet linear regression assumptions with the exception of the GCID Freshwater Creek station and Walker Creek at Highway 99 and County Road 33. Station data sub-grouped by season more often met linear assumptions, although both seasonal subsets remained in violation of linear assumptions for Funks Creek at McDermott Road, Stone Corral Creek at Fourmile Road, and Stone Corral Creek at Two Mile Road. Foothill tributary non-irrigation rating curves generally explained more variance in C_{SS} (with higher R^2 values and lower RMSE) than found for stations in the CBD and lateral drains, with the exception of Hunter Creek, Logan Creek and Walker Creek at Highway 99 and County Road 33. The seasonal subset rating curves differed significantly in terms of both slope and offset for all of the foothill tributary stations with sufficient data sets, except for Freshwater Creek, Hunter Creek, Logan Creek, and Walker Creek at Highway 99 and County Road 33, which were statistically coincident by season. The rest of the stations found to differ seasonally had non-irrigation season rating curves with higher slopes and offsets than irrigation season rating curves.

Table 4.3.24. Foothill tributary log-linear and rating curves and seasonal ANCOVA.

Sample set information		C_{SS} - Q log-linear regression descriptors						LR Test	LR Seasonal ANCOVA		
Station	Season	log (*a*)	P-value	log (*b*)	P-value	R^2	RMSE	Global Statistic	Coincidence	Parallelism	Offset
T1. Buckeye-Rd2	Non-Irrigation	3.07	***	0.54	**	0.46	0.39	Y			
T2. Freshwater-Creek	All	1.97	***	0.63	***	0.49	0.29	Y	Coincident	Parallel	Equivalent
T2. Freshwater-Creek	Irrigation	1.91	***	0.56	***	0.38	0.26	Y			
T2. Freshwater-Creek	Non-Irrigation	2.16	***	0.91	***	0.63	0.29	Y			
T3. Funks-Lenahan	Non-Irrigation	1.69	*	0.84	ns	0.42	0.67	Y			
T4. Funks-McDermott	All	1.56	***	0.60	***	0.34	0.48	N	*	*	**
T4. Funks-McDermott	Irrigation	1.51	***	0.35	**	0.08	0.35	N			
T4. Funks-McDermott	Non-Irrigation	1.70	***	0.73	***	0.46	0.59	N			
T5. Hunter-Creek	All	1.53	***	-0.08	ns	0.01	0.53	N	Coincident	Parallel	Equivalent
T5. Hunter-Creek	Irrigation	1.53	***	-0.19	**	0.26	0.25	Y			
T5. Hunter-Creek	Non-Irrigation	1.55	***	0.02	ns	0.05	0.73	Y			
T7. Logan-Creek	All	1.65	***	0.17	*	0.08	0.26	N	Coincident	Parallel	*
T7. Logan-Creek	Irrigation	1.56	***	0.06	ns	0.02	0.19	Y			
T7. Logan-Creek	Non-Irrigation	1.74	***	0.21	ns	0.07	0.31	Y			
T8. Lurline.cr.a.99W	Irrigation	2.25	**	-0.55	*	0.70	0.23	Y			
T10. SCC-Cemetery	Non-Irrigation	1.55	**	0.84	*	0.54	0.63	Y			
T11. SCC-Delevan	Irrigation	1.58	***	0.34	ns	0.06	0.15	N			
T12. SCC-Fourmile	All	1.75	***	0.30	***	0.16	0.36	N	***	***	***
T12. SCC-Fourmile	Irrigation	1.82	***	-0.04	ns	0.01	0.26	N			
T12. SCC-Fourmile	Non-Irrigation	1.87	***	0.59	***	0.48	0.38	N			
T18. SCC-Frontage	All	1.63	***	0.61	***	0.40	0.41	N	***	***	**
T18. SCC-Frontage	Irrigation	1.52	***	0.02	ns	0.01	0.29	Y			
T18. SCC-Frontage	Non-Irrigation	1.84	***	0.87	***	0.65	0.42	N			
T13. SCC-GCID	All	1.75	***	0.38	***	0.21	0.31	N	*	*	***
T13. SCC-GCID	Irrigation	1.69	***	0.20	ns	0.03	0.24	Y			
T13. SCC-GCID	Non-Irrigation	1.89	***	0.62	***	0.52	0.31	Y			
T14. SCC-Lovelace	Irrigation	1.45	***	-0.18	ns	0.00	0.21	N			
T15. SCC-McDermott	All	1.64	***	0.75	***	0.55	0.43	N	***	***	***
T15. SCC-McDermott	Irrigation	1.46	***	0.08	ns	0.01	0.32	Y			
T15. SCC-McDermott	Non-Irrigation	1.78	***	0.85	***	0.71	0.47	N			
T17. SCC-Twomile	All	1.67	***	0.35	***	0.15	0.40	N	***	***	***
T17. SCC-Twomile	Irrigation	1.57	***	0.02	ns	0.01	0.22	N			
T17. SCC-Twomile	Non-Irrigation	1.96	***	0.68	***	0.48	0.44	N			
T16. SCC-Sites	Non-Irrigation	2.52	*	0.68	ns	0.56	0.57	Y			
T22. Walker.cr.nr.99W.CR33	All	1.31	***	0.33	**	0.31	0.33	Y	Coincident	Parallel	Equivalent
T22. Walker.cr.nr.99W.CR33	Irrigation	1.35	***	0.45	ns	0.24	0.25	Y			
T22. Walker.cr.nr.99W.CR33	Non-Irrigation	1.34	***	0.30	*	0.27	0.40	Y			
T23. Willow-Creek	All	1.44	***	0.36	***	0.12	0.43	N	*	*	***
T23. Willow-Creek	Irrigation	1.25	***	0.12	ns	0.01	0.34	Y			
T23. Willow-Creek	Non-Irrigation	1.72	***	0.55	***	0.44	0.36	Y			

P-value and ANCOVA results: ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001, note that significant ANCOVA test results indicate that seasonal regression subset rating curves differ significantly as a whole (Coincidence test), in terms of slope (Parallelism test) or intercept (Offset test). Global Statistic: Y = linear assumptions satisfied, N = linear assumptions not satisfied.

Log-linear C_{SS}-Q rating curves for the two irrigation supply stations produced R^2 values of 0.17 to 0.64 with high RMSE values of 0.20 to 0.55 log (mg/L) (Table 4.3.25). The lateral drain station aggregate data sets (including both irrigation and non-irrigation season data) were found to not meet linear regression assumptions. Station data sub-grouped by season met linear assumptions with the exception of the GCID Main Canal during the irrigation season. Non-irrigation season rating curves differed significantly in terms of slope but not offset for both irrigation supply stations, and in both cases slope was higher during the non-irrigation season.

Table 4.3.25. Foothill tributary log-linear and rating curves and seasonal ANCOVA.

Sample set information		C_{SS} - Q log-linear regression descriptors						LR Test	LR Seasonal ANCOVA		
Station	Season	log (*a*)	P-value	log (*b*)	P-value	R^2	RMSE	Global Statistic	Coincidence	Parallelism	Offset
GCID-Main-Canal	All	0.70	***	0.36	***	0.26	0.46	N	***	***	Equivalent
GCID-Main-Canal	Irrigation	2.03	***	-0.49	***	0.43	0.20	Y			
GCID-Main-Canal	Non-Irrigation	0.59	*	0.50	***	0.50	0.55	Y			
GCID-Supply	All	1.37	***	0.38	***	0.38	0.29	N	***	***	Equivalent
GCID-Supply	Irrigation	1.56	***	0.22	***	0.17	0.28	N			
GCID-Supply	Non-Irrigation	0.92	***	0.65	***	0.64	0.25	Y			

P-value and ANCOVA results: ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001, note that significant ANCOVA test results indicate that seasonal regression subset rating curves differ significantly as a whole (Coincidence test), in terms of slope (Parallelism test) or intercept (Offset test). Global Statistic: Y = linear assumptions satisfied, N = linear assumptions not satisfied.

Log-linear C_{SS}-Q rating curves for the two stations on the Sacramento River (above and below the CBD outlet) produced R^2 values of 0.01 to 0.65 with high RMSE values of 0.14 to 0.40 log (mg/L) (Table 4.3.26). The Sacramento River aggregate data sets (including both irrigation and non-irrigation season data) were found to not meet linear regression assumptions. Station data sub-grouped by season met linear assumptions with the exception of the Sacramento River below Knights Landing during the non-irrigation season. The seasonal subset rating curves for the Sacramento River above the CBD differed significantly in terms of slope but not offset, with a higher non-irrigation season slope. The seasonal curves for the Sacramento River below Knights Landing were found to be coincident; however this was a moot point as simple log-linear C_{SS}-Q curves explained almost no variability in C_{SS} at this station.

Table 4.3.26. Sacramento River log-linear and rating curves and seasonal ANCOVA.

Sample set information		C_{SS} - Q log-linear regression descriptors						LR Test	LR Seasonal ANCOVA		
Station	Season	log (*a*)	P-value	log (*b*)	P-value	R^2	RMSE	Global Statistic	Coincidence	Parallelism	Offset
S2.sac.r.ab.cbd	All	-0.69	***	0.96	***	0.54	0.21	N	***	***	Equivalent
S2.sac.r.ab.cbd	Irrigation	1.28	**	0.11	ns	0.01	0.14	Y			
S2.sac.r.ab.cbd	Non-Irrigation	-1.28	***	1.18	***	0.65	0.24	Y			
S3.sac.r.bl.KnLnd	All	1.63	***	0.03	ns	0.00	0.32	N	Coincident	Parallel	Equivalent
S3.sac.r.bl.KnLnd	Irrigation	1.76	***	-0.03	ns	0.01	0.24	Y			
S3.sac.r.bl.KnLnd	Non-Irrigation	1.52	***	0.08	ns	0.01	0.40	N			

P-value and ANCOVA results: ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001, note that significant ANCOVA test results indicate that seasonal regression subset rating curves differ significantly as a whole (Coincidence test), in terms of slope (Parallelism test) or intercept (Offset test). Global Statistic: Y = linear assumptions satisfied, N = linear assumptions not satisfied.

4.3.2.4 LOESS rating curves and temporal dependence analysis of residuals

Rating curve residuals, which are the difference between sample values of C_{SS} and the value of the rating curve, can be used to reveal systematic departures in sample C_{SS}-Q relationships from that of the simple rating curve model – including analysis of temporal trends in C_{SS}. For such an analysis to be effective the data must adhere to the modeled relationship, otherwise d systematic bias can be introduced to the residuals as an artifact of poor fitting. The data sets used to develop log-linear rating curves for surface water stations in the Colusa Basin drainage area and the Sacramento River in the vicinity of the CBD outfall often failed to meet linear regression assumptions (see Section 4.3.2.3). It has been recognized that the C_{SS}-Q relationships of many episodic river systems on the west coast of North America often systematically depart from the log-linear rating curve, particularly at low and high Q (Farnsworth and Warrick, 2007; Warrick *et al.*, 2013; Gray *et al.*, 2014).

Closer examination of log-linear rating curves used in this study found that changes in C_{SS}-Q relationships over the Q domain was a probable culprit for many of the poor linear fits found above. For example, log-linear curves fit to the station on the Sacramento River below the CBD outfall explained almost no variability in C_{SS}, even when subdivided by season (Figure 4.3.8). Visual inspection reveals a relatively flat relationship between C_{SS}-Q at $Q < 100$ m^3/s, followed by a relatively steep linear-like relationship for $Q > 100$ m^3/s; a situation that is not alleviated by seasonal partitioning.

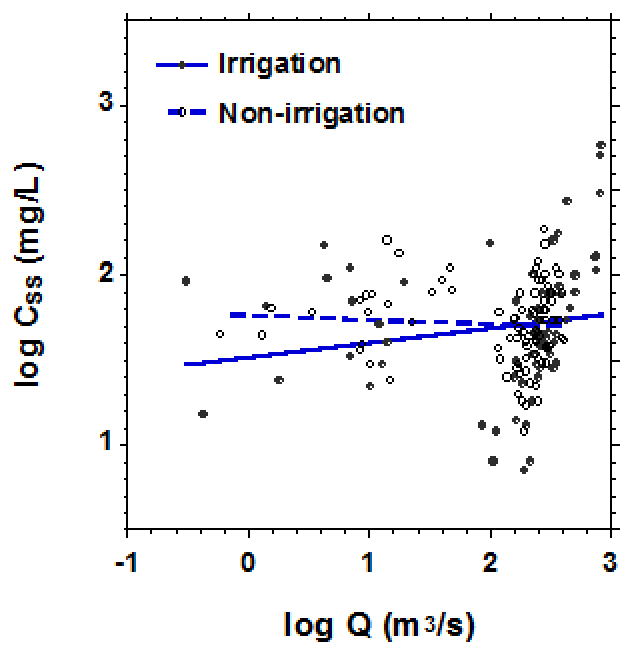

Figure 4.3.8. Sacramento River below CBD.

To avoid potential bias from the systematically poor fit of log-linear curves, a localized regression approach was used to the construct rating curves that would be used for subsequent residual analysis. The particular local regression scheme employed is known as 'LOESS' (see Section 3.3), which was fitted to each station $\{Q, C_{SS}\}$ data set and seasonal subsets if applicable, using the smoothing parameter $\alpha = 0.75$ and second-degree polynomials (Cleveland, 1979; Cleveland and Devlin, 1988; Helsel and Hirsch, 2002). Note that rating curves in this portion of the study were not adjusted for log-transform bias (i.e., Ferguson, 1986), as they were used solely for inter-curve comparison rather than prediction of C_{SS} in terms of untransformed units of measure.

Residual values calculated from LOESS rating curves were then examined for temporal trends in Q corrected C_{SS} values. Both a parametric (linear regression) and non-parametric (Mann-Kendall) approaches were employed to evaluate residual temporal trends. The Mann-Kendall approach is a rank based correlation analysis that produces a *Tau* value, ranging from -1 to 1, which indicates the direction and strength of the correlation, and P-value indicating significance. Linear regression tests of temporal dependence involve a host of assumptions detailed in Section 3.4, most of which are not required for the Mann-Kendall approach. However, both methods are strictly applicable to only monotonic trends, which will be investigated further at the end of this section.

Significant temporal trends in LOESS rating curve residuals were found for the following stations on the CBD: CBD-2, CBD-2B, CBD-3, CBD-4 and CBD-6 (Table 4.3.27). All significant trends were negative and based on data sets collected over 3 or 4 year base periods from the late 1970s to early 1980s. As noted in the review of the UCD/USEPA NPS CBD, these apparent trends are probably motivated in part by an increase in sediment concentrations during water year 1979 due to an accumulation of sediment supplies after years of drought from 1975-1978. The only interdecadal scale record, that of CBD-1, was collected from 1975-1998 and did not show a significant trend despite significant increases in irrigation water supply and changes to land use during that time period.

Table 4.3.27. CBD LOESS rating curves and residual temporal trends.

Sample set information		Date range		LOESS	MK Temporal Trend	
Station	Season	Beginning	End	RMSE	Tau	P-value
CBD-1	All	9/24/1975	4/15/1998	0.27	0.01	ns
CBD-1	Irrigation	9/24/1975	4/15/1998	0.29	0.09	ns
CBD-1	Non-Irrigation	10/22/1975	3/11/1998	0.26	-0.04	ns
CBD-2	All	4/11/1978	9/28/1981	0.28	-0.11	*
CBD-2	Irrigation	4/11/1978	9/28/1981	0.26	-0.11	ns
CBD-2	Non-Irrigation	10/3/1978	3/30/1981	0.29	-0.16	*
CBD-2B	All	5/2/1978	9/29/1980	0.24	-0.33	***
CBD-2B	Irrigation	5/2/1978	9/29/1980	0.25	-0.33	***
CBD-2B	Non-Irrigation	10/3/1978	11/5/1979	0.14	0.09	ns
CBD-3	All	1/31/1978	9/28/1981	0.28	-0.31	***
CBD-3	Irrigation	4/2/1978	9/28/1981	0.25	-0.20	**
CBD-3	Non-Irrigation	1/31/1978	3/30/1981	0.28	-0.32	***
CBD-4	All	10/3/1977	9/15/1981	0.29	-0.12	*
CBD-4	Irrigation	4/3/1978	9/15/1981	0.26	-0.02	ns
CBD-4	Non-Irrigation	10/3/1977	3/17/1981	0.29	-0.11	ns
CBD-6	All	10/3/1977	9/15/1981	0.34	-0.16	*
CBD-6	Irrigation	4/3/1978	9/15/1981	0.21	0.02	ns
CBD-6	Non-Irrigation	10/3/1977	3/17/1981	0.38	-0.19	ns
CBD-7	All	10/3/1977	9/15/1981	0.38	0.06	ns
CBD-7	Irrigation	4/3/1978	9/15/1981	0.31	0.14	ns
CBD-7	Non-Irrigation	10/3/1977	3/17/1981	0.32	0.31	ns

ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001

Only two significant temporal trends were found for among the lateral drain stations, in the aggregate records of the GCID Drain 55 and Kuhl Weir (Table 4.3.28). Both of these were relatively weak, negative trends over the time period of 1977 to 1981.

Table 4.3.28. Later drain LOESS rating curves and residual temporal trends.

Sample set information		Date range		LOESS	MK Temporal Trend	
Station	Season	Beginning	End	RMSE	Tau	P-value
LD3. Bondurant-slough	All	10/3/1977	9/15/1981	0.49	-0.14	ns
LD3. Bondurant-slough	Irrigation	4/3/1978	9/15/1981	0.29	0.02	ns
LD3. Bondurant-slough	Non-Irrigation	10/3/1977	3/17/1981	0.49	-0.11	ns
LD7. GCID-Drain-55	All	10/3/1977	9/23/1980	0.46	-0.29	***
LD7. GCID-Drain-55	Irrigation	4/3/1978	9/23/1980	0.35	-0.16	ns
LD7. GCID-Drain-55	Non-Irrigation	10/3/1977	3/18/1980	0.40	-0.20	ns
LD9. Kuhl-Weir	All	10/3/1977	8/31/1981	0.40	-0.24	*
LD9. Kuhl-Weir	Irrigation	4/3/1978	8/31/1981	0.24	-0.09	ns
LD9. Kuhl-Weir	Non-Irrigation	10/3/1977	3/2/1981	0.33	-0.27	ns
LD13. Salmon-hole	All	1/8/1978	8/31/1981	0.52	-0.16	ns
LD13. Salmon-hole	Irrigation	4/3/1978	8/31/1981	0.28	-0.27	ns
LD13. Salmon-hole	Non-Irrigation	1/8/1978	3/2/1981	0.64	-0.21	ns
LD8. GCID-section-25	All	10/3/1977	8/31/1981	0.45	-0.02	ns
LD8. GCID-section-25	Irrigation	4/3/1978	8/31/1981	0.37	0.10	ns
LD8. GCID-section-25	Non-Irrigation	10/3/1977	3/2/1981	0.26	-0.09	ns

ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001

Only two Foothill tributary stations displayed significant temporal trends in C_{SS} values over time: the aggregate record of Logan Creek, and the aggregate and irrigation season records of Willow Creek (Table 4.3.29). Both were relatively weak negative trends over the period between 1977 or 1978 and 1981.

Table 4.3.29. Foothill tributary LOESS rating curves and residual temporal trends.

Sample set information		Date range		LOESS	MK Temporal Trend	
Station	Season	Beginning	End	RMSE	Tau	P-value
T1. Buckeye-Rd2	Non-Irrigation	1/9/1978	3/3/1980	0.32	0.05	ns
T2. Freshwater-Creek	All	10/3/1977	8/31/1981	0.30	0.00	ns
T2. Freshwater-Creek	Irrigation	4/3/1978	8/31/1981	0.27	0.24	ns
T2. Freshwater-Creek	Non-Irrigation	10/3/1977	3/2/1981	0.29	-0.19	ns
T3. Funks-Lenahan	Non-Irrigation	1/12/1978	3/6/1978	0.00	0.14	ns
T4. Funks-McDermott	All	1/12/1978	9/28/1981	0.43	0.07	ns
T4. Funks-McDermott	Irrigation	4/18/1978	9/28/1981	0.35	-0.04	ns
T4. Funks-McDermott	Non-Irrigation	1/12/1978	3/30/1981	0.52	0.12	ns
T5. Hunter-Creek	All	10/3/1977	8/31/1981	0.48	-0.09	ns
T5. Hunter-Creek	Irrigation	4/3/1978	8/31/1981	0.24	-0.12	ns
T5. Hunter-Creek	Non-Irrigation	10/3/1977	3/2/1981	0.60	0.10	ns
T7. Logan-Creek	All	10/3/1977	8/31/1981	0.26	-0.21	*
T7. Logan-Creek	Irrigation	4/3/1978	8/31/1981	0.20	-0.21	ns
T7. Logan-Creek	Non-Irrigation	10/3/1977	3/2/1981	0.24	-0.09	ns
T8. Lurline.cr.a.99W	Irrigation	4/18/2007	8/22/2007	NA	-0.60	ns
T10. SCC-Cemetery	Non-Irrigation	1/12/1978	3/28/1978	0.48	-0.33	ns
T11. SCC-Delevan	Irrigation	5/2/1978	9/15/1978	0.14	-0.08	ns

T12. SCC-Fourmile	All	4/25/1978	9/28/1981	0.32	0.05	ns
T12. SCC-Fourmile	Irrigation	4/25/1978	9/28/1981	0.25	0.11	ns
T12. SCC-Fourmile	Non-Irrigation	10/3/1978	3/30/1981	0.34	0.02	ns
T18. SCC-Frontage	All	4/25/1978	8/21/2178	0.36	0.02	ns
T18. SCC-Frontage	Irrigation	4/25/1978	8/21/2178	0.28	-0.08	ns
T18. SCC-Frontage	Non-Irrigation	10/3/1978	3/30/1981	0.40	0.01	ns
T13. SCC-GCID	All	10/3/1977	8/31/1981	0.31	-0.09	ns
T13. SCC-GCID	Irrigation	4/3/1978	8/31/1981	0.22	0.11	ns
T13. SCC-GCID	Non-Irrigation	10/3/1977	3/17/1981	0.29	-0.10	ns
T14. SCC-Lovelace	Irrigation	5/2/1978	8/1/2014	0.21	-0.14	ns
T15. SCC-McDermott	All	1/12/1978	9/28/1981	0.38	0.06	ns
T15. SCC-McDermott	Irrigation	4/25/1978	9/28/1981	0.32	0.01	ns
T15. SCC-McDermott	Non-Irrigation	1/12/1978	3/30/1981	0.41	0.08	ns
T17. SCC-Twomile	All	4/25/1978	9/28/1981	0.32	0.05	ns
T17. SCC-Twomile	Irrigation	4/25/1978	9/28/1981	0.21	0.02	ns
T17. SCC-Twomile	Non-Irrigation	10/3/1978	3/30/1981	0.38	-0.02	ns
T16. SCC-Sites	Non-Irrigation	1/10/1978	2/7/1978	NA	0.55	ns
T22. Walker.cr.nr.99W.CR33	All	2/19/2009	1/24/2012	0.31	-0.13	ns
T22. Walker.cr.nr.99W.CR33	Irrigation	4/22/2010	7/20/2011	0.27	-0.07	ns
T22. Walker.cr.nr.99W.CR33	Non-Irrigation	2/19/2009	1/24/2012	0.26	-0.43	ns
T23. Willow-Creek	All	10/3/1977	9/15/1981	0.38	-0.31	***
T23. Willow-Creek	Irrigation	4/3/1978	9/15/1981	0.34	-0.39	***
T23. Willow-Creek	Non-Irrigation	10/3/1977	3/17/1981	0.29	-0.20	ns

ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001

Of the two irrigation supply stations that were monitored, the only significant temporal trend was found in the GCID Main Canal aggregate record from 1977 to 1980 (Table 4.3.30). This was a relatively weak decreasing trend.

Table 4.3.30. Irrigation supply LOESS rating curves and residual temporal trends.

Sample set information		Date range		LOESS	MK Temporal Trend	
Station	Season	Beginning	End	RMSE	Tau	P-value
GCID-Main-Canal	All	10/3/1977	8/31/1981	0.34	-0.04	ns
GCID-Main-Canal	Irrigation	4/3/1978	8/31/1981	0.20	-0.31	*
GCID-Main-Canal	Non-Irrigation	10/3/1977	3/3/1980	0.42	-0.04	ns
GCID-Supply	All	11/14/1977	9/28/1981	0.27	-0.03	ns
GCID-Supply	Irrigation	4/4/1978	9/28/1981	0.28	0.04	ns
GCID-Supply	Non-Irrigation	11/14/1977	3/30/1981	0.25	-0.07	ns

ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001

The Sacramento River stations above and below the CBD were sampled over time periods extending from the 1960s to the 1980s. No significant trends were found for the Sacramento River above the CBD outfall, but the aggregate and both seasonal records below the CBD outfall were found to have significant negative trends over the 14 year period between 1967 and 1981 (Table 4.3.31).

Table 4.3.31. Sacramento River LOESS rating curves and residual temporal trends.

Sample set information		Date range		LOESS	MK Temporal Trend	
Station	Season	Beginning	End	RMSE	Tau	P-value
S2.sac.r.ab.cbd	All	1/18/1961	7/26/1989	0.20	-0.01	ns
S2.sac.r.ab.cbd	Irrigation	4/3/1972	7/26/1989	0.13	-0.18	ns
S2.sac.r.ab.cbd	Non-Irrigation	1/18/1961	2/21/1989	0.23	0.09	ns
S3.sac.r.bl.KnLnd	All	7/12/1967	11/24/1981	0.27	-0.26	***
S3.sac.r.bl.KnLnd	Irrigation	7/12/1967	9/29/1981	0.22	-0.33	***
S3.sac.r.bl.KnLnd	Non-Irrigation	10/11/1967	11/24/1981	0.30	-0.30	***

ns = non-significant with P-value > 0.05, * P-value < 0.05, ** P-value < 0.01, *** P-value < 0.001

5. Sediment Impact Assessment Methodology

This section begins with an introduction to the environmental impacts of watershed sediment production, transport and deposition, including a discussion of adverse and beneficial impacts to aquatic biota and human uses (Section 5.1). The major types of sediment impact methodologies that have been used to establish water quality standards in terms of sediment are then explored (Section 5.2). Finally, the most prominent methodologies are considered in terms of the Colusa Basin watershed and its downstream recipients of water and sediment, and a synthesis of relevant methods is proposed (Section 5.3). Electronic copies of much of the literature reviewed in this section are available in Section 10.1.

5.1 Impacts of Sediment on the Aquatic Environments and Human Beneficial Uses

Watershed sediments are a key component of terrestrial and aquatic systems along the entire continuum of sediment production to burial (Syvitski, 2003). All natural channelized flows (e.g., rills, gullies, streams, creeks, and rivers) transport sediments (Ryan, 1991). Therefore the presence of fluvial sediment in and of itself is not an indication of an impaired or adversely impacted waterbody (Bilotta and Brazier, 2008). Definition of adverse sediment impacts (referred to hereafter as sediment impacts) is dependent on location of the landscape of interest, and the ecosystem services and/or human beneficial uses derived from the system. Sediment impacts may include: (i) erosional effects on uplands and channels, (ii) effects of sediments in suspension, (iii) effects of deposited sediment, and (iv) effects of sediment mediated pollutants (US EPA, 2003a; 2006). These groups of impacts can be broadly divided into terrestrial and aquatic spheres, i.e. impacts of hillslope erosion and fluvial sediments, respectively.

Although the focus of this report is on fluvial sediments and their effects, production of these sediments from the landscape can also have significant effects on local stakeholders and the environment. Degradation of land surfaces through erosion can cause loss of productive soils, disruption of transportation networks, destruction of homes, and alteration of channel habitats. Upland erosion generally occurs through interaction of surface sediments, soils and bedrock with water, waterborne chemicals, air and temperature regimes over time. In temperate to subtropical dry summer Mediterranean climates, most sediments in low gradient terrains such as the Colusa valley lands are generally eroded from the land surface through diffuse interactions with precipitation and shallow, precipitation driven surface flow such as sheet flow and rilling, and through channel erosion associated with channel meandering or avulsion (Walling, 2005). Higher relief landscapes can also produce sediment through more discrete ‘point-source’ processes including gullying and mass wasting (i.e. land-slides) (Gomez *et al.*, 2004; Booth and Roering, 2011). Gullying can also impact generally low relief landscapes in localized areas of high slope, such as the transition between farm fields and drainage ditches, and drainage ditches to higher order streams (Wells *et al.*, 2013). Channel beds and banks can also be significant sources of sediment when net channel erosion occurs, which from a watershed scale perspective means that more bed and bank material are eroding throughout the channelized system then being deposited within it.

Sediments eroded from hillslopes and the channelized network become fluvial sediments. The amount of sediment carried in suspension, and transported along the bed (i.e. bedload) and the qualities of these sediments play important roles in the physical and biotic functioning of aquatic systems (see Section 3 of this study; Bilotta and Brazier, 2008; Naden, 2010). Increased C_{SS} has been found to be associated with increased detrimental impacts on aquatic organisms (i.e. fish, benthic invertebrates and vegetation) (e.g. Reynolds et al. 1988; Newcombe and MacDonald, 1991), although this is not universally the case. In some systems aquatic biota rely on suspended and deposited sediments for nutrient and energy inputs, and elevation maintenance (Brown, 1987; Bronmark, 2005, Nittrouer and Viparelli, 2014).

The manner in which increasing C_{SS} has been found to have adverse impacts on aquatic biota is species specific and also dependent on sediment characteristics and the duration of exposure (Birtwell, 1999; Bilotta and Brazier, 2008). Sediment qualities that are known to be important components of the impact of suspended sediments on the aquatic environment include particle size distribution, mineralogy, angularity, organic content and character, and the load of chemicals associated with the sediment surface (Lake and Hinch, 1999; Bilotta and Brazier, 2008). Each of the characteristics and functions of suspended sediment can be described as a continuum of values, certain ranges of which are beneficial, detrimental or even completely prohibitive for the needs of any given beneficial use, aquatic organism, ecosystem component, or human beneficial use of interest.

The most important roles of suspended sediment in terms of aquatic habitat and human beneficial uses of surface water can be broadly subdivided into the effects of sediments that are in suspension or after deposition. For an in depth description of the sediment transported in suspension, see Section 3.1. Sediments in suspension can impose direct impacts through interactions between the sediments and aquatic organisms and human beneficial uses, as well as indirect impacts through the mediation of other characteristics of the water body in question. Many studies have been conducted on the direct physiological and behavioral effects of suspended sediment on salmonids (see Cook-Tabor, 1995 for a list of publications). Direct impacts on aquatic organisms include mechanical abrasion of periphyton and macrophytes (Francoeur and Biggs, 2006), the clogging of the gills (Alabaster and Lloyd, 1982; Lake and Hinch, 1999), increased mortality of invertebrates and fishes (Robertson, 1957; Alabaster, 1972; Gray and Ward, 1982; Wagener and LaPerriere, 1985; Reynolds *et al.*, 1988), and avoidance behavior and feeding habit changes in fishes (Boubée *et al.*, 1997; Robertson *et al.*, 2006). Direct impacts on human beneficial uses include sedimentation and clogging of water entrainment and distribution facilities, particularly for irrigated agriculture, and increased pretreatment demands if used for drinking water sources (US EPA 2003a,b) or as a water source for fish hatcheries. Indirect impacts on aquatic ecosystems include increasing light attenuation (turbidity) and chemical changes imposed by the dynamics of surface associated chemicals – discussed in detail below (Newcomb and McDonald, 1991; Koch, 2001; Bilotta and Brazier, 2008). Increasing turbidity in turn can decrease primary productivity (Lloyd *et al.*, 1987) and increase the amount of effort required for visual feeders to forage successfully (Redding *et al.*, 1987). Increases in turbidity can also have adverse impacts human valuations of water bodies, including decreasing aesthetic qualities and posing an impediment to visualization of underwater hazards for bathers and navigation purposes (US EPA, 2003a).

Alteration of channel beds through suspended sediment deposition can impose physical habitat effects such as clogging of interstitial spaces between larger bed materials, changing the particle size distribution of bed surface sediments, and presenting a physical barrier to points of attachment or grazing resources for invertebrates (Ryder, 1989; Graham, 1990). These changes to the structure of the channel bed can result in direct impacts on organisms that live on or within the channel bed (Yamada and Nakamura, 2002; Rabeni *et al.*, 2005; Matthaei *et al.*, 2006; Heywood and Walling, 2007; Niyogi *et al.*, 2006). Fining of surficial channel bed sediment and filling of pore spaces can reduce the amount of habitat used by benthic invertebrates and fish as refugia and egg-laying sites (Sedell *et al.*, 1990; Heppell *et al.*, 2009). Changes to the particle size distribution and porosity of the channel bed in turn influence the dynamics of water movement through the bed (i.e. the hyporheic flow regime), which can reduce channel bed oxygen saturation profiles (Chapman, 1988; Beschta and Jackson, 1979; Acornley and Sear, 1999; Soulsby *et al.*, 2001; Greig *et al.*, 2005). Furthermore, deposition of labile organic compounds and subsequent decomposition can decrease oxygen levels in the channel bed and water column, which can impair or kill aquatic biota (Ryan, 1991).

An additional dimension of both suspended and deposited sediment impacts involves the conveyance of surface bound/associated chemicals and micro-organisms. Fine sediment (i.e., mud, which is composed of clay and silt, $D < 63$ µm) represents the largest proportion of solid surface area moving through fluvial systems, which along with the high surface charges of clays results in most surface associated materials transported through rivers and streams in association with suspended fine sediments (see Section 3.1) (Naden, 2010). Surface-mediated materials transported with fine sediments include organic carbon, nutrients (particularly P), hydrophobic organic chemicals, heavy metals, and microbia (Meybeck, 1982; Weston *et al.*, 2004; Smalling 2005; Springborn *et al.*, 2011; Pandey and Soupir, 2014). These materials can have a wide range of effects, including mediation of oxygen availability in stagnant waters and bed sediments through the delivery of labile (consumable) carbon, eutrophication, and toxic effects on aquatic organisms and humans, and impacts on human beneficial uses (Bilotta and Brazier, 2008).

5.2 Review of Sediment Impact Assessment Methodologies

A wide range of aquatic responses to sediments have been observed due to the specific characteristics of biota, sediment composition, and sediment associated constituents (Section 5.1). For these reasons, an ideal sediment impact assessment methodology would employ an approach based on site-specific information in term of both sediment characteristics and the demands of the aquatic habitat/human beneficial uses in question. In practice such specificity is rarely employed (Bilotta and Brazier, 2008). Sediment is generally only considered in terms of turbidity or C_{SS} levels, without any handling of the timing or duration of these conditions, much less further characterization of the sediments themselves (Bilotta and Brazier, 2008). Impairment is generally assessed in terms of (i) specific qualities required of the water body for given components of the aquatic system (i.e. the needs of aquatic biota) and/or human beneficial uses, (ii) general guidelines in terms of absolute values of sediment metrics, or (iii) guidelines relative to some condition considered to be natural or 'undisturbed' by humans (US EPA, 2006; Bilotta and Brazier, 2008). The latter two assessment methods are the most prevalent, and tend to be employed in a highly general manner, with rote guidelines that vary little, if at all, with site characteristics (Bilotta and Brazier, 2008). None of these methodologies address all of the modalities of fluvial sediment impact detailed in Section 5.1. Thus, development of a sediment impact methodology for the Colusa Basin drainage area necessitates the employment of a combination of methodologies to fully consider the impacts of Colusa Basin drainage area fluvial sediments.

As discussed in Sections 3.1 and 5.1, unlike many human-generated pollutants, sediment is a naturally occurring and important component of aquatic ecosystems (US EPA, 2003a; Naden, 2010). This natural or 'background' sediment production presents a need for characterizing not only sources of sediment, but also the role of human activity in determining sediment qualities and production. The highly altered nature of many watersheds throughout the USA, including California, in combination with limited interdecadal monitoring and historical data from time periods of lesser human impacts presents a significant challenge to the characterization of human impacts on watershed-scale sediment regimes (Napolitano *et al.*, 2007). Methodologies that seek to discriminate between 'natural' baselines and human-elevated levels of fluvial sediment are often hampered by this paucity of data. As a result, water quality mangers often use simple generalizations, speculation or monitoring data within the time period of human impacts to develop baseline fluvial sediment condition estimates (Billota and Brazier, 2008). Reference reaches of similar unaltered systems are also sought when possible, or more sophisticated empirical methods may be applied to estimate a 'natural' state of a given water body (see Section 5.2.1.3)

The following subsections detail sediment impact assessment methodologies/frameworks recommended and/or employed by federal agencies in the USA and Canada, and US state and regional agencies. The legacy and ongoing guidance from the US EPA for water quality criteria and sediment impact assessment methodology development is a major factor in steering state and local applications. Thus, recent US EPA framing of the aquatic sediment issue was drawn upon heavily to outline the generic approaches to developing sediment impact assessment methods (Section 5.2.1). This is followed by discussion of state and regional examples of sediment impact methodologies employed for given projects (generally related to sediment TMDL development) in terms of the generic approaches defined by the US EPA (Section 5.2.2).

5.2.1 US EPA Defined Sediment Impact Assessment Methods

A great deal of guidance on the development of methods to address the direct impacts of suspended and deposited sediments has been produced by the US EPA (US EPA, 2003a). A critical US EPA (2003a) draft on 'Developing water quality criteria for suspended and bedload sediments (SABS)' presented the basis for much of this section. The US EPA recognized that developing regional/site specific methodologies to produce new and improved water quality criteria for aquatic sediment was one of the highest priorities of water quality standard and criteria development for the first decade of the 21st century (US EPA, 2003a,b).

The US EPA defines water quality standards as a three component system consisting of (i) designating beneficial use(s) for a water body, (ii) developing water quality criteria to protect designated use(s), and (iii) developing and implementing policies to maintain or return to said water quality (US EPA, 2003a). In the 21st century, the US EPA has chosen to focus mainly on the protection of aquatic life (US EPA, 2003a). Aquatic life is nearly ubiquitous and generally requires the most stringent water quality criteria of any of the mixed uses commonly required of a given water body, with the occasional exception of drinking water requirements (US EPA, 2003a). However, there is also a long legacy of considering sediment impacts on a wide range of beneficial uses of water bodies.

Sediment oriented water quality criteria recommendations from the US EPA have evolved over the past 40 years. Early criteria in the 1960s and 1970s focused on turbidity before transitioning to more explicit incorporation of the major suspended and depositional impacts of sediments on aquatic biota and human beneficial uses over the last 20 years. A 1976 report introduced a focus on light reduction as summarized in the US EPA Quality Criteria for Water (US EPA, 1986). This report recommended that all solids in the water column "should not reduce the depth of the compensation point for photosynthetic activity by more than 10% from the seasonally established norm for aquatic life."

While the photosynthetic criterion has not been subject to widespread adoption in the US, other aesthetic standards proposed by the US EPA have seen significant incorporation into water quality standards of the states (US EPA, 2003a; Pflüger *et al.*, 2010). The US EPA aesthetic standard is that, "all waters shall be free from substances attributable to wastewater or other discharges that: settle to form objectionable deposits; float as debris, scum, oil, or other matter to form nuisances; produce objectionable color, odor, taste or turbidity; injure or are toxic or produce adverse physiological response in humans, animals, or plants; produce undesirable or nuisance aquatic life," (US EPA, 1986).

Two early reports utilized by the US EPA Quality Criteria for Water (1986) in formulating recommendations for sediment were from the National Technical Advisory Committee (NTAC, 1968) and the National Academy of Science, National Academy of Engineering (NAS/NAE, 1972). These reports included the following recommended criteria for sediment in terms of drinking water and aquatic biota: (i) "Raw drinking water with treatment: turbidity in water should be readily removable by coagulation, sedimentation and filtration; it should not be present in any extent that will overload the water treatment plant facilities, and should not cause unreasonable treatment costs. In addition, turbidity should not frequently change or vary in characteristics to the extent that such changes cause upsets in water treatment processes (NAS/NAE, 1972)." (ii) "Freshwater aquatic life: combined effect of color and turbidity should not change the compensation point more than 10 percent from its seasonally established norm, nor should such a change take place in more than 10 percent of the biomass of photosynthetic organisms below the compensation point (NTAC, 1968)."

Consideration of recreational uses also imposes aesthetic and risk mitigating criteria on sediment levels in surface waters (USEPA, 2003a; Parametrix, 2003). Visual qualities of water (i.e. color and clarity) are important aesthetic components for recreational activities such as swimming, boating, hunting, fishing, and sightseeing (Smith *et al.*, 1995). Mitigation of risk for humans entering surface waters for swimming and bathing includes sufficient clarity to visualize submerged hazards (NAS/NAE, 1973), which was quantified as a minimum secchi disk visibility of four feet (NTAC, 1968).

An operational flow chart for application of the general US EPA guidelines to developing fluvial sediment criteria would begin with (i) the water quality parameters of interest and potential environmental indicators of their impacts, and then progression through (ii) establishing expectations for water bodies, (iii) linking water quality parameters with indicator responses, and (iv) defining and interpreting impacts (Figure 5.2.1 (US EPA 2003a,b; 2006). The US EPA (2003a) report also outlined five potential approaches that were under consideration for the development of water quality criteria in terms of SABS, the first four of which focus on aquatic life: (Section 5.2.1.1) the toxicological dose-response approach, (Section 5.2.1.2) the conditional probability approach to establishing thresholds, (Section 5.2.1.3) the reference condition approach, (Section 5.2.1.4) the fluvial geomorphic approach, and (Section 5.2.1.5) the water body use functional approach. These approaches are outlined below.

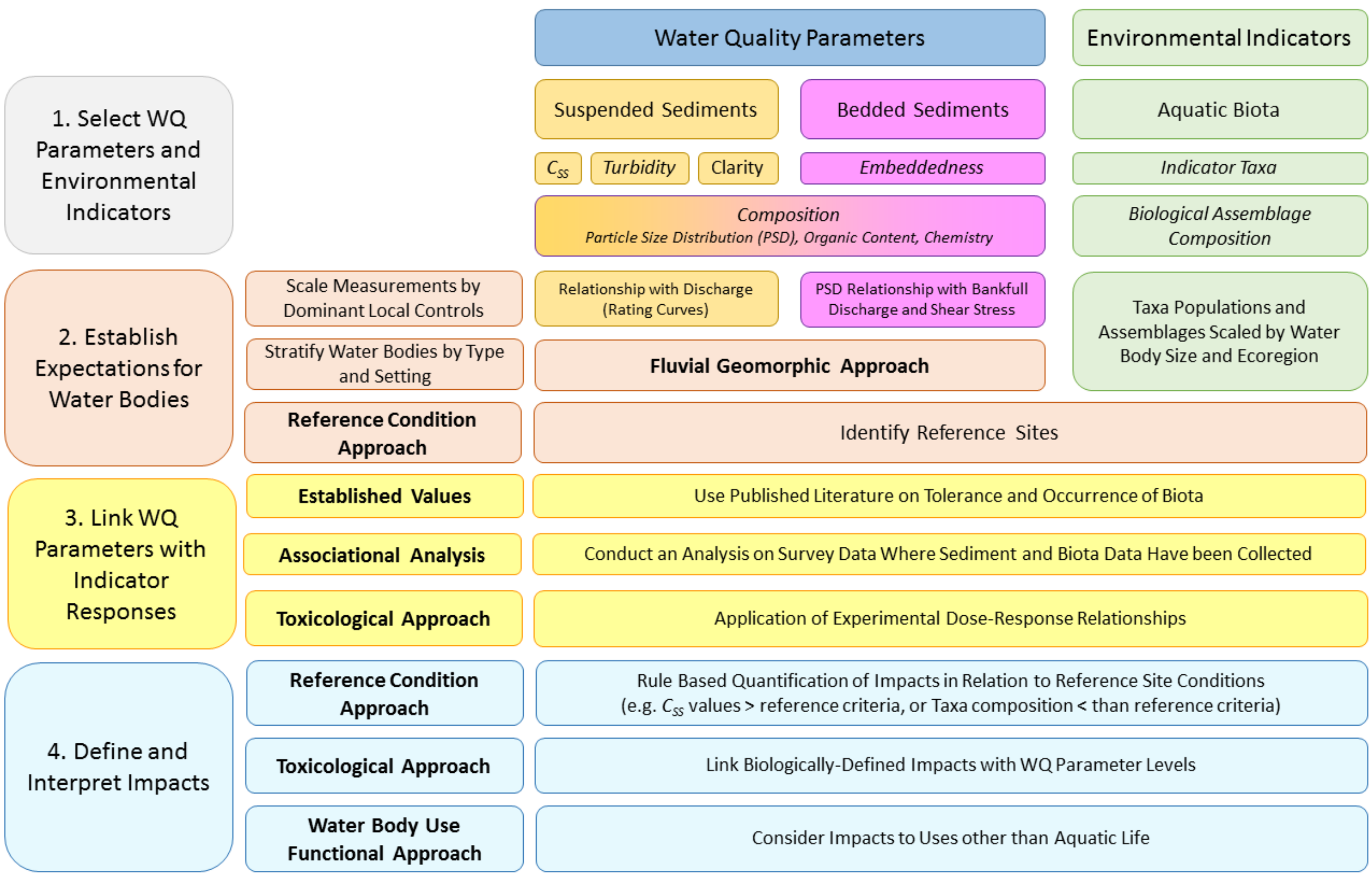

Figure 5.2.1. Synthesis of US EPA guidelines for developing water quality criteria and environmental impact assessment in terms of fluvial sediments (see US EPA 2003a,b; 2006).

5.2.1.1 Toxicological Dose-Response Approach

The toxicological dose-response approach stems from water quality criteria development to address the requirements under Section 304(a) of the Clean Water Act, and is primarily based on methodologies presented in US EPA (1985) 'Guidelines for Deriving Numerical National Aquatic Life Criteria for Protection of Aquatic Organisms and

Their Uses'. This approach requires acute toxicity data from at least 8 families of organisms with an additional requirement of minimum taxonomic diversity, and chronic toxicity test data from at least three families. These test data are then analyzed to compose a number of acute and chronic toxicological metrics. The Final Acute Value (FAV) and Final Chronic Value (FCV) are estimates of the 5th percentile of a sensitivity distribution of the average LC50/EC50s of the tested organisms for short term and long term exposure, respectively. The Criterion Maximum Concentration (CMC) is calculated as 0.5 x FAV, and the Criterion Continuous Concentration (CCC) is similarly 0.5 x FCV. However, it is only advisable to estimate CCC if chronic toxicological data are available from at least 8 families of organisms. Thus, CCC is usually computed using a simple ratio relationship to CMC. The CCC and CMC metrics then serve as targets that should not be exceeded for certain durations related to base of their test periods, with certain return intervals.

Some examples of suspended and bedload sediment dose-response models include recommendations from Newcombe and Macdonald (1991), the British Columbia Guidelines in Caux *et al.* (1997) and the Chesapeake Bay Water Clarity Guidelines in US EPA (2003c). Despite such applications, the US EPA has decided that this approach is not generally applicable to SABS due to the lack of species-specific data and generally acceptable methods for determining sediment effects on biota, as well as the fact that suspended sediments are diverse in composition. However, simplification to fewer (i.e. single) indicator organisms could render this approach more tenable. Even further simplification is possible if general dosage rates and durations are simply culled from the small body of experimental literature and applied to a given system.

5.2.1.2 Conditional probability approach to establishing thresholds

The development of a conditional probability approach to establishing water quality thresholds is based on the probability of a give impact occurring if a given water quality threshold is exceeded (Long and Morgan, 1991; MacDonald and Ingersoll, 2002; US EPA, 2003b). The fundamental concept behind this approach is 'conditional probability', which is the probability of an event occurring given the occurrence of another event. The common notation for conditional probability is P(Y|X*), where X* is the other event that is known to have occurred, and Y is the impact in question. When applied to a threshold based water quality framework, X* indicates a given $X > X_c$ scenario, where X_c is the water quality criterion or threshold (Long and Morgan, 1991). This approach is subject to the following requirements: (i) a metric (X) quantifying the water quality parameter, (ii) X must be a strong stressor on Y that is not obscured by other factors/stressors, (iii) a biologic impact metric must be available, and (iv) the data/results from a probabilistically designed study must be available in order to extrapolate impact probability estimations to larger spatial scales. Problems with (ii) are particularly important due to the correlative nature of this approach.

The conditional probability approach has been used specifically in the context of channel bed sedimentation in a US EPA assessment of streams in the Mid-Atlantic Highlands (US EPA, 2000). This study employed a channel sedimentation index (CSI) quantifying the deviation of channel fines content from expected conditions, which was then used to find the probability of benthic community impairment, defined as EPT taxa < 9. Benthic invertebrate survey data was sourced from the Environmental Monitoring and Assessment Program (EMAP) - a USEPA monitoring program for the environmental characterization of water bodies and assessment of environmental impacts of water quality impairments. Sub-setting of stream reach segments by CSI value was used in conjunction with benthic community data to develop an empirical curve for benthic community impact probability in relation to CSI.

5.2.1.3 Reference condition criteria derivation approach

The reference condition criteria derivation approach is derived from the regional reference approach for developing biocriteria (Barbour *et al.*, 1999; US EPA, 2003a,c). This approach is based on the theory that empirical models can use known relationships between environmental parameters, channel morphology and sediment dynamics in order to establish reference conditions that can then be used as the basis for establishing levels of impairment and impact (Knighton, 1984, Gordon *et al.*, 1992). A caveat is that relationships should be derived from non-disturbed or minimally disturbed streams, which are often unavailable in many regions. Reference site selection is further complicated by the interdecadal to centennial effects of historic land use/disturbances, the elucidation of which can require considerable research/paleo-environmental reconstruction (see Trimble, 1974; Schumm, 1977; Brundsden and Thornes, 1979, Trimble, 1999). Direct modification to the channelized system, including straightening, reinforcement and impoundment can also effect stream response over longer (interdecadal to centennial) time scales (Gregory and Madew, 1982; Walkerp, 1985; Reiser *et al.*, 1989; Simon and Hupp, 1992; Gordon *et al.*, 1992; Kondolf and Wilcock, 1996).

Hughes (1995) advanced the following criteria or optimal conditions for reference watershed selection: (i) approximately 95% under undisturbed/natural cover, (ii) historic land use disturbances ≤ 10% in the last 50 years, 25% in the last 100 years, (iii) human land use activities are not known sediment generators, such as mining, timber harvesting or steep slope agriculture, (iv) the spatial distribution of stream crossings by roads ≤ 1/mile, (v) no hydrologic modification of the stream ≤ 10 miles upstream of the sampling region, and (vi) no alteration of the stream in the last 50 years (US EPA, 2003a). In general five reference streams per 'type' are considered the minimum, while up to thirty are desirable (Elliot, 1977). Many reference sites have been identified and sampled as part of state biocriteria programs, EMAP, and the National Water Quality Assessment Program (NAWQA). The NAWQA is the USGS program to systematically collect chemical, biological, and physical water quality data from 51 study watersheds in the US (USGS, 2015). Note that many watersheds and subbasins in the US (including the Colusa Basin watershed) do not have corresponding reference watersheds that meet these criteria. However, this issue is generally dealt with by relaxing criteria.

Empirical models are developed on the basis of suspended and bed sediment characteristics found in reference streams, and the environmental characteristics of their watersheds. This requires P, Q, C_{SS} and bed sediment data sets, along with historic and current land use, geology, soil, vegetation, and topography survey data from reference watersheds. Continuous empirical models use the reference reach data to develop relationships between 'independent' variables and sediment response variables. In a site-specific application, the relevant independent variable data for a study site are then used to predict study site conditions of interest (in this case suspended and bed sediment characteristics). In contrast, a discrete predictive approach is used to estimate the sediment characteristics of types or classes of streams, under which the stream reaches of interest are classified. An example of the site-specific approach applied directly to aquatic communities is the River Invertebrate Prediction and Classification System (RIVPACS) (Wright *et al.*, 1984; Hawkins *et al.*, 2000; Wright, 2000). Examples of the discrete predictive approach include biological assessment models such as the fluvial geomorphic approach, notably the David L. Rosgen/US EPA WARSSS approach to sediment impact assessment and management (Section 5.2.1.4).

The USEPA has reported it to be 'highly likely' that EMAP and NAWQA datasets would "have sufficient data, including extensive sediment, physical and hydrologic data, to develop good predictive models of reference sediment conditions" (US EPA, 2003a). The authors find this assertion to be highly unlikely for most Californian watersheds experiencing high variability in rainfall/runoff event and sediment loads over time.

5.2.1.4 Fluvial geomorphic approach

The US EPA funded an extensive study to develop a sediment assessment framework named Watershed Assessment of River Stability and Sediment Supply (WARSSS) (US EPA, 2015). The project was conducted by private practitioner David L. Rosgen, who previously developed a river classification system using secret data he won't allow scientists to evaluate. The sediment assessment approach is based on geomorphic analysis of watersheds and channels with a focus on directing sediment management through the elucidation of hillslope and channel processes controlling sediment production and deposition, rather than developing water quality criteria. However, the US EPA also considers this particular approach to be potentially useful in developing suspended and bed sediment criteria.

The WARSSS approach to assessing hillslope and channel processes begins with a simple 'screening level' assessment and proceeds through a more complex, process-based assessment of sediment sources and hydrologic responses in the context of land use. Much of the WARSSS approach hinges on the relationships between channel type and stability, which by extension implicates sediment production, as found by Rosgen and many others (Meyers and Swanson, 1992; Simon, 1992; Montgomery and Buffington, 1993; Rosgen, 1994; Buffington and Montgomery, 1999). An extension of these river classification schemes proposed by Rosgen through the WARSSS framework is the development of reference C_{SS}-Q rating curves. The US EPA has expressed interest in extrapolating C_{SS}-Q rating curve coefficients to entire regions (i.e. Hawkins, 2002) and to detect unstable streams (Troendle *et al.*, 2001). Development of reference C_{SS}-Q rating curves has primarily occurred in the Rocky Mountain states.

5.2.1.5 Water body use functional approach

This approach focuses on the human uses of a given water body rather than aquatic life. Thus the water body use functional approach is generally constrained to those systems that do not contain aquatic organisms, or where the human use is paramount. This is sometimes the case for waterbodies that are used as drinking water sources (US EPA, 2003b). In terms of Colusa Basin waterways, which are primarily used for agricultural drainage and irrigation, and recreational purposes, human beneficial uses would not likely be the limiting factor in terms of fluvial sediment magnitudes and characteristics.

5.2.2 State and Regional Examples

While the previous section provided an overview of the wide array of methods recognized by the US EPA to assess sediment impacts on aquatic systems, there is also a wide range of sediment-oriented water quality criteria imposed by state governments. These criteria are formed on the basis of quantitative, qualitative, or narrative criteria, or in some cases from no criteria at all (US EPA, 2003a). Most qualitative approaches rely on turbidity measurements for water quality criteria, which may be fixed, related to a predetermined background value, and may also vary seasonally with the needs of aquatic organisms, such as migrating Salmon (Bilotta and Brazier, 2008). Most states use the US EPA method 180.1 to measure turbidity and method 160.2 to measure *TSS* (USEPA, 2003a). There is very little effort by states to correlate turbidity with *TSS* or biological impacts. A few states measure C_{SS}, and very few measure particle size distributions. No states measure bedload. Criteria for *TSS* range from 30–150 mg/L. Some states use deposition depths for a given time period or on an event basis – typically on the order of 5–10 mm for streams.

5.2.2.1 Previous Work in California

The California Legislature created the State Water Resources Control Board (SWB) in 1967 for the regulation of state water resources. As an extension of, and in collaboration with the SWB, nine Regional Water Quality Control Boards were tasked with the regulation of water pollution as mandated by the Federal Clean Water Act and the California Porter-Cologne Act. The Regional Water Boards develop, adopt and implemented water quality control plans, which include (i) identifying beneficial uses of water, (ii) developing water quality objectives, and (iii) developing and implementing plans and policies to meet or exceed water quality objectives. Section 303(d) of the Clean Water Act requires biennial assessments to determine if water quality standards are being met.

Regional Water Boards have developed sediment related TMDLs for several rivers in California, four of which are discussed below. Three of these sediment TMDL cases, those of the Alamo River, the New River, and Imperial Valley drains are examples of flux-based sediment source investigations applied to ambient C_{SS} based TMDLs, with sediment budgets developed in relation to both adverse and target ambient sediment conditions. The Alamo and New Rivers, and the Imperial Valley drains have watersheds that are primarily impacted by irrigated agriculture, which has resulted in sediment and contaminant loading issues. The third case of the Napa River sediment TMDL employed a geomorphic approach that sidestepped the construction of sediment budgets to address sediment impacts on cold water fish and freshwater shrimp.

Salton Sea Tributaries TMDLs

The Colorado River Basin Regional Water Quality Control Board (CRBRWQCB) identified fluvial sediment issues in the Alamo and New Rivers and a series of agricultural drains in the Imperial Valley, all of which discharge directly into the Salton Sea. The influx of surface water to each of these watersheds is dominated by irrigation supply from the Colorado River (CRBRWQCB, 2002a,b; 2005). For example, the Alamo River drains 340,000 acres, greater than 90% of which is used for irrigated agriculture, which receives an average of 3 in. of rain and 650,000 ac-ft (i.e. 23 inches of water distributed over the watershed area) of irrigation supply waters annually (CRBDWQCB, 2002a). Agricultural products are mostly field crops and sugar beets, which are irrigated through furrow and border methods that can produce considerable off-field transport of sediments.

Ambient C_{SS} levels were found to violate the water quality standards set by the CRBRWQCB for these waterways, particularly in terms of parameters established for warm water fish and migratory bird habitats (CRBRWQCB, 2002a,b; 2005). At the time of these studies (i.e. the late 1990s to early 2000s) the average ambient conditions in these water ways was nearly 400 mg/L. High levels of sediment mediated contaminants such as DDT and DDT metabolites (e.g. DDE) were found in bottom sediments in these systems (Setmire *et al.*, 1990; Setmire et al., 1993; CRBRWQCB, 2002a). Some of the highest levels of DDE on record in California have been found in tissues of birds and fishes in the Alamo River (Mora et al., 1987; CRBRWQCB, 2002a). Fluvial sediments were also known to be the primary contributor of the nutrient P to the Salton Sea, which is the major cause of its eutrophication, a condition that has resulted in numerous algal blooms, followed by die-offs and low DO conditions in the lake (Cagle, 1998). These observations led to further investigations into the processes affecting sediment production in these watersheds, and eventually to the development of TMDLs and sediment management frameworks.

Development of sediment TMDLs for the Salton Sea tributaries was based on proscribed maximum average ambient C_{SS} conditions, from which target sediment loads for each system and sediment source area were estimated (CRBRWQCB, 2002a,b; 2005). The targeted maximum annual C_{SS} for each system was set at 200 mg/L on the basis of generic guidance for adverse impacts of fine sediment on warm water fishes obtained from NAS/NAE (1972), US EPA (1986) and the European Inland Fisheries Advisory Council (1964). The NAS/NAE (1972) and US EPA (1986) guidelines list annual average C_{SS} levels of 80 mg/L and 400 mg/L as providing a moderate and low level of protection, respectively, for warm water fish. The European Inland Fisheries Advisory Council (1964) notes that death rates are significantly higher for warm water fishes living under chronic C_{SS} conditions in excess of 200 mg/L.

Flux-based approaches were used to investigate the sediment sources of the Salton Sea tributaries (CRBRWQCB, 2002a,b; 2005). In each of the Salton Seas tributary systems sediment loads from each source and the tributary outlet to the Salton Sea were calculated as monthly average Q multiplied by monthly average C_{SS}. Nonpoint sources from agriculture, routed through minor and then major agricultural drainage ditches were found to be the primary source of sediment in all systems. Sediment load reduction to reach the targeted reduction in ambient C_{SS} levels were then prescribed for each watershed, and source area.

The Napa River Watershed Sediment TMDL

The San Francisco Bay Regional Water Quality Control Board (SFBRWQCB) listed the Napa River watershed and its tributaries as impaired by sediment in 1990 on the basis of reports of widespread erosion (USDA/NRCS, 1985; White, 1985), which were thought to threaten fish habitat (Cordone and Kelly, 1961), as evidenced by declines in abundance and distribution of steelhead trout in the region since the 1940s (see US FWS, 1968; Leidy *et al.*, 2005). In 1990 the Napa River and its tributaries were listed by the SFBRWQCB under Section 303(d) of the federal Clean Water Act as impaired by too much sediment. This required that the Regional Board determine if aquatic habitat was indeed impaired by sediments, and then develop a plan for the protection of aquatic habitat and biota. This resulted in funding of a two-year study by Stillwater Sciences and the University of California, Berkeley to investigate the factors limiting populations of steelhead, Chinook salmon and California freshwater shrimp – all native species that are considered to be at risk (Stillwater Sciences and Dietrich, 2002) and a further study to determine a sediment TMDL (Napolitano *et al.*, 2007) .

The main goals of the Stillwater Sciences and Dietrich (2002) study were to determine (i) the primary factors limiting populations of the aforementioned aquatic biota, (ii) the importance of sediment relative to the field of forcing factors, (iii) the actions needed to conserve and restore self-sustaining populations of the biota in question. This study involved the collection of new data sets to characterize factors affecting limiting populations of the aquatic biota of interest, including (i) documentation of channel pools filling with fine sediment, (ii) measurements of channel bed gravel permeability, (iii) duration of elevated turbidity following storms (surface grab samples, 18 sites in 16 tributaries after 4 to 5 storm events, and 6 mainstem sites after 5 storm events), (iv) stream temperature, (v) late dry-season surface flow throughout the watershed.

Only about 10% of measured pools were found to fill with fine sediment. Storm monitoring showed that turbidity values fell below the 10 NTU threshold of chronic impairment in 1–2 days after peak *Q*. Fine sediment impacts on the biota of interest appeared to primarily occur through fine sediment deposition in the channel bed – resulting in decreases in interstitial spaces, porosity and permeability. The authors compared the permeability values for Napa River and tributary stream beds with literature results to predict up to 50% or greater mortality rates of fish eggs and larvae before emergence. However, an aerial-imagery-based analysis of the mainstem of the Napa River found that much of its habitat loss for the fish of interest was related to incision of the channel by 4 to 6 ft. (1 to 2 m), which simplified the channel and reduced the quality and quantity of spawning grounds (gravel bars).

Despite the fact that fine sediments were not found to be the largest impact on the persistence of the aquatic biota, the results were sufficient to support a continuation of listing the Napa River and tributaries as sediment impaired by the SFBRWQCB, and a mandate for additional research to determine if fine sediment impairment was due to human influenced sediment sources. This study recommended that such research include a "detailed sediment budget to quantify relationships between land use and delivery of fine sediment to channels, and additional vigilance to prevent increased delivery, or preferably to reduce the delivery, of sediment to channels." The recommended sediment source analyses are reported in Chapter 3 of Napolitano *et al.* (2007).

Napolitano *et al.* (2007) presented the development of a sediment TMDL for the Napa River watershed as well as plans to regulate and mitigate sediment supply to the channelized system and begin habitat enhancement/restoration. The primary foci of the sediment TMDL in the Napa River watershed were those defined by the study of Stillwater Sciences and Dietrich (2002), namely fine sediment deposited in channel bed gravels and channel incision. A novel aspect of this study is the presentation of channel incision as a 'controllable water quality factor.' Magnitude and spatial distribution of sediment supply to the channelized system was estimated as mandated by the TMDL development protocol (US EPA, 1991; 1999). They employed a 'rapid sediment budget approach' based on professional opinion, established empirical values, and limited field analysis to identify important processes of sediment production and estimate rates of sediment delivery to channels from 1994 – 2004.

This sediment supply assessment approach was founded on a spatial classification of the watershed area through the development of sediment supply terrain types that shared attributes related to operative sediment supply processes. Professional assessment of the region led to the identification of four major sediment supply processes. Sediment supply terrain types (derived from Ellen and Wentworth (1995) hillside material units) were based on the physical properties, spatial distribution and topography of regional geologic formations. The result was five terrain types: (i) hard rocks, (ii) sedimentary rocks, (iii) ash-flow tuffs, (iv) intensively deformed Franciscan mélange, and (v) a lowland terrain type. The first four types are listed in order of increasing erosion potential. Sediment supply was then linked to gravel permeability (the main environmental impact of interest), by testing the relationship between permeability, sediment supply and stream power. The results showed that higher sediment supply and lower stream power resulted in lower channel bed permeability. In this way the authors were able to quantitatively link sediment load with an in-channel habitat characteristic target.

5.2.2.2 Sediment Assessment and Criteria Development in Other States: Deep Creek, Montana

Endicott and McMahon (1996) produced a study of Deep Creek, Montana with goals to (i) identify non-point sources of fine sediment, (ii) develop TMDL targets for fine sediment, (iii) define remedial actions for achieving TMDLs, and (iv) develop a monitoring framework or assessing the efficacy for remediation. All of this work was motivated by trout fisheries in Deep Creek and water bodies that benefitted from trout spawning in its reaches. This study utilized comparison between water quality values and those of less impacted streams in Montana. Sediment source determination was achieved through analysis of suspended sediment data collected from stations on Deep Water Creek and tributaries, including rudimentary sediment load estimations. Channel banks were determined to be major sources of sediment on the basis of low estimations of sediment load from the tributaries, and professional assessment of the geomorphic trajectory of the Deep Water Creek Channel and banks. The development of a fine-sediment TMDL was based on suspended sediment concentrations and a very small data set on the particle size characteristics of trout spawning habitats (riffles).

5.3 Proposed Sediment Impact Assessment Methodology for the Colusa Basin

A framework for assessing sediment impacts in the Colusa Basin drainage area and water bodies receiving its outflow was outlined on the basis of the synthesis of US EPA approaches detailed in Section 5.2.1 (Figure 5.3.1). Sections marked with stars are those that were not fully assessed for this study due to insufficient data, which will be further explored in Sections 7 and 8. Monitoring of suspended sediment in the Colusa Basin drainage area and its immediate receiving water bodies has provided sufficient material for some impact evaluations, particularly those related to ambient C_{SS} and gross estimates of sediment flux. However, a general lack of decadal scale, high resolution paired monitoring of C_{SS} and Q, along with almost no data on the abundance of most suspended sediment associated constituents of interest such as heavy metals and pesticides precludes efforts to assess the direction of impact change over time and the role of sediment mediated pollutants. Evaluations within the confines of available data are presented in Section 6 on a geographically stratified basis.

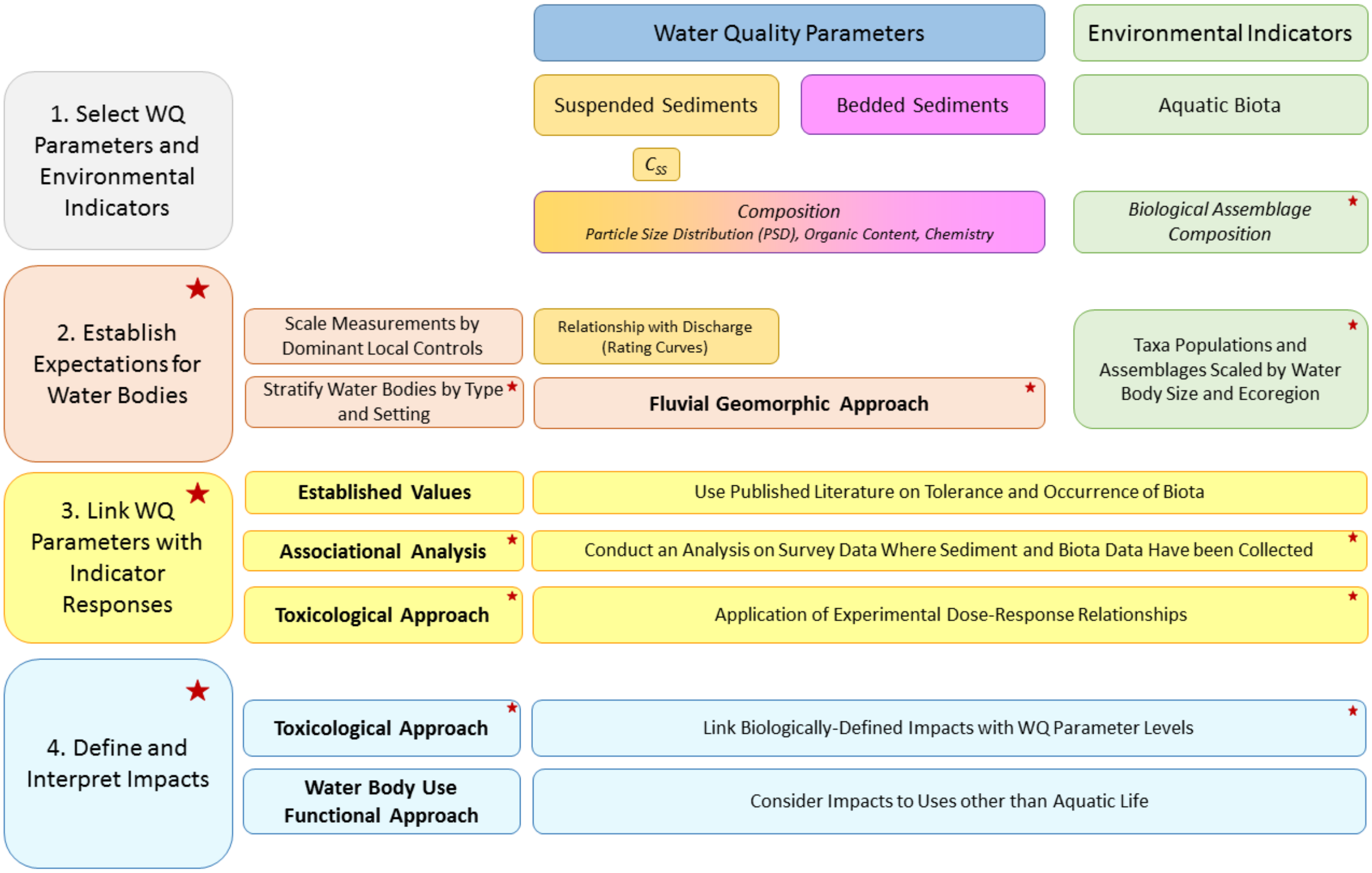

Figure 5.3.1. Sediment impact assessment methodology outline for the Colusa Basin Drainage Area. Areas marked with a red star were not fully implemented due to insufficient monitoring data. See Section 6 for presentation of the sediment impact assessment, Section 7 for a discussion of the data gaps limiting the implementation of this methodology, and Section 8 the monitoring program proposed to address these gaps.

Step 1. Selection of water quality parameters and environmental indicators of interest: Water quality parameters of interest were determined to be C_{SS} and the characteristics of suspended load and bedload, including particle size distribution, organic content and chemical properties (Figure 5.3.1). Attempting to characterize fluvial sediment impacts on aquatic ecosystems in the Colusa Basin drainage area and beyond requires knowledge of the organisms present in these regions. Colusa Basin drainage area aquatic environments support freshwater habitats for warm water fish, including migration and spawning grounds, and wildlife habitat, particularly for migratory waterfowl (Table 5.3.1 and Table 5.3.2; DFG, 1982). The downstream systems also serve as habitat, migratory pathways and spawning grounds for warm water fish and cold water fish, and provide habitat for many forms of wildlife. These human and ecosystem services provided by the Colusa Basin drainage area and downstream waterways are the basis for considering the role of fluvial sediments in these systems, both in terms of benefits and negative impacts. Aquatic biota of interest were found to include warm water fish, salmonids, periphyton and aquatic invertebrates. Insufficient data on both fluvial sediments and environmental indicators hampered the overall ability to conduct a thorough sediment impact assessment. However, a more limited approach involving available data was possible.

Step 2. Establishment of expectations for water bodies in terms of fluvial sediment and aquatic biota characteristics. Available suspended sediment data were assessed in terms of C_{SS} dynamics and ambient conditions to assess changes in fluvial sediment over time. (Figure 5.3.1). The fluvial geomorphic approach was employed only in terms of qualitative assessments of channel degradation and the processes based insights into sediment transport in the watershed (see Section 4.1). Establishment of expectations for individual water bodies within the Colusa Basin drainage area was deemed beyond the scope of the present study. However, this would be possible for future studies aimed at establishing sediment TMDLs with more intensive monitoring of current conditions under the guidance of Sections 7 and 8.

Step 3. Linking fluvial sediment characteristics with aquatic biota responses. Ambient fluvial sediment magnitudes and durations were considered in terms of the general requirements of aquatic taxa known to inhabit the Colusa Basin drainage area and its receiving water bodies. However, explicit analysis of the correlation between fluvial sediment and aquatic biota characteristics was not possible with the available data sets. Some dose/response studies had been conducted using Colusa Basin drainage area surface waters on macroinvertebrates, but no studies focusing on the role of suspended sediments and sediment mediated constituents have been found for this watershed.

Step 4. Defining and interpreting sediment impacts. The general results of Step 3 were interpreted in terms of environmental impacts for specific aquatic biota, as permissible with the current data set. Human beneficial uses were also considered in terms of sediment characteristics to identify further potential impacts. Some 18 beneficial uses are recognized by the CVRWQCB in the Basin Plan for the Sacramento and San Joaquin Rivers (Table 5.3.1) (CVRWCB, 2011). Beneficial uses of surface waters in the drainage system of the Colusa Basin watershed and the Yolo Bypass include diversion for agricultural purposes, and recreational activities (primarily waterfowl hunting and fishing) (Table 5.3.2). Most agricultural withdrawals are for irrigation purposes and occur lower in the basin on the basis of established water rights. Indeed, the outfall gates near Knights Landing are used to maintain stage in the lower CBD for agricultural withdrawals during periods of the irrigation season. Beneficial uses in the lower Sacramento River (here indicated as "CBD to I Street Bridge") are more extensive, and also include municipal water supplies, while the Sacramento/San Joaquin Delta also serves as a source of industrial water.

Table 5.3.1. Beneficial uses of water bodies as defined by the CVRWQCB[1].

Beneficial Use		Definition
Acronym	Complete Term	
MUN	Municipal and Domestic Supply	Uses of water for community, military, or individual water supply systems including, but not limited to, drinking water supply.
AGR	Agricultural Supply	Uses of water for farming, horticulture, or ranching including, but not limited to, irrigation (including leaching of salts), stock watering, or support of vegetation for range grazing.
IND	Industrial Service Supply	Uses of water for industrial activities that do not depend primarily on water quality including, but not limited to, mining, cooling water supply, hydraulic conveyance, gravel washing, fire protection, or oil well re-pressurization.
PRO	Industrial Process Supply	Uses of water for industrial activities that depend primarily on water quality.
GWR	Ground Water Recharge	Uses of water for natural or artificial recharge of ground water for purposes of future extraction, maintenance of water quality, or halting of saltwater intrusion into freshwater aquifers.
FRSH	Freshwater Replenishment	Uses of water for natural or artificial maintenance of surface water quantity or quality.
NAV	Navigation	Uses of water for shipping, travel, or other transportation by private, military, or commercial vessels.
POW	Hydropower Generation	Uses of water for hydropower generation.
REC-1	Water Contact Recreation	Uses of water for recreational activities involving body contact with water, where ingestion of water is reasonably possible. These uses include, but are not limited to, swimming, wading, water-skiing, skin and scuba diving, surfing, white water activities, fishing, or use of natural hot springs.
REC-2	Non-contact Water Recreation	Uses of water for recreational activities involving proximity to water, but where there is generally no body contact with water, nor any likelihood of ingestion of water. These uses include, but are not limited to, picnicking, sunbathing, hiking, beachcombing, camping, boating, tidepool and marine life study, hunting, sightseeing or aesthetic enjoyment in conjunction with the above activities.
COMM	Commercial and Sport Fishing	Uses of water for commercial or recreational collection of fish, shellfish, or other organisms including, but not limited to, uses involving organisms intended for human consumption or bait purposes.
AQUA	Aquaculture	Uses of water for aquaculture or mariculture operations including, but not limited to, propagation, cultivation, maintenance, or harvesting of aquatic plants and animals for human consumption or bait purposes.
WARM	Warm Freshwater Habitat	Uses of water that support warm water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish, or wildlife, including invertebrates.
COLD	Cold Freshwater Habitat	Uses of water that support cold water ecosystems including, but not limited to, preservation or enhancement of aquatic habitats, vegetation, fish, or wildlife, including invertebrates.
EST	Estuarine Habitat	Uses of water that support estuarine ecosystems including, but not limited to, preservation or enhancement of estuarine habitats, vegetation, fish, shellfish, or wildlife (e.g., estuarine mammals, waterfowl, shorebirds).
WILD	Wildlife Habitat	Uses of water that support terrestrial or wetland ecosystems including, but not limited to , preservation and enhancement of terrestrial habitats or wetlands, vegetation, wildlife (e.g., mammals, birds, reptiles, amphibians, invertebrates), or wildlife water and food sources.
BIOL	Preservation of Biological Habitats of Special Significance	Uses of water that support designated areas or habitats, such as established refuges, parks, sanctuaries, ecological reserves, or Areas of Special Biological Significance (ASBS), where the preservation or enhancement of natural resources requires special protection.
RARE	Rare, Threatened, or Endangered Species	Uses of water that support aquatic habitats necessary, at least in part, for the survival and successful maintenance of plant or animal species established under state or federal law as rare, threatened or endangered.

[1] Reference: CVRWQCB Basin Plan for the Sacramento and San Joaquin Rivers, 2011, p. ii.1-2.

Table 5.3.2. Designated beneficial uses of water bodies affected by Colusa Basin sediments[1].

Surface Water Bodies	MUN	Agriculture		Industry			Recreation			Freshwater Habitat		Migration		Spawning		WILD	NAV
		AGR		PROC	IND	POW	REC-1		REC-2	WARM	COLD	MIGR		SPWN			
	Municipal and Domestic Supply	Irrigation	Stock Watering	Process	Service Supply	Power	Contact	Boating	Other Non-contact	Warm	Cold	Warm	Cold	Warm	Cold	Wildlife Habitat	Navigation
CBD[2]		E	E				E	E		E	P	E		E		E	
CBD to I St. Bridge	E	E					E	E	E	E	E	E	E	E	E	E	E
Yolo Bypass		E	E				E		E	E	P	E	E	E		E	
Sacramento San Joaquin Delta	E	E	E	E	E		E		E	E	E	E	E	E		E	E

Legend: E = Exisiting Beneficial Uses; P = Potential Beneficial Uses. [1]Reference: CVRWQCB Basin Plan for the Sacramento and San Joaquin Rivers, 2011. [2]Incl. the tributaries of the CBD.

6. Evaluation of Sediment Impacts

The evaluation of sediment impacts is organized into four potential regions of interest: erosional effects in the Colusa Basin watershed (Section 6.1), and fluvial sediment effects in the Colusa Basin drainage area (Section 6.2) and its receiving bodies (Section 6.3). Water bodies receiving Colusa Basin sediments include the Sacramento River (Section 6.3.1), the Yolo Bypass (Section 6.3.2), and the Sacramento-San Joaquin Delta and San Francisco Bay (referred to hereafter as the Delta and SF Bay) (Section 6.3.3). The sediment impact assessment was performed using the methodology developed in Section 5.3, which was applied to data collected by the previous studies detailed in Section 4. Gaps in these data were found to have significant impacts on the ability of this study to comprehensively assess sediment impact, which are more fully explored in Section 7, and form the basis for additional monitoring recommendations presented in Section 8.

Presentation of the effects of fluvial sediments were separated into those that result from direct physical implication of the sediments themselves (e.g. impacts of C_{SS} regimes on aquatic organisms), and impacts of sediment constituents such as heavy metals and pesticides. Although water quality parameters have been studied in the Colusa Basin drainage area for decades, little information has been obtained on sediment mediated pollutants (Table 6.1). Sediment monitoring for associated contaminant levels has been mostly restricted to channel bed and bank deposits, rather than suspended sediments, which renders the determination of flux based impacts on receiving basins particularly difficult.

Table 6.1. Studies on sediment associated pollutants in the Colusa Basin drainage area.

Study Group	Study Name	Publications	Sample Period	Pollutants monitored	Mode[1]	Results[2]	Section (This Study)
CVRWQCB	ILRP and SWAMP	CEDEN, Wood *et al.*, 2005; Larry Walker and Associates, 2007	8/9/2004-9/18/2013	51 potential pollutants: mostly heavy metals and pesticides.	D, SA	Colusa Basin: 17 constituents found at above detection limits at least once: Arsenic, Chromium, Cadmium, Copper, Lead, Nickel, Selenium, Silver, Zinc; DDT(p,p'), Dicofol, Esfenvalerate/ Fenvalerate, Bifenthrin, Chlopryrifos	**6.2.5**
UCD/US EPA	NSP CBD	Tanji *et al.*, 1980b; 1981c	1980-1981	MCPA, molinate, ethyl parathion	D, SA	Molinate: high (drainage laterals: 4300 μg/L max, CBD 120 μg/L max), MCPA and ethyl parathion: nd	**6.2.5**
	Water-Quality Assessment of the Sacramento River Basin	MacCoy and Domagalski, 1999; Domagalski *et al.*, 2000	1995-1998	A wide range of pollutants including heavy metals and pesticides.	D, SA	Sacramento River: total mercury - C_{SS} correlation; heavy metals and pesticides found in bed sediments.	**6.3.1**
USGS	Yolo Bypass Pesticides	Smalling *et al.*, 2005	2004-2005	27 pesticides	D,SA	Pesticide concentrations generally correlated with subbasin application rates, Colusa Basin a large contributor of sediment associated pesticides.	**6.3.2**
	Yolo Bypass Mercury	Springborn *et al.*, 2011	1996-2003	Total mercury	SA	Colusa basin estimated to contribute approximately 3% of the Yolo Bypass total mercury load.	**6.3.2**

[1]Mode indicates whether the studied pollutant was sampled in the D = dissolved, or SA = sediment associated phase. Note that all sediment associated samples were collected from channel beds or banks. [2]nd = no detection.

6.1 Erosional Effects in the Colusa Basin Watershed and the Issue of Sediment Provenance

Significant work has been done to characterize erosion in the Colusa Basin watershed, including studies that addressed erosion in agricultural lands, rangelands, and channels. Most of this work was motivated by efforts to characterized watershed-scale fluvial sediment sources. Indeed, review of reports from local stakeholder groups revealed that negative impacts of erosion on agricultural lands does not seem to be a current issue of general concern in the Colusa Basin watershed (see CBDD, 1993; 1995a,b; CCRCD, 2012, Betsy Karle, Mark Lundy, and Bruce Linquist, UC ANR CEs, personal communication). No explicit examination of erosion has occurred in irrigated agricultural fields or rangelands, although some studies have addressed the issue indirectly (Tanji *et al.* 1981b, Gatske, 2010; Section 6.1.1). Recent CCRCD studies have directly observed and characterized probable intensification of channel bank and bed erosion, particularly in the reaches of foothill streams located on alluvial fans and over-deepened, straightened channels in the valley lands (H.T. Harvey and Associates, 2008; Section 6.1.2).

6.1.1 UCD/US EPA Erosion Findings and Recommendations

The UCD/US EPA ITM and NPS CBD in the Colusa Basin drainage area advanced recommendations for sediment abatement from irrigation agricultural fields, drainage ditches, channels and roadways (this study Sections 4.1.2.2 and 4.1.4; Tanji *et al.* 1981b; 1983 for project summaries and recommendations) (Table 6.1.1). Recommended agriculturally oriented BMPs included two main approaches aimed at decreasing sediment flux to the channelized system through reducing off-field transport of sediments through decreased runoff and/or erosion, and capturing sediments transported off field either before they reach the channelized system or by interception in the channel. Channel BMPs were mostly oriented toward engineering to reduce channel bed and bank sediment production. Roadway BMPs focused on gravel/dirt roads and involved engineered solutions as well as changes in roadway management, including the closure of many little used gravel roadways in poor condition. Recommended BMPs for the reduction of off-field transport include relatively radical changes to agricultural operations, most of which have not been widely adopted.

Table 6.1.1. UCD/US EPA recommendations for agricultural sediment abatement.

Land Use/Type	Main Approach	Recommended BMPs	Mechanism
Agriculture	Reduce off-field transport of sediment	Contour cropping	Slope decrease
		Wet season vegetation	Increase interception, ET, roughness; Decrease rain detachment
		No-till or minimum-till practices	Increase hydraulic conductivity
		Minimization of field compaction from vehicular traffic	Increase hydraulic conductivity
		Chemical or organic matter additions	Increase hydraulic conductivity
	Capturing sediments between field and channel	Settling basins for agriculture tailwaters	Sedimentation
		Irrigation tailwater reuse	Sedimentation
		Vegetated buffer strips along channels and drainage ditches	Increased roughness and sediment trapping
Rangeland	Hillslope erosion reduction	Optimizing grazing levels	Decrease surface disturbance
		Livestock water trail development	Decrease surface disturbance
		Improved rangeland plant growth practices	Increase interception, ET, roughness; Decrease rain detachment
Channel	Channel engineering	Grade stabilization	Slope modification, usually decreased
		Inlet structures	Increasing channel bank and bed strength
		Channel reshaping	Increasing channel bank strength
		Channel bank stabilization	Increasing channel bank strength
		Settling basins	Sedimentation
Roadways	Road engineering	Water bars	Decrease road slope length
		Water spreaders	Decrease depth of water leaving roadway
		Culverts	Route channelized flow under roadway
	Road management	Road closures in wet weather	Decrease automotive erosion
		Road decommissioning	Decrease automotive erosion

It should be noted that land surface engineering and agricultural operations have advanced over the intervening decades, perhaps obviating some of these recommendations. Widespread re-contouring of irrigation agricultural lands was implemented throughout California from the 1970s – 1990s on the basis of research conducted by UC Davis agronomist Dr. Jim Hill. Re-contouring results in uniformed, low slope fields, which can reduce off-field sediment transport. Irrigation of tomatoes has shifted from furrow to sub-surface drip over the beginning of the 21st century, rising from 10% to 90% implementation over the last ten years (Dr. Mark Lundy, UC ANR CE, *personal communication)*. Drip irrigation generally results in much lower off field transport of water and sediment than furrow irrigation (e.g. McHugh *et al.*, 2008). Conversion to drip irrigation has only been economically feasible for tomatoes due to the high price of tomatoes and the large increases in yields that result from this practice. As tomato fields are commonly rotated with other crops, employment of drip irrigation in other row crops is also taking place. Thus, erosion of sediment from row crop fields in the Colusa Basin may have already decreased significantly in the Colusa Basin watershed since the recommendations of Tanji *et al.* (1983), although sediment monitoring since this time has not been sufficient to test this hypothesis (see Section 4.3).

The UC Davis/US EPA study on nonpoint source sediment production in the Colusa Basin drainage area also found evidence that the Inner Coast Ranges foothills portion of the watershed produced the majority of the suspended sediment flux through the CBD (see Tanji *et al.*, 1980c; 1981c; 1983). Suspended sediment load estimations from the CBD and some foothill streams led to this conclusion, which was supported by a watershed-scale sediment production model. As the primary land use in this region is for grazing, recommended erosion reduction BMPs were oriented toward reduction of rangeland erosion and sediment flux, including optimizing grazing levels, development of livestock water trails, and practices to improve plant growth (Table 6.1.1). Since this region was found to produce the highest sediment yields and the majority of the sediment load of the Colusa Basin watershed, the rangeland BMPs were noted as potentially having the highest impact to cost/effort ratio.

The UC Davis/US EPA NPS CBD study provided recommendations for channel bank erosion abatement without any explicit field based inquiry (Tanji *et al.*, 1978; 1980b; 1980c; 1981c; 1983). Their recommendations were mostly non-specific channel engineering applications, including reshaping channels, channel bank stabilization through vegetation, rock structure and riprap emplacements, and installation of large boulders with wire fences and revetments, and installation of settling basins (Table 6.1.1).

Much of the recommendations from the UC Davis/ US EPA study on nonpoint source sediment production in the Colusa Basin drainage area were the result of watershed-scale models utilizing a modified USLE and a flux based approach to monitoring suspended sediment production primarily at the basin to sub-basin scale. The few observations of sediment flux at the field scale were primarily produced during the UC Davis/US EPA irrigation tailwater management studies, and from multiple sites monitored on given reaches of the CBD and tributaries such as Stone Corral and Funks Creeks. These components of the study were sufficient for determination of broad, subbasin-scale characterizations of sediment production, such as foothill rangelands vs. valley and basin land sediment production. However, field-scale, operation specific studies were not conducted. Thus, recommendations for sediment abatement were mostly based on the accepted science at the time and previous studies conducted during the UCD/US EPA ITM. No observations of erosion damages in the basin, from agricultural fields and ditches, to rangelands, were collected. Point source considerations, such as minor and major gullying, drainage ditch degradation, etc., were not explicitly incorporated into these studies and their recommendations.

6.1.2 CCRCD Erosion Findings and Recommendations

The CCRCD studies characterized channel erosion in the Colusa Basin watershed through a combination of historical studies, channel mapping and expert opinion that resulted in assessments of channel bank and roadway stability/erosion potential (Section 4.1.3) (Table 6.1.2). Highest bank erosion potential was found generally in channels on steep alluvial fan/foothill front, with lower erosion potentials found upstream in the interior foothill valleys, and downstream in the Colusa valley and basin lands, which is in general agreement with the natural geomorphic pattern of streambank erosion potentials found in this region (Geomorph *et al.*, 2010). Although reaches with high streambank erosion potential were found in each geomorphic zone, the highest erosion potentials in the interior foothill valley and alluvial fan regions were found to be mostly driven by natural geomorphic characteristics. Human-induced channel bank instability was most notable in the lowland channelized reaches where straight, over-deepened channels often possess very steep un-vegetated banks running up to road topped levees. Rills and slumps are commonly observed on such banks. Channel instability coupled to road degradation was posited to drive a 'sediment conveyor', whereby channel bank erosion leads to road degradation, necessitating road grading, which moved more sediment downslope to the streambanks and ultimately the channel.

Table 6.1.2. CCRCD streambank erosion study: findings and recommendations.

	Findings				Recommendations	
Geographic Zone	**General Streambank Erosion Potential**	**Areas of Highest Streambank Erosion Potential**	**Causality of Highest Streambank Erosion Areas**	**Human Influence Importance**	**BMPs**	**Mechanisms**
Interior foothill valleys	Low to moderate	Wider valleys incising Cretaceous marine rock	Natural geomorphic processes,; livestock grazing	Secondary	Rangeland management	Decrease disturbance of hillslopes to reduce foothill water and sediment export
Alluvial fan/ foothill front	Moderate to high	Incision into larger and steeper sloped alluvial fan incision	Natural geomorphic processes; livestock grazing	Secondary	Rangeland management	Decrease disturbance of hillslopes to reduce foothill water and sediment export
Colusa valley lands	Low to moderate	Narrowly channelized reaches	Straightening, channelization, road topped levees	Primary	Channel and levee road management	Size channels to discharge regime; increase channel bank stability; end road-channel 'sediment conveyor'; conserve remaining intact channels

[1]Geomorph *et al.*, 2010.

The CCRCD studies presented recommendations for channel bank erosion management that were made with the explicit realization that all foothill streams pass through a patchwork of privately held land of primarily agricultural use (Table 6.1.2). Channel bank management strategies were recommended to focus on reaches with high erosion potential, and in consideration of bank material, geomorphic setting, and human influences. It was suggested that erosion management concentrate on reaches with high potential erosion of channel banks with particle size characteristics that were of most concern for water quality purposes (i.e. fines). Subbasins draining Cretaceous marine rock were identified as having greater fine sediment content in bank materials. Reaches with unstable banks that were highly impacted by human land use were identified as potential targets for 'passive restoration', whereby relaxing or discontinuing certain land use practices, such as livestock grazing, could result in significant reductions in erosion without the large monetary investment necessary for active (i.e., construction) projects. Active projects, such as channel belt/floodplain widening, bank slope relaxation and re-vegetation, etc. were recognized as requiring stream-wide planning, which could be implemented by the range of land owners during times of crises or during periodic maintenance. Re-vegetation in the riparian zone was recommended only in areas where flood risk would not be increased, and where physical conditions (channel bank slope, substrate, etc.) were amenable. Sediment management suggestions from the CCRCD studies were similar to those of the UCD/US EPA, namely improvements in road engineering, limiting usage of degraded roads, and decommissioning some roads all together, with the additional recognition of the coupling of streambank erosion and road sediment production.

6.2 Fluvial Sediment Effects in the Colusa Basin Drainage Area.

As outlined in Section 5.3, the effects of fluvial sediments in the Colusa Basin drainage area was assessed here in terms of the effects of gross fluvial and deposited sediments on aquatic biota and human beneficial uses. Some previous work has been done to characterize the effects of fluvial sediment on the Colusa Basin watershed in terms of fine sediment deposition in channelized systems (Section 6.2.1) and on adjacent land surfaces (Section 6.2.2), suspended sediment impacts on aquatic life (Section 6.2.3) and human beneficial uses (Section 6.2.4), and the impacts of sediment mediated pollutants (Section 6.2.5).

6.2.1 Impacts of Fine Sediment Deposition in Channel Beds

Components of the aquatic ecosystem involved in or impacted directly by the drainage network of surface waters in the Colusa Basin include in-channel habitats, channel margin wetlands, riparian corridors, and more extensive perennial wetlands in the basin lands region (DWR, 1990b). Direct physical impacts of suspended sediments on the Colusa Basin aquatic ecosystem include moderation of channel bed particle size distributions through deposition and resuspension. In-channel habitats grade from the seasonally wet reaches of foothill streams to more consistently wetted lower stream and drainage ditch reaches that regularly receive irrigation return flows during the spring and summer months. Bed material of these streams generally fine with decreasing slope, with gravel/sand transitions often found low on alluvial fan reaches or in reaches located in the upper valley lands, while low slope reaches in the valley and basin lands grade from sandy to muddy (see Section 4.1 and 4.2). The lowest drainage reaches in the basin, namely the lower reaches of the CBD are generally very fine, mostly composed of silt and clay, although sands and gravels are incorporated, likely delivered during winter stormflow primarily from southern foothill streams whose coarse bedded alluvial fans extend almost to the CBD (Geomorph *et al.*, 2010; Tanji *et al.*, 1983). Due to seasonal to interannual cycles of fine sediment production, transport, deposition and re-suspension, channel beds probably also experience changes in particle size distributions over similar time scales. This is likely to be the case in tributary reaches that experience significant inputs from irrigation return flows, as well as occasional high *Q* events from winter storm runoff.

The UC Davis/US EPA study on nonpoint source sediment production in the Colusa Basin drainage area found evidence for fine sediment deposition and resuspension in the CBD and lower tributaries operating on a seasonal cycle (Tanji *et al.*, 1978, 1980b; 1980c, 1981c, 1983). Sediments were found to deposit widely throughout the CBD and the lower elevation reaches of tributaries during irrigation return flows and low *Q* non-irrigation season storm flows, which then re-suspended and flushed through the system during high storm flow events. These conclusions were derived from flux-based suspended sediment monitoring, which were generally corroborated by a one-dimensional sediment flux model (Tanji *et al.*, 1981c, Mirbagheri, 1981; Mirbagheri *et al.*, 1988a; 1988b). However, the 1-D model results also suggested that portions of the CBD were most likely aggrading, which was also supported by a few observations of aggrading channel cross sections. As no systematic monitoring of channel elevations has taken place in the Colusa Basin, and responsibilities for the maintenance (i.e. dredging) of tributaries, drainage laterals and the CBD itself falls across a large number of local operators and drainage districts, very little is known about interdecadal fine sediment deposition and resuspension characteristics throughout the watershed. Fine sediment deposition in tributary channels and the CBD may have significant impacts on local flora and fauna, particularly on benthic invertebrates which live on and in the channel bottom. Many studies have addressed the toxicology of sediment mediated pollutants on benthic organisms in stream channels and concomitant effects across food webs, however these studies are generally lacking within the channels of the Colusa Basin (see Section 6.2.5).

The high organic content of suspended sediments are also of concern for aquatic habitats in the Colusa Basin drainage area, particularly in the lower CBD. The UCD/USEPA NPS CBD study found that a very high proportion (average of 18% by mass) of the suspended load of the CBD was labile organic material, and high organic contents were also found in lower CBD bed materials (Section 4.1.4). Labile organic matter is by definition highly available for microbial degradation, which can lead to the reduction of dissolved oxygen in channel bed pore spaces and overlying waters. This could pose a problem in the lower CBD during ponding of waters due to backwater effects during irrigation and non-irrigation season operations of the CBD outfall flood gates. Further monitoring of bed and near bed DO conditions during periods of ponding would be required to assess these impacts (see Sections 7 and 8).

6.2.2 Impacts of Overbank Deposition of Fine Sediments

Although the SRFCP decreased flooding impacts from the Sacramento River, basin and valley lands remain prone to flooding from storm runoff and irrigation return flows generated within the Colusa Basin watershed itself (DWR, 1962). Rainfall-runoff events during the non-irrigation season cause local flooding of valley lands adjacent to foothill tributaries, and larger scale flooding in the lower Colusa Basin when the CBD overtops its banks. The lower Basin also floods during the irrigation season in the spring and late summer/early fall when widespread rice field drawdown can result in lower CBD flood stages. As most of the land area in the flood prone portions of the watershed is used for agricultural purposes, flooding is of greatest concern in terms of crop interference, which is mostly due to the timing and magnitude of the inundation itself rather than the flux and deposition of sediments. However, overbank deposition of sediment can also pose a problem for farmers. This is particularly the case for local flooding from sediment rich tributaries draining the foothills, which have been known to deposit sediments of considerable depth (up to a couple of feet) onto nearby fields and orchards (USBR, 1973b). In these cases it is the magnitude of deposition that poses a problem to land owners, who may have to mechanically remove or re-contour newly deposited sediment in order to maintain operations. However, very little information was found on this issue and it is assumed to be a minor component of the suite of sediment impacts on the Colusa Basin drainage area.

6.2.3 Direct Physical Impacts of Ambient Suspended Sediment Conditions on Aquatic Life.

Although the effects of suspended sediment on aquatic habitat and the beneficial uses of surface waters in the Colusa Basin drainage area have been studied in terms of the effects of turbidity and sediment mediated nutrients and pollutants (see Section 4.1.1), previous investigations of direct physical impacts of ambient suspended sediments on aquatic biota in the CBD are completely lacking. More specific organism oriented studies in the basin will be required to adequately assess the effects of suspended sediment concentration dynamics on aquatic biota. However, sufficient information on ambient suspended sediment conditions were collected during previous studies (Section 4.1) and synthesized by the present study (Section 4.3.1), which allowed for a general appraisal of potential impacts of suspended sediment on aquatic organisms, particularly warm water fishes, in the Colusa Basin drainage area.

Peak suspended sediment concentrations throughout the Colusa Basin drainage area's channelized network have been found to reach hundreds to thousands of mg/L, which are generally considered deleterious to regional warm water fishes (i.e. bass, carp, etc.) (see Section 4.3.1). Indeed, peak C_{SS} values measured in foothill streams can reach thousands of milligrams per liter, which has been found to be fatal to a range of freshwater fish in experimental scenarios (see Section 5.1). These high C_{SS} conditions are short lived however, persisting for hours or days on the rare occasions that they were measured (see Section 4). Intermittent, high C_{SS} conditions were certainly a feature of the pre-European settlement foothill stream function, although peak values and durations have most likely increased substantially due to human activities (see Section 4.1).

Longer duration ambient suspended sediment concentrations commonly observed in the Colusa Basin drainage area may also pose a threat to warm water fishes utilizing these areas as habitat and spawning grounds, particularly during the typically higher C_{SS} magnitudes experienced during the non-irrigation season (see Section 4.3.1). The range of C_{SS} thresholds commonly employed in assessments of chronic impacts on warm water fish run from approximately 10-100 mg/L (Section 5). The high end of this threshold spectrum (100 mg/L) is lower than the average conditions found at 5 of 8 CBD stations, 3 of 7 lateral drain stations, and 13 of 16 foothill tributary stations sampled during non-irrigation seasons. Thus, ambient non-irrigation season suspended sediment conditions would be considered generally detrimental to warm water fishes, although site/regional specific assessment is lacking.

Average ambient suspended sediment conditions during the irrigation season were lower. The sampling station SCC at Sites (the most upstream station on Stone Corral Creek) was the only location in the watershed reporting average C_{SS} in excess of the 100 mg/L threshold, with the exception of a few stations with only a handful of irrigation season samples (Section 4.3). The physical impacts of these magnitudes and durations of suspended sediment concentrations and compositions on aquatic biota requires further investigation for accurate assessment (see Sections7 and 8).

6.2.4 Impacts of Suspended Sediment on Human Beneficial Uses.

The major human beneficial uses of water bodies in the Colusa Basin drainage are recreational, with hunting and fishing featuring most prevalently (see Section 2.3), and water withdrawals for irrigated agriculture. As recreational interests depend on aquatic biota, adverse impacts of suspended sediment concentrations on aquatic biota would also impact recreational interests in the region. The levels of sediment encountered in Colusa Basin drainage waters during the irrigation season have not been reported as problematic for irrigation purposes (DWR, 1964; USBR 1973b; Tanji *et al.*, 1977; 1978). Furrow, flood and border irrigation methods do not have strict suspended load requirements and would not be expected to be impaired by irrigation season C_{SS} levels. However, the Colusa Basin, like much of California, has experienced large increases in drip irrigation usage for row crops (particularly tomatoes) over the past 25 years (see Section 2.3.2). Drip emitters require an absence of coarse sediment grains and very low C_{SS}, so they generally run with groundwater rather than surface water on farms in the Colusa Basin watershed in part for this reason (Mark Lundy, UC ANR CE*, personal communication*). Increased demand for reuse of irrigation return water with irrigation technologies that have a low tolerance for suspended load, such as drip, may lead to increased economic impact of irrigation season ambient suspended sediment conditions where water is drawn from the CBD and its natural tributaries, particularly in the lower CBD, which is commonly used for irrigation withdrawals.

6.2.5 Impacts of Sediment Mediated Pollutants

The CBD is the largest point source of irrigation return waters and suspended sediments entering the Sacramento River (DWR, 1964). For this reason sediment-mediated constituents are of concern for the Colusa Basin watershed and its receiving water bodies. However, little has been done to characterize the sediment-mediated pollutants carried by fluvial suspended sediment in the Colusa Basin drainage area. Previous studies that examined the concentrations of toxins associated with fluvial sediment in the Colusa Basin Drainage area are as follows: the UCD NSP CBD project, monitoring programs under the CVRWQCB including ILRP and SWAMP, and the USGS Water-Quality Assessment of the Sacramento River Basin (Table 6.2.1). None of these studies focused explicitly on sampling the suspended load, beyond labile carbon, and as such the role of Colusa Basin drainage area fluvial sediments on water quality in the region remains largely unexplored. Studies on mercury transport in the suspended load of the CBD will be discussed below, as this issue has primarily been examined in relationship to the mercury budgets of the Sacramento River and the Yolo Bypass (see Section 6.3).

Table 6.2.1. Studies on sediment associated pollutants in the Colusa Basin watershed.

Study Group	Study Name	Publications	Sample Period	Pollutants monitored	Mode[1]	Results[2]
UCD/US EPA	NSP CBD	Tanji et al., 1980b; 1981c; Mirbagheri, 1981; Mirbagheri and Tanji, 2007	1980-1981	Nutrients (P) and labile organic compounds	SS, D, B	Sediment associated P largely controlled periphyton levels in the CBD; High amounts of labile organic materials found in CBD fluvial sediments.
USGS	Water-Quality Assessment of the Sacramento River Basin	MacCoy and Domagalski, 1999; Domagalski *et al.*, 2000	1995-1998	A wide range of pollutants including heavy metals and pesticides.	B, D	Sacramento River: total mercury - C_{SS} correlation; heavy metals and pesticides found in bed sediments.
CVRWQCB	ILRP and SWAMP	CEDEN, CVRWQCB, 2005; Larry Walker Associates, 2008	2004-2013	51 potential pollutants: mostly heavy metals and pesticides.	D, SA	Colusa Basin: 17 constituents found at above detection limits at least once: Arsenic, Chromium, Cadmium, Copper, Lead, Nickel, Selenium, Silver, Zinc; DDT(p,p'), Dicofol, Esfenvalerate/Fenvalerate, Bifenthrin, Chlopryrifos

[1]Mode indicates whether the studied pollutant was sampled in the D = dissolved, or SA = sediment associated phase. Note that all sediment associated samples were collected from channel beds or banks. [2]nd = no detection.

One aspect of sediment impacts on aquatic biota in the CBD that has been evaluated is the role of suspended sediment associated nutrients in moderating periphyton levels, with results suggesting that physical and chemical attributes of suspended sediment can act to suppress or increase periphyton levels, respectively. The UCD/USEPA ITM study on the effects of CBD irrigation return flow on periphyton found that periphyton algae and eroded cropland soils, including mineral sediment, dissolved organic matter (DOM), and particulate organic matter (POM) were contained in the CBD outflow – all of which contributed to turbidity levels (Tanji *et al.*, 1977). The UCD/US EPA NPS CBD studies followed up with explicit analyses relating suspended sediment associated P levels and algae abundance. Sediment associated P levels were found to predict about 77% of the variability in algal abundance (Tanji *et al.*, 1981b; Mirbagheri, 1981; Mirbagheri and Tanji, 2007). Algal material represents a highly labile organic carbon pool that can lead to decreased dissolved oxygen levels when eventually oxidized in the water column or after deposition. As the organic carbon/algal content of CBD suspended sediments have been found to be very high (10 to 30% by mass), the production of algae as mediated sediment associated P may result in significant impacts in the CBD and downstream at times. However, no issues with low dissolved oxygen levels have been reported in the lower CBD at this point.

More recent studies conducted by the CVRWQCB have found lower amounts of legacy chlorinated organic contaminants in CBD channel bed sediments (i.e. DDT break-down constituents such as DDE) (Larry Walker Associates, 2008). However, no characterizations of fluvial suspended sediments have been conducted in this regard, and bed sediment characterization has been performed infrequently on a relatively small amount of samples. Thus temporal trends in the effects of legacy contaminants on aquatic habitats in the Colusa Basin drainage area cannot be rigorously assessed due to a lack of data.

6.3 CBD Sediment Effects on Receiving Basins

Sediments eroded from hillslopes, agricultural fields, channel banks and channel beds are transported through the Colusa Basin drainage network to the CBD, which empties into the Yolo Bypass and the Sacramento River, and then on to the Delta, SF Bay and finally the Pacific Ocean. Colusa Basin watershed sediments may be considered anthropogenic in origin in their entirety due to the large scale alteration of the hydrologic and sediment transport regimes of the system (i.e. the construction of the CBD). Before the construction of the CBD the Colusa Basin drainage area deposited most of its sediment in the valley basin lands internal to the watershed (see Section 2). The CBD effectively connected sediment production in the Colusa Basin drainage area to the greater Sacramento River system. Thus, the channelized delivery of Colusa Basin suspended sediment through the CBD to the Sacramento River system is essentially a human derived condition, and all impacts of their presence in receiving bodies could be considered anthropogenic.

As winter storm waters from these basins and summer irrigation return flows are now discharged to the Sacramento River as channelized flow, the discharge of sediments from this watershed to the Sacramento River has most likely increased since development of the irrigation, drainage and flood control systems. During periods of low Sacramento River stage the CBD captures the drainage of several small to moderately sized (10^2 to 10^3 km^2 scale) interior Coast Ranges streams, agricultural irrigation return flows and the relatively small amount of municipal wastewaters generated in the basin and routes them to a single outfall in the Sacramento River above Knights Landing. Measurements by DWR, USGS and UC Davis scientists performing studies for the US EPA have shown that the suspended sediment concentration (C_{SS}) of CBD discharges are significantly greater than that of the Sacramento River upstream of the CBD outfall. During periods of high stage in the lower CBD, CBD waters are discharged eventually to the Sacramento River via the KLRC and the Yolo Bypass.

The impacts of CBD sediments are considered here for each receiving body (Section 6.3.1: The Sacramento River; Section 6.3.2: The Yolo Bypass; Section 6.3.3: the Delta and SF Bay) in terms of direct physical interactions with aquatic organisms and their habitats, and the effects of sediment mediated pollutants as per the sediment impact assessment methodology developed in Section 5.3. In summary, the most impactful direct physical effects of CBD sediments is the potential barrier to fishes migrating up the Sacramento River that may be imposed by the turbid plume emanating into the Sacramento River from the CBD outfall (Section 6.3.3.1). The largest concerns regarding the export of sediment mediated contaminants from the CBD include total mercury and pesticides (Sections 6.3.1.2, 6.3.2, and 6.3.3.2).

Studies by the CVRWQCB have confirmed that total mercury and methylmercury concentration of waters exported from the CBD were similar to those of the lower mainstem Sacramento River during the Sacramento River Watershed Program monitoring from 1997 to 2003 (CVRWQCB, 2005). Total mercury load from the Colusa Basin drainage area between 1984 and 2003 has been estimated as 2.7% of the total load to the Sacramento/San Joaquin Delta, and 3.7% for the years 2000-2003 (CVRWQCB, 2005). The Colusa Basin drainage area has been estimated to contribute approximately 3% of the average annual mercury load of the Yolo Bypass on the basis of Q and suspended sediment concentration data collected between 1996 and 2003 (Springborn *et al.*, 2011, see Section 4.1.2.3). Thus, mercury export from the Colusa Basin drainage area has been considered a minor component of the mercury budgets of its receiving basins.

Conversely, high application rates of pesticides in the Colusa Basin drainage area probably cause it to be second only to the Sacramento/Feather River in terms of fluvially transported pesticide flux to the Yolo Bypass (Section 6.3.2). Export of pesticides on Colusa Basin sediments may be a significant component of the pesticide load to the Sacramento River (Section 6.3.1.2), the Delta and SF Bay (6.3.3.2). However, very few CBD suspended sediment samples have been analyzed for pesticide levels, and much more flux based work would be required to assess environmental impacts of these pesticides on the Yolo Bypass aquatic environments. See Sections 7 and 8 for further discussion of the issue of ongoing data needs and the presentation of a plan to meet those needs.

6.3.1 CBD Sediment Impacts on the Sacramento River

The impacts of CBD sediments on the Sacramento River include those related to increases in ambient suspended sediment conditions and fining of the channel bed in the vicinity of the CBD outfall (Section 6.3.1.1), and fluxes of sediment mediated contaminants and nutrients (Section 6.3.1.2). Increases in ambient C_{SS} and turbidity may result in adverse impacts on periphyton and invertebrate communities, and may present a barrier to fish passages upstream. Fining of Sacramento River channel bed is not of great concern for salmonids as the CBD outfall is downstream of the gravel to sand transition and thus does not represent an impact on salmonid spawning habitat. Sediment-associated mercury loading of the Sacramento River appears to be relatively small. Of greater concern is loading of current and legacy pesticides due to the large areal extent of irrigated agriculture in the Colusa Basin watershed. In both cases more data is required to accurately assess impacts (see Sections 7 and 8).

6.3.1.1 Physical Impacts of CBD Sediments on the Sacramento River

The most valued ecological and human beneficial use components of the Sacramento River are its use as a migratory corridor for cold water fish (upstream migration of adults for spawning, and downstream outmigration of juveniles), and as municipal and agricultural water supply for humans (see Section 5.3). Direct effects of CBD sediments on the Sacramento River are driven by increases in ambient C_{SS} and the deposition of fine sediment into the Sacramento River channel bed. The impact of CBD suspended sediment on lower Sacramento River ambient C_{SS} depends on the contribution of water and sediment from the CBD into the mass flux of water and sediment from the upper Sacramento River at any given time. This effect is highly variable over time due to the unsteady transport of water and sediment from both water bodies, which is further complicated by the operation of the CBD outfall gates which can block the flux of water and sediment from the CBD entirely. A general lack of monitoring of this critical boundary prevents a quantitative assessment of CBD impacts on the Sacramento River at the outfall. However, two observations indicated that CBD sediments generally increase lower Sacramento River C_{SS}: (i) C_{SS} present in the lower CBD is generally higher than that of the upper Sacramento River during all but the highest Sacramento River flows, which often results in (ii) a turbid plume of sediment emanating from the CBD into the Sacramento River (see Section 4).

An investigation of the structure of the CBD sediment plume was performed during the UCD/US EPA NPS CBD study with measurements of a number of components including turbidity collected from 9 locations across the Sacramento River on a bi-monthly basis from May through September, 1980 (Tanji *et al.*, 1981c; Figure 6.3.1). Although data collection only spanned the irrigation season of one year, the results showed that CBD outflows altered the composition of Sacramento River waters in terms of color, salinity, *EC* and turbidity, with peak turbidity values in the plume up to approximately 4 times that of unmixed Sacramento Rivers waters (Figure 6.3.2).

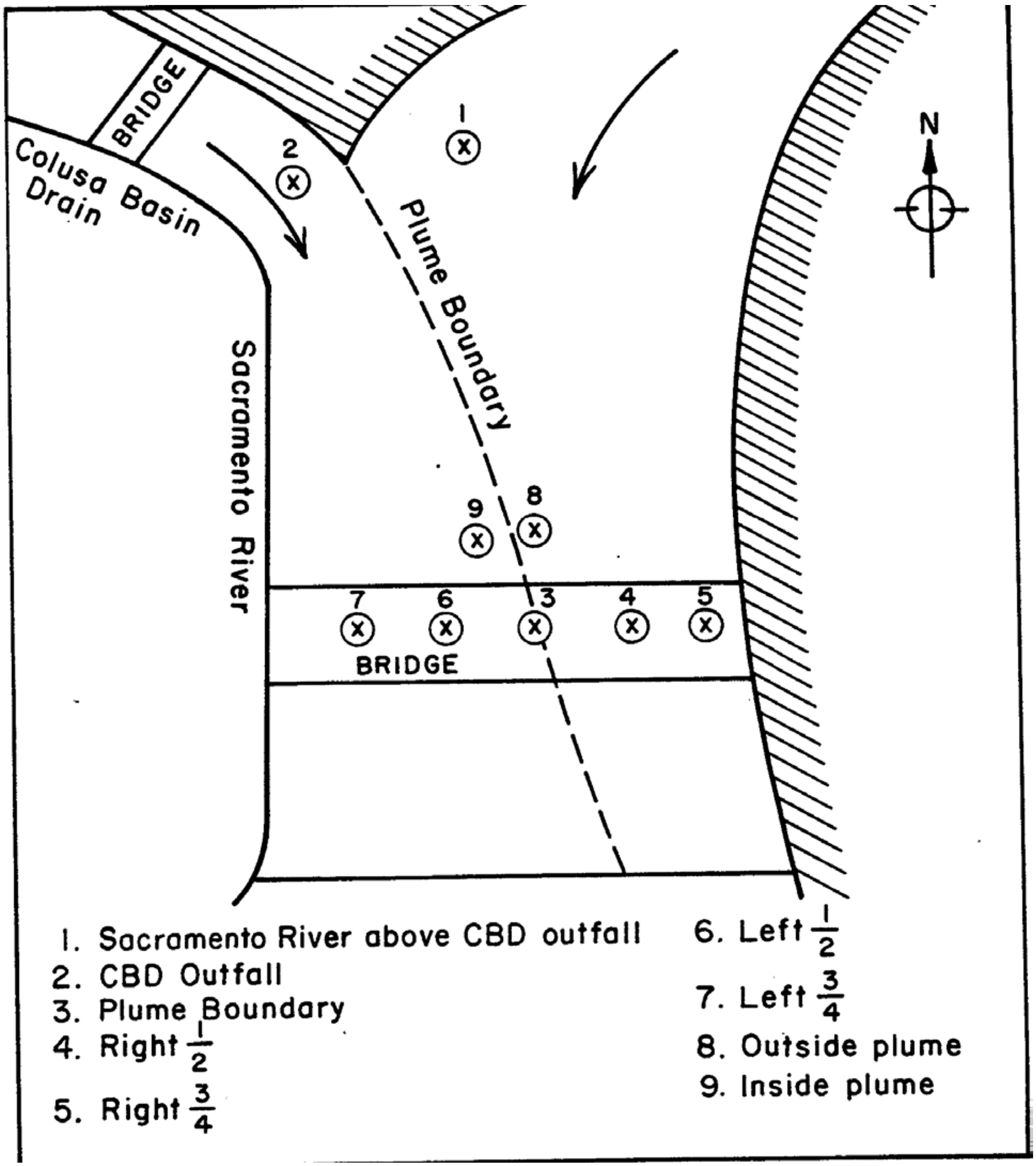

Figure 6.3.1. Diagram of the Sacramento River at the CBD outfall with sampling stations from the UCD/US EPA NPS CBD study (adapted from Tanji *et al.*, 1981c).

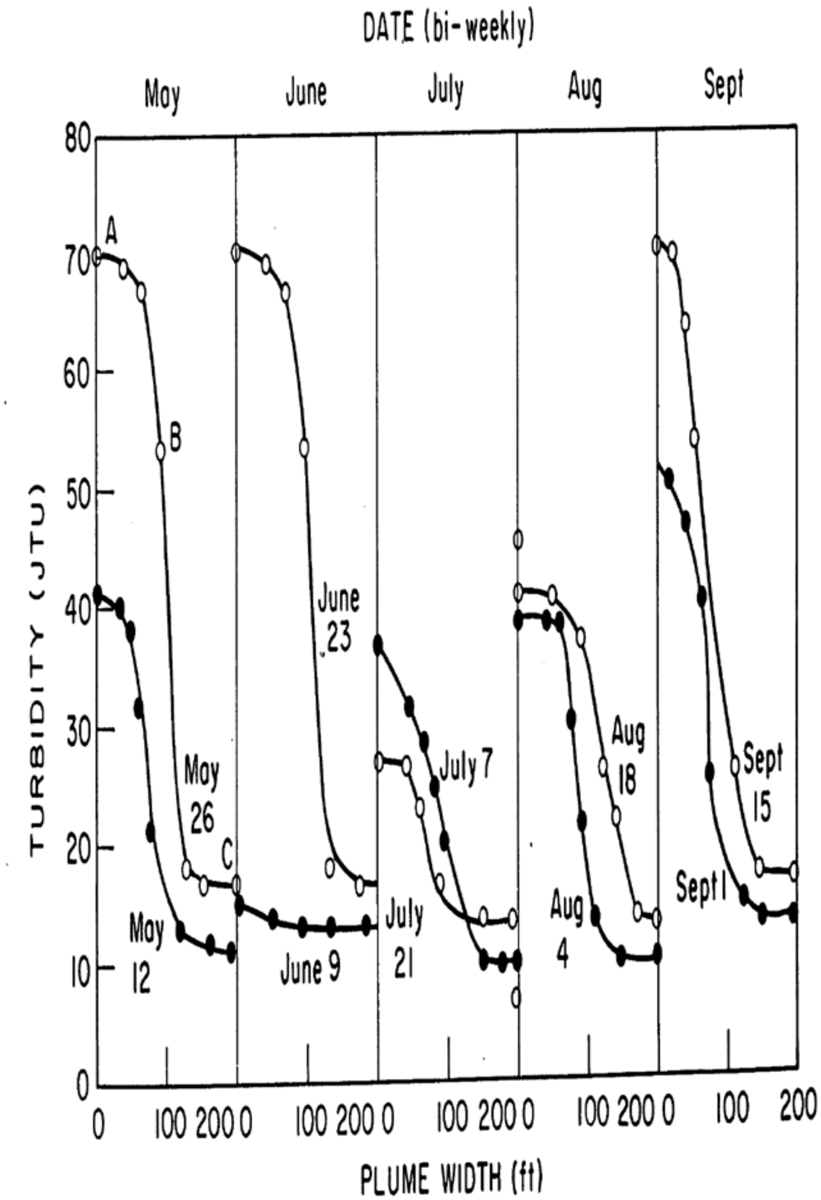

Figure 6.3.2. Turbidity structure of the CBD plume transect in the Sacramento River during the 1980 monitoring conducted by the UCD/US EPA NPS CBD (from Tanji *et al.*, 1981c). A = CBD water, B = plume boundary, and C = unmixed Sacramento River water.

The turbid plume of the CBD is generally most pronounced during larger outflows from the CBD during the irrigation season and during rainfall-runoff events early in the non-irrigation season when Sacramento River flows have not increased in Q (and C_{SS}) and the CBD flood gates remain open. The most turbid conditions occur closest to the right (west) bank of the Sacramento River near the CBD outfall and decrease downstream and further toward the east bank. The turbid conditions found by the UCD/US EPA NPS CBD study were most likely not of great concern for fish migrating through the region during the sampled conditions, as the plume never extended entirely across the channel and the turbidity values (maximum approximately 70 NTU) were most likely not sufficient to impose an acute barrier to fish passage. However, the lower CBD is known to reach more than 10x the turbidity sampled here in the irrigation season (see Section 4), and such conditions with higher CBD outflows could potentially impede spring or fall migrations of cold water fish such as Salmonids. Increases in Sacramento River sediment load introduced by the CBD may have impacts on municipal water supplies derived from the lower Sacramento River, particularly during more turbid discharges during the irrigation season, however indications of impaired water supply due to high C_{SS} have not been found.

Periphyton concentrations (by mass) have been found to decrease in the Sacramento River directly downstream of the CBD outfall, while periphyton density (number of algal cells per unit of water) was found to increase (Hayes et al, 1978). These seemingly contradictory observations were most likely caused by decreased light penetration due to turbidity increases and increased nutrient concentrations from CBD outflows.

Bed sediment fining has also been observed downstream from the CBD outfall into the Sacramento River (DWR, 1964). However, as the CBD outfall is located downstream of the gravel-sand transition of the Sacramento River channel bed, the additional bed fining introduced by CBD sediments does not adversely affect salmon spawning habitat (Singer, 2008). Effects of Sacramento River bed sediment particle size changes on benthic invertebrates induced by the CBD are unknown.

6.3.1.2 *Impacts of CBD Sediment Mediated Pollutants on the Sacramento River*

According to the Sacramento River Basin Water Quality plan, most fluvial constituents that are considered in terms of water quality are assessed in the dissolved state (CVRWQCB, 2011). The guidance of this document generally states that heavy metals and pesticides should be present at levels that are below those which would adversely affect aquatic organism and human beneficial uses, and those which would result from minimal effective use (specifically for current pesticides). Studies on aquatic impacts from specific pollutants and dose rates are ongoing, again with most focus on dissolved/total water column concentrations, and to some degree aquatic organism tissue levels, particularly for organisms utilized by humans as food sources (i.e. game fish). The limited focus on sediment-associated pollutants has mostly involved channel bed and bank sediments, with the exception of correlations found between total mercury and C_{SS} (Domagalski *et al.*, 2000; see Table 6.3.1). Much more monitoring and analysis will be required to gain the level of understanding of suspended sediment mediated pollutants required to adequately inform water quality assessments in the future.

Table 6.3.1. Studies on the impacts of CBD sediment associated pollutants on the Sacramento River.

Study Group	Study Name	Publications	Sample Period	Pollutants monitored	Mode	Results[2]
CVRWQCB	ILRP and SWAMP	CEDEN; CVRWQCB, 2005; Larry Walker Associates, 2008	2004-2013	Heavy metals and pesticides.	B	Colusa Basin: 17 constituents found at above detection limits at least once: Arsenic, Chromium, Cadmium, Copper, Lead, Nickel, Selenium, Silver, Zinc; DDT(p,p'), Dicofol, Esfenvalerate/Fenvalerate, Bifenthrin, Chlopryrifos
USGS	Water-Quality Assessment of the Sacramento River Basin	Domagalski, 1998; MacCoy and Domagalski, 1999; Domagalski *et al.*, 2000	1995-1998	A wide range of pollutants including heavy metals and pesticides.	SS, B	Sacramento River: total mercury - C_{SS} correlation; heavy metals and pesticides found in bed sediments.
		Roth et al., 2001	1996-1997	Total Hg	SS, D	Sacramento River Total Hg mostly colloid associated, increased downstream from Shasta Dam to Colusa

[1]Mode indicates whether the studied pollutant was associated with suspended (SS), or bed (B)

Between 1995 and 1998 the USGS California Water Science Center conducted the 'Water-quality assessment of the Sacramento River Basin (Table 6.3.1). This study was mostly concerned with measuring heavy metals, nitrates and pesticides in the Sacramento River Basin (Domagalski, 1998; MacCoy and Domagalski, 1999; Domagalski *et al.*, 2000). Their results generally show a clear relationship between mercury and suspended sediment concentrations in the Sacramento River. The USGS survey for contaminants in bed sediment and tissues in the Sacramento River Basin study unit focused on the perennial reach of the main stem of the Sacramento River and tributaries to this reach within the Sacramento Valley. Bed sediment data was collected from 17 sites between October and November 1995. These samples were analyzed for polychlorinated biphenyls (PCBs), organochlorine pesticides, semi-volatile organic compounds, and trace elements including heavy metals. Clams and fish were collected at 18 sites in October-November 1992. The tissues from these samples were analyzed for PCBs, organochlorine pesticides, and trace elements. Average total mercury levels in CBD bed sediments were found to be 0.06 µg/kg, in comparison to 0.07 µg/kg at S1 (Sacramento River at Colusa, CA). Colusa Basin Drain sediments and tissue samples were found to contain elevated levels of legacy contaminants, including DDE levels that were 2 to 100 times greater those collected from other stations in the Sacramento Watershed (Domagalski *et al.*, 2000; H.T. Harvey and Associates *et al.*, 2008).

Again, examination of sediment associated contaminants in the CBD and their impacts on the Sacramento River were largely limited to sampling and analysis of bed sediments rather than suspended sediments. Much more work is required to characterize the flux of sediment mediated contaminants from the CBD into the Sacramento River.

6.3.2 CBD Sediment Impacts on the Yolo Bypass

The Yolo Bypass is a 60,000 acre (243 km^2) farmed floodway that was constructed as part of the SRFCP to convey overflow waters routed from the Sacramento River at Freemont Weir. Previously this area was a natural floodplain, and despite its highly managed state, remains the largest contiguous floodplain in the lower Sacramento Valley (Smalling *et al.*, 2005). Although designed as a conveyance for flood waters, the Yolo Bypass continues to be used extensively for irrigated agriculture, primarily as corn (approximately 8,000 acres) and rice fields (approximately 3,000 acres). Over recent decades management of the Yolo Bypass for wetland and shallow water habitats has increased to levels that eclipse agricultural uses, with the expansion of the state managed Yolo Bypass Wildlife Area from 3,700 acres to 17,000 acres since its creation in 1997. Similar to other rice cultivation areas in the state, private hunting clubs maintain wetland habitats and also lease and manage water levels in rice fields during the duck hunting season. Many aquatic organisms, including some 42 species of fish (Sommer *et al.*, 2001) and numerous birds, particularly those that utilize the migratory Pacific Flyway, rely on the ecosystem services of the Yolo Bypass.

The Yolo Bypass receives water from up to 6 different sources for a total watershed area of 27,512 mi.^{2} (71,255 km^2), including the Sacramento and Feather Rivers, the KLRC, Cache Creek, Putah Creek, and Willow Slough (Table 6.3.1). The Colusa Basin watershed (4,231 km^2), as the primary contributor of Q to the KLRC, is a significant source of water and water transported materials delivered to the Yolo Bypass. The Colusa Basin is a major source of agricultural pollutants discharged to the Yolo Bypass, including sediment-mediated hydrophobic pesticides and herbicides (Smalling *et al.*, 2005). Although total annual pesticide applications in the Colusa Basin watershed are generally lower than the Sacramento/Feather contributing area, areal average application rates are on average approximately 10 times higher in the Colusa Basin due to the high proportion of the watershed used for agriculture (California Department of Pesticide Regulation (DPR, 2003 as per Smalling *et al.*, 2005). Annual pesticide application rates in the Colusa Basin watershed are also generally greater than the sum of applications to the Coast Ranges tributaries (Cache Creek, Putah Creek, and Willow Slough). A USGS study of pesticides concentrations in the Yolo Bypass found that the KLRC discharged the highest number of pesticides and either the highest or second highest concentrations of dissolved and suspended sediment associated pesticides of the tributaries, second only to Willows Slough for some compounds (Smalling *et al.*, 2005).

Table 6.3.2. Contributing areas to the Yolo Bypass.

Catchment	Area	
	(mi^2)	(km^2)
Sacramento River and Feather River	23,668	61,299
KLRC (Colusa Basin Drainage Area)	1,688	4,373
Cache Creek	1,142	2,957
Putah Creek	651	1,685
Willow Slough	269	697

[1]Springborn *et al.*, 2011.

The primary management concerns involving fluvial sediments delivered to the Yolo Bypass are sediment-mediated pollutants/toxins, particularly mercury and hydrophobic herbicides and pesticides (Table 6.3.3; Domagalski *et al.*, 1998; Roth *et al.*, 2001; Smalling *et al.*, 2005; Springborn *et al.*, 2011).

Table 6.3.3. Studies on the flux of sediment mediated contaminants from the CBD to the Yolo Bypass.

Study Group	Publications	Sample Period	Pollutants monitored	Results
USGS	Smalling *et al.*, 2005	2004-2005	27 pesticides	Pesticide concentrations generally correlated with subbasin application rates, Colusa Basin a large contributor of sediment associated pesticides.
	Springborn *et al.*, 2011	1996-2003	Total mercury	Colusa basin estimated to contribute approximately 3% of the Yolo Bypass total mercury load.

The joint use of the Bypass for agricultural production and valuable habitat, and its role as a tributary of the Sacramento-San Joaquin Delta, has led to concern over the impacts of sediment-associated pollutants on human and ecosystem health, including pesticides and heavy metals. Also of great concern is the production of methylmercury from deposits of sediment bound elemental mercury, a process that is favored by the organic rich soils that are exposed to inundated, stagnant conditions that dominate the Yolo Bypass during both the non-irrigation and irrigation seasons (Springborn *et al.*, 2011). The discovery of high levels of methylmercury production in the rice fields and wetlands of the Yolo Bypass, and other locations throughout the Central Valley have prompted a great deal of interest in characterizing and remediating this issue, as it presents a major stumbling block in restoring some of the areal extent of the approximately 91% of pre-settlement wetlands destroyed in the region.

The latest estimates of suspended sediment and total mercury flux to the Yolo Bypass were conducted by Springborn *et al.* (2011) for the decade of 1993–2003. They estimated that the major sources of sediment flux to the Yolo Bypass were Cache Creek (38%) and the Sacramento/Feather Rivers (47%), with the Colusa Basin delivering approximately 10% of the average annual load (see Section 4.1.2.3). Likewise, Cache Creek and the Sacramento/Feather Rivers were also found to dominate the delivery of total mercury at 64% and 31% of the total load respectively, with the Colusa Basin contributing approximately 3%. Thus Cache Creek plays a dominant role in the delivery of sediment and mercury to the Yolo Bypass, despite the fact that it deposits approximately 60% of its sediment and approximately40% of its mercury in the Cache Creek Settling Basin before debouching into the Yolo Bypass. Previous studies of sediment and mercury in the Yolo Bypass also identified Cache Creek as an important contributor of sediment and mercury to the Yolo Bypass (Foe and Croyle, 1998; Foe, 2001; Domagalski, 2001; Larry Walker Associates, 2002; Domagalski, 2004). Although Cache Creek drains a smaller area than the Colusa Basin watershed, it possesses a much greater average topographic relief, and captures drainage from higher Inner Coast Ranges Mountains to the west of the Colusa Basin high country, which contributes to its higher sediment loads. Most of the historic mercury mines within the entire Sacramento River Basin are also located in the Cache Creek watershed, resulting in higher mercury yields.

However, much remains uncertain regarding the role of Colusa Basin in the delivery of sediment and sediment-mediated pollutants to the Yolo Bypass. The above Smalling *et al.* (2005) study on pesticide delivery was conducted from a water quality observation perspective rather than with the goal of developing mass flux budgets. In this case a small number of samples were characterized for concentrations of pesticides, which were then compared to watershed scale annual application rates. This ‘dip-stick’ approach in useful for exploratory purposes, but would ideally be a first step toward developing estimations of pesticide flux into the system. Further flux-based characterization would necessitate a more intensive pesticide sampling regime conducted over a longer period of time with concomitant water and sediment flux measurements.

The latest sediment and mercury mass balance study of the Yolo Bypass (Springborn *et al.*, 2011) presents the basic methodology for such a flux-based approach, but also displays the limitations associated with low resolution data from highly variable systems, which result in large flux estimate uncertainties. For example, only 15 suspended sediment and mercury samples were used to develop sediment and mercury rating curves from which to estimate an entire decade of fluxes from Cache Creek – the major source of mercury to the Yolo Bypass. Similarly, estimates for the Colusa Basin were based on 56 suspended sediment samples and only 4 mercury samples. Further complications arose from dislocation between monitoring sites and the actual sites of interest, such as sediment samples collected from the Hwy. 20 overpass of the CBD (CBD-5), which were used to estimate fluxes through the KLRC, some 30 mi. (50 km) downstream, and only one of two major outlets for the Drain. The estimation techniques used to compute the amount of water and sediment routed through the KLRC, and similar scenarios for some of the other boundary conditions in this study, increase the uncertainty around the presented flux estimates. Furthermore, a full accounting of error estimates was not conducted for this study. The typical sources of error that must be propagated through flux calculations to arrive at total error include: (i) errors in measurement and reporting of all constituents (water, sediment, and sediment associated species of interest), (ii) rating curve errors, and (iii) extrapolation of rating curves beyond the sampled Q domain (Farnsworth and Warrick, 2007). In this case only rating curve errors were estimated. Additional error was also introduced in this study through the assumption that surface grab samples adequately represent the composition and concentration of suspended sediment throughout the flow field.

An initial characterization of the concentration and flux of sediment and sediment-mediated pollutants entering the Yolo Bypass has been made, but further understanding of the delivery of these materials, their impact on humans and the ecology of the Bypass requires an intensification of monitoring toward the goal of flux-based system characterization. It should also be noted that all point samples represent a snapshot of system function, and time series of data a moving picture that lasts as long as the base period of sample collection. Applying such system characterizations to time periods before and after the period of monitoring is to assume 'stationarity', which is to say that the system continues to function in the same way over time. With dynamic changes in human land use and climate, and examination of long term data sets, we know watershed functions, including fluvial sediment production, tend to violate the assumption of stationarity (Hestir *et al.*, 2013; Warrick *et al.*, 2013; Gray *et al*., 2015a,b). Thus it is not enough to accurately characterize a system once, but interdecadal monitoring plans should be enacted if critical functions are to be observed and altered over time.

6.3.3 CBD Sediment Impacts on the Sacramento/San Joaquin Delta and San Francisco Bay

The Delta and SF Bay are host to numerous aquatic organisms, including several endangered species such as the Delta smelt and Chinook salmon, many mammals and birds, which include migratory waterfowl traversing the Pacific flyway. Human beneficial uses of these water bodies include large scale water withdrawals for municipal and agricultural uses. Indeed, more than 30 million people depend on the Sacramento/San Joaquin Delta as a water source. Fluvial sediments play a role in mediating water quality in these systems, and are also important components of the accretionary processes that maintain marsh elevations and play a large role in their expansion or decline.

The role of Colusa Basin drainage sediments in the terminal estuaries and embayments at the mouth of the Great Central Valley of California is complex. On the one hand, the overall supply of sediment to the Delta and SF Bay has been drastically reduced due to large scale damming of rivers, particularly those ushering out of the Sierra Nevada (Section 6.3.3.1). On the other hand, sediments carrying associated toxins are a major water quality concern for the region (Section 6.3.3.2). The decrease in sediment loading of the Delta and SF Bay reduces the ability of subsiding wetlands to maintain accretion rates, particularly in the face of eutrophication and rising sea level. New supplies of 'clean sediments', those with low associated loads of surface associated pollutants, can also bury deposits of older sediments containing legacy contaminants such as heavy metals and chlorinated organic compounds, decreasing their interaction with the water column. Thus the key question regarding the effects of Colusa Basin watershed sediments on the Delta and SF Bay is whether their associated contaminant load outweighs their potential benefits.

The average Colusa Basin drainage area suspended sediment load is approximately 5-10% of the average influx of suspended sediment discharged into the Sacramento/San Joaquin Delta. While the fate and transport of Colusa Basin sediments *en route* to these regions is not well constrained (Section 6.3.3.1), the Colusa Basin watershed is one of the largest single un-impounded sediment sources for this region. The role of Colusa Basin sediments in the Delta and SF Bay in the future will be assessed on the basis of weighing their benefits against their adverse impacts, which will ultimately depend on sediment quality (i.e. the status of their associated contaminant load). On balance, sediments from the Colusa Basin drainage area appear to be relatively low in associated mercury, but may represent a significant supply of sediment associated pesticides (Section 6.3.3.2).

6.3.3.1 Physical Impacts of CBD Sediments on the Sacramento/San Joaquin Delta and SF Bay

The Sacramento/San Joaquin Delta is a network of channels, sloughs, relic wetlands and diked and drained "islands" used primarily for agriculture. The Delta empties into SF Bay, whose watershed is 62,605 mi.^{2} (162,145 km^2), of which the Central Valley watershed is 59,460 mi.^{2} (154,000 km^2), and the 482 small watersheds directly adjacent to the San Francisco Bay together drain 3,145 mi.^{2} (8,145 km^2) (Table 6.3.4; McKee *et al.*, 2013). Before human intervention, expansion of inundated area in the Delta and SF Bay at tidal, storm event and seasonal scales would result in the deposition of fluvial sediments on floodplains and wetlands. Today the Central Valley watershed has been highly modified, with 48% of area situated behind moderate to large dams (i.e. those capturing areas > 100 miles^2 (260 km^2), Minear, 2010); and much of the lowlands impacted by irrigated agriculture, livestock operations, and urbanization. Many studies have indicated that sediment loading from the Central Valley into the Delta and Bay has decreased over the course of the 20th Century (Wright and Schoellhamer, 2004; Ganju *et al.*, 2008; Schoellhamer, 2011). More recent advances in estimating sediment loads from small tributaries of the Bay have indicated that these loads may be larger than previously estimated (Lewicki and McKee, 2010, McKee *et al.*, 2013).

Table 6.3.4. Studies on sediment dynamics of the Delta and SF Bay.

Location	Lead Group	Publications	Study Period	Results
The Delta	OBA	Ogden Beeman and Associates, 1992	1955-1990	Estimated sediment loading to the Delta of 3.17 Mt/yr
	UCD	Hestir *et al.*, 2013	1975-2010	Sacramento River suspended sediment load decreased after 1983 El Niño flood.
	USGS	Ganju *et al.*, 2008	1851-2005	Sediment loading of the Delta from the Central Valley has decreased since the early 1900s due to exhaustion of hydraulic mining sediment supplies followed by impoundment of major river reaches.
		Gilbert, 1917	1849-1914	Estimated sediment loading to the Delta of 7.12 Mt/yr
		Porterfield, 1980	1909-1966	Estimated sediment loading to the Delta of 3.48 Mt/yr
		USGS NWIS, 2007	1990-2006	Estimated sediment loading to the Delta of 2.22 Mt/yr
		Wright and Schoellhamer, 2005	1999-2002	Sediment budget over the 4 year period of monitoring: Influx = 6.6 ± 0.9 Mt; Export = 2.2 ± 0.7 Mt; Deposition 4.4 ± 1.1 Mt
SF Bay	SFEI	Lewicki and McKee, 2010; McKee *et al.*, 2013	1957-2010	Estimates of sediment loading to SF Bay from small, directly adjacent tributaries (1.39 Mt/yr) and the Central Valley (0.89 Mt/yr).
	USGS	Shoellhamer, 2011	1991-2007	Step decrease in SF Bay C_{SS} may be associated with exhaustion of recent depositional pulse.

A four year study (1999-2002) of the Delta sediment budget showed that about 2/3 of the average annual sediment influx of 1.65 Mt was deposited, for an average flux to SF Bay of 0.55 Mt (Table 6.3.4; Wright and Schoellhamer, 2005). The latest estimates of sediment supply to SF Bay indicate that from 1995 to 2010 annual sediment loading from the Central Valley watershed via the Sacramento/San Joaquin Delta varied from 0.13 Mt to 2.58 Mt (mean = 0.89 Mt) (McKee *et al.*, 2013).

In contrast the collection of small mountainous tributary watersheds of the Bay Area contributed 0.081 Mt to 4.27 Mt (mean = 1.39 Mt) of sediment (McKee *et al.*, 2013). Thus, on average the smaller tributaries directly adjacent to the Bay produced the majority (61%) of sediment entering the Bay over this recent time period, despite the fact that they drain only 5% of its total watershed and provide only 7% of its annual Q (McKee *et al.*, 2013). Note that this study focused only on the fine sediment fraction (fine sands and mud). Bed load was not accounted for, which could raise sediment influx estimates to the bay by approximately 5 to 20%. Furthermore, step changes were observed in sediment mass flux from both the Central Valley and SF Bay tributary watersheds after large climatic events (Hestir *et al.*, 2013) and during the first decade of the 21st Century (after water year 1999) (Schoellhamer, 2011; McKee *et al.*, 2013). Causes for this latest change in suspended sediment regime remain unknown, but may be related to decadal scale oscillation climatic states.

The Colusa Basin drainage area has been estimated to export an average ~ 0.25 Mt of suspended sediment per year (Section 4.1.4), which is on the order of 10-15% of the average loading of the Delta in the early 20th Century (Table 6.3.4; Wright and Schoellhamer, 2005; Ganju et al., 2008). It is unclear how much of the CBD sediment load is generally deposited along its transport path through the Yolo Bypass and lower Sacramento River to the Delta. Recent estimations of the sediment budget of the Yolo Bypass could not resolve whether it was accreting or eroding (Section 6.3.2). Transfer of sediment through the lower Sacramento River is certainly more effective in the present due to efforts to reduce connectivity with its natural floodplain (ie. the SRFCP). If it is assumed that most of the Colusa Basin sediment load reaches the Delta, and is deposited at the average proportion of 2/3 found by Wright and Schoellhamer (2005), then CBD sediments may be as much as 20% of Central Valley sediments reaching SF Bay, and 7% of its total sediment influx. These are very rough estimates based on differing periods of observation (1978-1981 for the CBD and 1995-2010 for SF Bay). While the present study found no indication of decreasing sediment-discharge relationships for the lower CBD (Section 4.3.2), comprehensive monitoring of sediment flux from the CBD would be required to more accurately assess the role of Colusa Basin watershed sediments in terms of the Delta and SF Bay sediment budgets.

The observed decreases in sediment fluxes to the Delta and SF Bay have effects that can be viewed as positive or negative depending on stakeholder perspective (Table 6.3.5). For example, higher turbidity levels have been found to decrease phytoplankton abundance in southern SF Bay (May *et al.*, 2003). Turbidity imposed decreases in primary productivity can be detrimental to food webs, but may also help to inhibit eutrophic blooms that could otherwise cause further impacts on water quality, such as decreases in DO. A portion of sediment loads are also deposited in SF Bay. Intensive and expensive dredging of shipping channels occurs in the Bay, with some 1.23 million m^3 of sediment removed annually (2011 value) for eventual transport to the continental shelf, and to a much lesser degree constructed wetlands (Callaway *et al.*, 2011; Barnard *et al.*, 2013a). Deposited sediments may also adversely impact benthic invertebrate communities, although it is unclear if sediment loads are currently higher or lower than during pre-development levels. Sediment loads are also not a welcome component of waters abstracted for agriculture and municipal purposes from the Delta (see Section 5.3). Yet reduced sediment loads also result in less fine material for accretion of wetlands in the face of seal level rise and subsidence (Brand *et al.*, 2012; Shellenbarger *et al.*, 2013), and less supply of sand to coastal lotic cells, which seems to have led to degradation/erosion of beaches (Barnard *et al.*, 2013a,b).

Table 6.3.5. Studies on physical impacts of suspended sediment on the Delta and SF Bay.

Location	Lead Group	Publications	Study Period	Results
The Delta and SF Bay	USGS	Schoellhamer *et al.*, 2013	1950-2010	Adjustment to decreasing sediment supplies after hydraulic mining debris maxima in late 19th Century lagged increased distance from source (c. 1900 in Delta, c.1950 in central SF Bay).
		Shellenbarger *et al.*, 2013	2009-2011	Restoration of salt ponds with local or bay wide sediment sources alone would take 100s to 1000s of years.
SF Bay	USF	Callaway *et al.*, 2011	1800s-2010	Wetland losses in SF Bay have ranged from 70 to 93%, with only 25,000 acres (10,000 ha) of tidal marshes remaining. Restoration efforts must be designed and implemented with recognition of the complexity of these systems, and are threatened by climate change, and contaminant loading). Restoration efforts can be expedited by addition of dredged sediments.
	USGS	Brand *et al.*, 2012	2005-2009	Accretion to elevations required for vegetation possible with sufficient sediment supply
		May *et al.*, 2003	1978-2000	Turbidity decreases phytoplankton abundance in southern SF Bay.
SF Bay and the Pacific Coast	USGS	Barnard *et al.*, 2013a,b	various records: 1850s to 2012	150 million m^3 of sand has dissapeared from coastal beaches near SF Bay between 1960-2010, which appears to be caused by human activities including daming of Central Valley rivers, dreging of SF Bay and Delta channels, and aggregate mining.

Although the role of sediments in the Delta and SF Bay are complex, it is clear that these systems are experiencing shifting sediment regimes, with lower sediment loads in the early 21st century relative to both early human derived increases in sediment flux, and the natural conditions that preceded large-scale human activities in the region.

The Colusa Basin is in some ways typical of the basins that are now contributing the most to the Central Valley sediment flux, which has shifted from the western front of the Sierra Nevada to Coast Ranges foothills and agricultural lands. From a physical standpoint these sediments may pose a net benefit for the Delta and SF Bay due to their dominant role in wetland accretion in the face of sea level rise (Swanson *et al.*, 2014). However, even this benefit may be tempered in peat based accretionary systems by the offset of increased subsidence with the influx of denser mineral sediments (Deverel *et al.*, 2008). Thus, CBD sediments could be viewed as a valuable and declining resource, or a potential contaminant, depending on the component of the aquatic environment of interest. All sediments are not created equal – sediment composition is of major importance. Beyond particle size distribution and mineral composition, which have a large bearing on the physical and the net surface reactivity of sediments, differing particle histories can lead to the presence of a host of sediment associated chemicals. The role of CBD sediments as a resource or source of pollution in the Delta and SF Bay largely hinges on the contaminants that they may introduce (Section 6.3.3.2).

6.3.3.2 Impacts of CBD Sediment Mediated Pollutants on the Sacramento/San Joaquin Delta and SF Bay

Changes in the SF Bay sediment regimes to a smaller contribution of Central Valley sediments relative to small urbanized adjacent tributaries, along with a shift in the primary sediment source area of the Central Valley from the Sierra Nevada to the Coast Ranges and agricultural lands (Section 6.3.3.1), has further ramifications in terms of sediment mediated contaminant dynamics. Sediments sourced from watersheds highly impacted by agricultural, urban and industrial development generally carry higher loads of contaminants than those from less disturbed watersheds (US EPA, 2006). Sediments entering the Delta and Bay now have production and transport pathways that involve a high proportional exposure to human activities that result in contaminant loading (McKee *et al.*, 2013). Furthermore, the current net erosional condition of the Bay results in the resuspension of older sediments with surface associated legacy pollutants, which are reintroduced into the water column and trophic webs of the estuary (Table 6.3.6, Table 6.3.7).

Table 6.3.6. Studies on suspended sediment dynamics in the Delta and Bay.

Location	Lead Group	Publications	Study Period	Results
SF Bay	USGS	Schoellhamer, 1996	1991-1993	Elucidation of south SF Bay suspended sediment dynamics.
SF Bay	USGS	Schoellhamer, 2002	1992-1998	Suspended sediment concentration most highly controlled by tidal processes.
SF Bay	USGS	Downing-Kunz and Schoellhamer, 2013	2010	Clarification of seasonal and tidal variations in sediment dynamics of an SF Bay tributary

Many studies on sediment-associated pollutants have been conducted in the Delta and SF Bay, with the major parameters of interest including: PCBs, PAHs, pesticides, mercury, and other heavy metals (Table 6.3.7). The SF Bay tributaries have been found to produce higher concentrations of sediment associated pollutants including heavy metals and hydrophobic organic compounds such as PCBs and PAHs (Davis *et al.*, 2000; Davis *et al.*, 2001; Ross and Oros, 2004).

Sediment mediated constituents such as heavy metals and pesticides from the Central Valley also increase the pollutant load to these systems (Bergamaschi *et al.*, 2001; Yee *et al.*, 2011). Long-term studies based on sediment cores extracted from the region have also documented the rise in contaminant levels in association with human development (Hornberger et al., 1999; Venkatesan et al., 1999).

Table 6.3.7. Studies on the impacts of sediment associated pollutants in SF Bay.

Lead Group	Publications	Sample Period	Pollutants monitored[2]	Mode[1]	Results
SFEI	Ross and Oros, 2004	1993-2001	PAH	SS, D	South Bay PAH levels higher due to proximal urban and industrial sources.
	Davis, 2004; Davis *et al.*, 2006	1993-various	PCBs	SS, B, D	PCB half lives in Bay from 18 to 30 years;
	Davis *et al.*, 2000; Davis *et al.*, 2001	1993-2000	Pesticides, PAHs, PCBs, coliform, Hg, other heavy metals	SS, D	Bay area stormwater runoff large proportion of contaminant loading to SF Bay
	Leatherbarrow et al., 2005	2002-2003	PCBs, pesticides, Hg, PAHs	SS	Pesticides correlated with fluvial suspended sediment dynamics; PCB and PAH influenced more by tidal variation and localized sources; Loads of all pollutants estimated for WY 2002, 2003.
	Yee et al., 2011	2002-2006	Methyl-Hg	D	Methyl-Hg loading dominated by internal flux from deposited sediments and influx of water from external sources (Central Valley via the Delta)
Texas A&M	Choe *et al.*, 2003	2000-2001	Total Hg	SS, D	Hg strongly associated with suspended sediment; Colloidal transport of Hg strongly controlled by organic matter
UCLA	Venkatesan et al., 1999	late 1800s-1992	DDTs and PCBs	Core	Peak DDT deposition between 1969 and 1974; onset of PCBs in 1930s; dramatic drop in DDT and PCB levels in shallow sediments
UCSC	Conaway et al., 2003	1999-2000	Total Hg; Methyl-Hg, Dissolved gaseous Hg	SS, D	Total Hg correlated with fine suspended sediment, fluvial inputs; atmosphere net source of Hg of 40-240 kg yr^{-1}; MMHg from Delta and wastewater.
USGS	Hornberger et al., 1999	1850-1998	Metals	Core	Hg contamination onset c.1850-1880; Ag, Pb, Cu, Zn contamination onset c. 1910; Hg and Pb concentrations decreased since 1970s.
	Schoellhamer *et al.*, 2007;	1993-2000	Pesticides, PCBs, Hg, other heavy metals	SS	High correlation between C_{SS} and sediment associated contaminants
	Bergamaschi *et al.*, 2001	1996	19 Pesticides	SS	Sediment pesticide levels dependent upon source and transport history.

[1]Mode indicates whether the studied pollutant was associated with suspended (SS), bed (B), or deeper sediments (Core), or dissolved (D)

The role of Colusa Basin sediments in the complex scheme of contaminant loading, deposition and recycling in the Delta is unclear due to the paucity of data on the contaminant loads of suspended sediment exported from the CBD. As discussed in Section 6.3.2, total mercury levels in CBD suspended sediments do not appear to be of great concern in contrast to other Coast Ranges sources, such as Cache Creek. However, the levels of pesticide applications in the Colusa Basin watershed indicate that pesticide loads may be high. Further study, including an intensive fluvial sediment monitoring campaign are required to adequately address the question of Colusa Basin sediment impacts on all receiving bodies, including the Delta and SF Bay.

7. Data Gaps

Despite an interdecadal history of intermittent monitoring and analysis, the current state of information on fluvial sediment, discharge, and aquatic organisms is insufficient for a comprehensive assessment of fluvial sediment impacts on the aquatic environments of the Colusa Basin watershed (Section 7.1) and its receiving water bodies (Section 7.2). The most critical data gap relates to sediment-associated contaminant fluxes through and out of the watershed for recent time periods. This is the least studied problem, and yet of greatest concern. It is also necessary to further develop and monitor estimates of fluvial sediment flux, as sediment carries the contaminants, but also because clean sediment is important for desirable ecosystem services. Flux-based monitoring of sediments and associated contaminants is critical for quantification of Colusa Basin sediment impacts on receiving bodies, and also valuable for internal assessments of sediment sources to inform future sediment management decisions. Finally, because land use and water management has changed so much and will continue to change, it is important to track how these changes are affecting processes involving sediment and sediment-associated contaminants.

Current sediment monitoring in the watershed is primarily performed as ambient characterizations of turbidity values, in most cases without sufficient C_{SS} and Q monitoring to develop estimates of suspended sediment flux. Very little information is available on recent suspended sediment composition, including the magnitude and composition of sediment associated contaminants. Sediment associated pesticides are of particular interest, as they may be the most significant impact of the Colusa Basin watershed sediment on both internal and downstream aquatic systems. Accurate assessment of sediment impacts within the watershed would require additional efforts to monitor the response of aquatic biota to fluvial sediment conditions (Section 7.1). Although some studies have addressed the impacts of Colusa Basin watershed sediments on aquatic organisms, particularly periphyton, direct investigations on CBD fluvial sediment toxicity are also lacking. Efforts to understand impacts on downstream water bodies are further undermined by insufficient Q monitoring in the lower CBD and at the two outlets of the CBD (the KLRC and the CBD outfall), which inhibits accurate estimates of contaminant export from the watershed (Section 7.2).

7.1 Colusa Basin Watershed: Data Gaps Impeding Fluvial Sediment Impact Assessment

Although sediment production and transport in the Colusa Basin watershed was well characterized during a snapshot of monitoring over a four year period that ended about 35 years ago, recent monitoring of aquatic sediment parameters in the Colusa Basin watershed is not sufficient for the elucidation of sediment production and transport processes as they operate today.. Several changes in the human utilization of the Colusa Basin watershed have occurred over the past 35 year, including shifting agricultural crops types, and land management and irrigation techniques, as well as the completion of the TCC, which increased the delivery of Sacramento River water for irrigation within the basin by approximately 250,000 acre-feet (ac-ft). The lack of modern characterization of fluvial sediment dynamics hampers both the accurate assessment of environmental impacts of these sediments, and the formulation of appropriate sediment management strategies. Changes in the production, transport, and composition of sediment in light of changing land use factors can only be assessed with the re-application of processes based monitoring and analysis in the region.

Several disparate programs have monitored suspended sediment in the Colusa Basin over the last 50+ years with generally short periods of sample collection (months to years) (see Section 4). As these sampling programs were designed to assess a range of questions, and their sampling strategies were similarly diverse. Early projects, such as those carried out by DWR and the UC Davis/US EPA studies, were focused primarily on process oriented sediment flux estimation. Latter projects, including the two ongoing SWB/CVRWQCB sampling programs operating in the region (ILRP and SWAMP), were/are conducted with a focus on monitoring ambient water quality conditions. This shifting mosaic of monitoring interests has produced a record of suspended sediment samples and turbidity measurements collected with a range of methodologies from many different sampling stations.

Although recent fluvial sediment monitoring has been sufficient to establish a rough picture of ambient sediment conditions in the Colusa Basin valley and basin lands in terms of turbidity and C_{SS}, data gaps prevented thorough assessment of impacts on aquatic environments (Section 6.2). The primary data deficits are the result of insufficient hydrologic monitoring and surveys of aquatic organisms in recent decades (Table 7.1.1). Rigorous assessment of fluvial sediment regime changes over the past 35 years was not possible due to a general shift away from paired $\{Q, C_{SS}\}$ monitoring toward a focus of monitoring fluvial sediments with C_{SS} or turbidity measurements alone. Little collection of samples for C_{SS} determination has been conducted in recent decades and even less characterization of suspended sediment in terms of particle size distribution, organic composition and sediment associated contaminants. This situation prevents the assessment of ambient sediment conditions in terms of sediment characteristics and contaminants, and does not allow for the flux based analyses that are critical components of sediment source evaluation and assessment of sediment impacts on downstream water bodies.

Aquatic organism studies will also be required for future assessments of fluvial sediment impacts in the Colusa Basin watershed (Table 7.1.1). Such studies will have to be designed in concert with changes to sediment monitoring programs in order to co-locate sampling and survey sites, and serve a basin scale assessment strategy (see Section 8).

Table 7.1.1. Data gaps impeding environmental impact assessment of fluvial sediments in the Colusa Basin.

Impact Assessment		Data			
Stage	Component	Type	Required	Currently Monitored/Available	Gaps
Establish expectations for water bodies	Stratify water bodies by type and setting	Hydrologic Parameters	Paired {Q, C_{SS}} values to construct modern rating curves for watershed and subbasins of interest.	Ambient turbidity, some C_{SS}	Q and C_{SS}
		Aquatic biota	Populations and assemblages of aquatic biota	n/a	Populations and assemblages
Link water quality parameters with indicator responses	Established values	Hydrologic Parameters	Ambient turbidity, C_{SS}, particle size distribution, contaminant load	Ambient turbidity, some C_{SS}	C_{SS}, particle size distribution, contaminant load
		Aquatic biota	Established tolerance to above parameters for aquatic taxa of interest	General values for broad groups of organisms	Regional specific tolerance information
	Associational Analysis	Hydrologic Parameters	Ambient turbidity, C_{SS}, particle size distribution, contaminant load	Ambient turbidity, some C_{SS}	C_{SS}, particle size distribution, contaminant load
		Aquatic biota	Survey aquatic taxa abundance	n/a	Survey aquatic taxa abundance
	Toxicological Approach	Hydrologic Parameters	Water and sediment samples for experimental dose/response tests	n/a	Water and sediment samples for experimental dose/response tests
		Aquatic biota	Aquatic organisms for experimental dose/response tests	n/a	Aquatic organisms for experimental dose/response tests

7.2 Receiving Water Bodies: Data Gaps Impeding Fluvial Sediment Impact Assessment

Accurate assessment of the environmental impacts of fluvial sediments discharged from the Colusa Basin depends on our ability to quantify suspended sediment flux and the flux of sediment-associated contaminants over time at the outlets of the watershed. The lack of hydrologic monitoring in this critical region of the Colusa Basin is a major current impediment to this process (Table 7.2.1). The lowest station on the CBD currently monitored for discharge is CBD-5, which is some 30 mi. (50 km) upstream. Indeed, the most recent studies quantifying total mercury loading from the Colusa Basin to the Yolo Bypass relied on extrapolation of sediment flux from this gauge (Section 6.3.2). Such studies are also hampered by the very small amount of suspended sediment samples actually analyzed for sediment associated contaminant levels. In terms of most of the pesticides, no information exists on suspended sediment loads from the Colusa Basin. Assessment of impacts on the Sacramento River, the Yolo Bypass, the Delta and SF Bay will require flux based monitoring of suspended sediment at CBD-1, the CBD outfall, and the KLRC (Table 7.2.1).

Table 7.2.1. Data Gaps for impact assessment of Colusa Basin fluvial sediments on receiving water bodies.

Receiving Body	Monitoring Station(s)	Flux	Data Required
Lower CBD	CBD-1	Suspended sediment	C_{SS}, Q, particle size distribution
		Sediment associated contaminants	Suspended sediment flux, concentrations of contaminants on fluvial sediments
Yolo Bypass	KLRC	Suspended sediment	C_{SS}, Q, particle size distribution
		Sediment associated contaminants	Suspended sediment flux, concentrations of contaminants on fluvial sediments
Sacramento River	CBD outfall	Suspended sediment	C_{SS}, Q, particle size distribution
		Sediment associated contaminants	Suspended sediment flux, concentrations of contaminants on fluvial sediments

8. Sediment Monitoring Recommendations

The strategy for ongoing monitoring in the Colusa Basin watershed should address data requirements for the assessment of the environmental impacts of fluvial sediment and eventually inform the management of sediment and sediment-associated contaminants. As noted above, assessment of the environmental impacts of Colusa Basin sediment were incomplete due to significant data gaps (see Section 5). These data gaps are not currently being addressed by ongoing monitoring, which necessitates a new monitoring plan for Colusa Basin watershed sediments.

To this end, we propose a new study to better assess the environmental impacts of fluvial sediments produced in the Colusa Basin drainage area (Table 8.1). The specific goals of this proposed study are to develop a modern budget for suspended sediment and sediment associated contaminants (Section 8.1) and assess their impacts on aquatic biota in the Colusa Basin watershed (Section 8.2). Work toward development of the sediment budget will involve four major components: a flux-based hydrologic monitoring campaign (Section 8.1.1), including fluvial sediment composition analysis (Section 8.1.2) and sediment source evaluation (Section 8.1.3) combined with hydrodynamic characterization of the lower CBD (Section 8.1.4).

As aquatic biota represent the most sensitive components of the aquatic environment, they will be the focus of sediment impact investigation. Two approaches will be employed to assess impacts on aquatic biota: pairing benthic invertebrate surveys with sediment monitoring (Section 8.2.1), and toxicological dose/response experiments employing Colusa Basin sediments and local benthic invertebrate taxa (Section 8.2.2). Benthic invertebrate surveys will be co-located with hydrologic monitoring sites in the Colusa Basin watershed, and the Sacramento River in the vicinity of the CBD outfall. Toxicological dose/response experiments will utilize sediment collected during the monitoring campaigns at these sites.

Table 8.1. Proposed fluvial sediment monitoring and impact assessment plan for the Colusa Basin watershed

Goal	Section	Step	Goals	Components	Locations
Budget for fluvial sediment and sediment associated contaminants	8.1.1	Hydrologic monitoring	Elucidate modern sediment dynamics; sediment composition; sediment source evaluation; service aquatic toxicology	High resolution Discharge monitoring	Agricultural drainages; lower CBD; CBD outfall; KLRC
				High resolution turbidity monitoring	
				Suspended sediment sampling	
	8.1.2	Fluvial sediment composition analysis	Estimate sediment associated contaminant ambient conditions and fluxes	Sediment composition analysis: current and legacy pesticides, total Hg	
	8.1.3	Sediment source evaluation	Estimate relative importance of sediment source areas and erosion modalities.	Sediment flux and cosmogenic radionuclide analysis	
				LiDAR based topographic analysis	
			Evaluate role of human influences on sediment production from these areas	Watershed scale sediment transport modeling	
	8.1.4	Hydrodynamic characterization	Determine water and sediment dynamics for the lower CBD	Bathymetric and hydrodynamic surveying	CBD outfall; KLRC; lower CBD;
				Hydrodynamic modeling	
Aquatic organism impact assessment	8.2.1	Aquatic biota survey	Determine ambient sediment concentration thresholds for most sensitive aquatic taxa in Colusa Basin waterways	Survey of aquatic taxa present in basin	Colusa Basin watershed
				Analysis of aquatic taxa abundance in terms of sediment conditions	
	8.2.2	Dose/response toxicological analysis	Determine toxicology of Colusa Basin sediments on benthic invertebrates	Collect benthic invertebrates	
				Collect suspended sediment samples from different regions of the Colusa Basin	
				Perform toxicological screening test on Colusa Basin sediments	

8.1 Fluvial Sediment and Sediment Associated Contaminant Budgets

A budget for any fluvially transported constituent requires some accounting of the time series of *Q* and the abundance of the constituent; in other words, a flux-based monitoring campaign (see Sections 3.2-3.4). The current state of sediment monitoring in the Colusa Basin watershed is dominated by ambient turbidity monitoring of agricultural drainages under the CVRWQCB ILRP (see Section 4.1.1.3). Re-initiation of paired *Q* and sediment monitoring (Section 8.1.1) and sediment composition analyses (Section 8.1.2) to augment existing monitoring schemes and expand into reoccupation of historical monitoring sites would allow for estimation of sediment fluxes throughout the watershed, and the tracking of changes in flux through time. A flux-based approach will be essential for sediment source evaluations (Section 8.1.3), which will also employ high resolution topographic analysis and natural sediment tracers to examine the importance of landslides and gully and drainage ditch erosion to inform future sediment management decisions.

Revisiting sites where flux-based monitoring was conducted in the 1970s and 1980s will allow for assessment of changes in sediment-discharge relationships in light of changing agricultural activities in the watershed. Of great importance for assessing impacts of Colusa Basin sediments on downstream water bodies is estimating the flux of sediments and sediment associated constituents out of the CBD. This will require hydrologic monitoring of the lower CBD (Section 8.1.1), suspended sediment composition analysis (Section 8.1.2), including the abundance of sediment associated contaminants, and hydrodynamic analyses to better resolve the apportionment of water and sediments to downstream recipients (Section 8.1.4).

8.1.1 Hydrologic Monitoring

The proposed hydrologic monitoring campaign is structured to examine fluvial sediment dynamics and estimate sediment and sediment associated contaminant fluxes at two scales: agricultural drainages and the full Colusa Basin watershed. Watershed-scale sediment dynamics will be investigated through high-resolution monitoring of Q and turbidity (i.e., preferably 5- and 15-minute intervals between measurements for turbidity and Q, respectively), and lower resolution sampling for C_{SS} (daily or weekly) and sediment composition analyses (weekly) at a number of UCD/US EPA locations in the lower CBD including UCD/US EPA and DWR stations. Paired C_{SS} and turbidity data will be used to develop rating curves to construct high-resolution C_{SS} time series from turbidity records (Gray and Gartner, 2009). High-resolution Q and estimated C_{SS} records will be analyzed for C_{SS}-Q dynamics and the computation of near-census Q_{SS}. Samples for further sediment analyses, including particle size distribution, sediment mediated contaminant concentrations, and cosmogenic radioisotope analyses, will require larger sample sizes and concomitant laboratory efforts, which necessitate the planned lower sampling resolution (see Section 8.1.2).

Due to the highly variable nature of water and sediment flux through the Colusa Basin watershed and the variability of climate in the regime, it is recommended that the initial period of monitoring extend over multiple irrigation and non-irrigation seasons in order to capture a better representation of the breadth of current conditions. After analysis of results from the initial phase of monitoring, subsequent monitoring could be restructured to a less intensive scheme on the basis of ongoing data demands.

The proposed monitoring campaign would focus on sites used in the last comprehensive fluvial sediment monitoring campaigns, the UCD/US EPA ITM and NPS CBD studies (see Section 4.1) in order to develop long term records. Select sites in agricultural drainages and foothill streams will provide information on subbasin-scale sediment dynamics, while lower CBD stations will provide information on watershed scale sediment dynamics. Agricultural drainage and foothill stream sites will be chosen to capture a range a variability in stream morphology, an also to target subbasins that have experienced the greatest changes in agricultural operations since the UCD/US EPA studies. Watershed scale sites in the lower CBD should include CBD-1 and CBD-5 (see Section 4.2), and preferably a few others in between in order to monitor changes related to influx from tributaries and settling due to backwater effects. It is also essential that flux based monitoring is initiated at the CBD outlet to the Sacramento River and in the KLRC.

Efforts to monitor discharge at the KLRC by DWR have already begun, but are complicated by the topography of the channel corridor, as flows move out of the KLRC channels at the higher discharges that transport most water and sediment (DWR, *personal communication*). Monitoring and analysis of sediment and water flux into the two receiving bodies of the CBD is further complicated by outflow structures and operations as well as backwater effects during such important high flow conditions. However, without a commitment to long-term, high-resolution Q measurement in this area the level of uncertainty in terms of sediment-associated pollutant fluxes to the Yolo Bypass and the lower Sacramento River will remain high. For this reason a hydrodynamic model of water and sediment discharge through the lower CBD, the KLRC and the CBD outlet should be constructed (Section 8.1.4).

Discharge monitoring for some sites will involve reviving old gauging structures, while others will require new installations of monitoring equipment. A review of *Q* monitoring is beyond the scope of this report, as there are many approaches that could be employed, and solutions will be site specific. However, most methods rely on a measurement of stage (water elevation) that is then used to calculate discharge, either through empirical relationships or direct area-velocity methods. Modern advances have increased the options for the latter approach, which can enable higher accuracy of *Q* monitoring in open channels, especially if there are different stages on rising and falling limbs of runoff events.

Turbidity monitoring will be performed at a single location for subbasin-scale sites, and the watershed-scale sites in the lower CBD and its outlets should be instrumented with turbidity meters at multiple depths to capture some of the effect of C_{SS} stratification with depth. Automated water sampling devices for C_{SS} analysis will have their inlets co-located with turbidity meters to capture samples representative of the turbidity values being collected. Sample collection for further characterization will require additional automated sampling apparatus or manual sampling devices to obtain the large sample sizes necessary (see Section 8.1.2).

8.1.2 Sediment Composition Analysis

The largest unknown in terms of fluvial sediment in the Colusa Basin is the composition and flux of sediment-associated contaminants. While the mass of pesticides applied to fields in the Colusa Basin region are relatively well constrained, their flux from the system has not been quantified, particularly for those that are mostly transported on suspended sediment surfaces. Suspended sediment associated mercury has been assessed, but on the basis of only 4 samples collected from the CBD between 1996 and 2003 (Springborn *et al.*, 2011). Particle size distribution analysis of suspended sediment is also lacking from most recent sampling efforts, and it is well know that Hg and other toxic elements and compounds only associate with clay and silt sizes.

A comprehensive suspended sediment and *Q* sampling plan should include analysis of suspended sediments for particle size distribution, the concentrations of total mercury and sediment-associated hydrophobic organic chemicals applied at large in the basin. Particle size distribution monitoring is important for quantifying the flux of fine fraction of sediment ($D < 63$ μm), particularly clays (D < 4 μm), which carry most of the contaminant load. Monitoring of sediment-associated constituents in conjunction with a flux-based approach to fluvial sediment monitoring is essential to developing an assessment of the impact of Colusa Basin drainage area sediments on its receiving basins, and would provide better insight into the question of whether these sediments are on balance beneficial or detrimental to the Delta and SF Bay.

8.1.3 Sediment Source Evaluation

Although previous studies have indicated the relative importance of different geographic regions and geomorphic areas in terms of sediment production (see Section 4.1), the contribution of certain erosion modalities, including mass wasting, gullying, and agricultural drainage ditches have not be sufficiently investigated. Questions also remain as to how changes to agricultural crop composition, irrigation technologies and increases in irrigation water imports through the TCC have affected agricultural sediment loads. We propose the use of high resolution topographic surveys to assess the roles of gully and mass wasting erosion in contributing to upland sediment production. This remote sensing approach will be aided by field and reach scale case studies of drainage ditches and gullies and cosmogenic radionuclide abundance in exported sediments to provide further indication of the role of these erosion modalities in upland and agricultural sediment budgets. Analysis of sediment flux and dynamics throughout the watershed will provide current information on the changing role of agricultural sediment production at the watershed scale. Comparison of modern results with those of the UCD/US EPA studies will provide for a quantitative assessment of changes in sediment dynamics within the watershed.

The UCD/US EPA projects made a convincing case that most sediment in the Colusa Basin drainage area is produced in the upland regions of the foothill tributary watersheds, which was exacerbated by rangeland management and roads (see Section 4.1.4). Irrigated agriculture (particularly for row crops, orchards and feed crops), and road management increased the sediment production of the lowlands. Sediment management decisions oriented toward decreasing sediment export from upland and lowland areas are best determined on a site specific basis. The technical aspects related to reducing sediment export from agricultural fields have been well studied in the basin, particularly in relation to row crops and orchards (Tanji *et al.*, 1977; Gatzke, 2010). Professional opinion, sediment production models and remote sensing techniques have also been applied to estimating both upland, lowland and channel erosion regimes (Tanji *et al.*, 1981b; Gatzke, 2010; H.T. Harvey and Associates *et al.*, 2008; Geomorph *et al.*, 2010).

However, no work has been done to explicitly account for sediment production from gullying, mass wasting, or agricultural drainage ditches. These sources of sediments in the uplands and agriculturally impacted lowlands require further study if sediment sources are to be better understood and used to inform future sediment management decisions. A comprehensive approach to quantifying these sediment sources would begin with using a combination of remote sensing and field surveying to map the gullies and landslides, at least in representative physiographic regions in the watershed, and field scale study areas with drainage ditches.

We propose the use of LiDAR, a technology that employs laser illumination and reflection to remotely map surfaces, to develop high resolution (meter scale) digital elevation models (DEMs; i.e. 3-D digital maps) of the watershed. The opportunities with LiDAR would be to assess locations and volumes of recent landslides and establish a baseline for future DEM differencing to see elevational/volumetric changes and classify them according to the different causal processes. Some LiDAR has already been flown in the region for the Central Valley Floodplain Evaluation and Delineation Program (DWR, 2009). However, coverage of previous LiDAR appears to be mostly in the valley and basin lands, and raw data will require post-processing with new algorithms. Repeat surveys of gully and landslide changes would also be required to quantify sediment export, while high resolution monitoring of sediment flux through agricultural ditches over multiple seasons would be required to assess mass balances in these systems.

A complementary approach to identifying the relative importance of gully and landslide contributions to the Colusa Basin sediment budget would be the analysis of cosmogenic radionuclide abundances in suspended sediments relative to sediment sources. This would involve collecting representative samples of sediments from a range of sediment sources throughout the basin and then comparing their radionuclide abundances to that of the suspended sediments collected from the lower CBD. Useful components for this analysis could include radionuclides such as ^{210}Pb and ^{7}Be. These quickly decaying radionuclides, with half lives of 22.3 years and 53.2 days, respectively, fall out of the atmosphere at known rates and then associate with fine surficial sediments. Thus their abundance can be used in conjunction to discriminate between contributions from surficial and deeply buried sediment pools (Small *et al.*, 2002, Smith and Dragovich, 2008; Smith *et al.*, 2012). Comparisons of sediment compositions of source material within the watershed of each sampling site to suspended sediment compositions will allow for an assessment of differences in sediment source areas and primary erosion modalities between subbasins and for the Colusa Basin watershed as a whole.

Changes in sediment production since the UCD/US EPA studies of the late 1970s will be further investigated by employing the techniques used in the present study (see Section 4.3) to examine changing C_{SS}-Q relationships over time. Higher resolution paired $\{Q, C_{SS}\}$ data will provide a basis for more rigorous assessment of whether sediment loading from the foothills and agricultural lands have decreased over the intervening decades. If such analyses are combined with further investigation into the timing and spatial characteristics of changes in agricultural operations, important insights could be developed into sediment management directions for the basin.

8.1.4 Hydrodynamic Characterization

Historical and ongoing gaps in the hydrographic characterization of flow through the lower CBD and its two outlets (i.e. the KLRC and the CBD outfall) have also prevented the development of rigorous sediment budgets for the Colusa Basin watershed as a whole, and the apportionment this flux to the receiving bodies. Measurement of discharge through the lower CBD is complicated by backwater effects from operation of the CBD outfall gates, which has resulted in only sporadic records of discharge at CBD-1 (see Section 4.3). Even fewer records of discharge through the KLRC and the CBD outlet exist. Recent efforts by DWR to gauge flows through the KLRC are only valid for low flows within its paired, shallow channels (DWR, *personal communication*). Larger flows that represent most of the sediment flux through the KLRC are not well constrained (Section 6.3.2). In order to accurately assess flux of sediments and sediment associated constituents from the CBD the hydrodynamics of the lower CBD and outlet regions must be further investigated. This will involve topographic, bathymetric and hydraulic surveying of the lower CBD, the results of which be used to construct and validate a 2-D hydrodynamic model of water through the CBD and into the KLRC and Sacramento River.

8.2 Aquatic Organism Impact Assessment

Although some work has been done to explore the toxicity of Colusa Basin drainage area surface waters to macroinvertebrates, more work is required to understand the effects of suspended sediments and sediment associated pollutants on aquatic organisms in Colusa Basin waterways. Suspended sediment monitoring efforts should be combined with collocated benthic invertebrate surveys (Boothroyd and Stark, 2000) (Section 8.2.1). Suspended sediments collected from the comprehensive monitoring campaign outlined above (Section 8.1) could provide the basis for dose/response tests on macroinvertebrates in a laboratory setting (Section 8.2.2). These two efforts combined would form a strong direct assessment tool for the effects of sediment and sediment mediated contaminants on some of the most sensitive taxa in the aquatic environments of the Colusa Basin watershed.

8.2.1 Aquatic Biota Survey Assessments

Surveys of aquatic macro-invertebrates should be conducted at each suspended sediment sampling location on multiple occasions throughout the monitoring program. Miller *et al.* (2013) and others have found that benthic invertebrates are generally the most sensitive aquatic biota to water quality parameters. Survey design and impact analysis should follow established methods according to the US EPA and USGS (Plafkin *et al.*, 1989; Cufney et al., 1993; Barbour et al., 1999; Peck *et al.*, 2000; Moulton *et al.*, 2002). Sites will be stratified by geophysical parameters (hydrologic and temperature regimes, substrate characteristics) and then benthic invertebrate community and population structure metrics will be analyzed for correlation with suspended sediment characteristics.

8.2.2 Toxicological Dose/Response Analysis

Experimental dosing of benthic invertebrates with suspended sediments collected at sampling locations in the Colusa Basin watershed would provide a controlled method of assessing suspended sediment impacts. Many other factors may contribute to differences in benthic invertebrate communities found in the aquatic invertebrate survey (Section 8.2.1), including water quality components that may not be monitored. Thus, the additional of an investigation into the toxicological effects of Colusa Basin suspended sediments on benthic invertebrates would provide a means of further testing the causality of any correlations found between suspended sediment characteristics and the state of invertebrates in the aquatic ecosystem. Guidance for the development of this portion of the study will come from the literature on aquatic toxicology (Klem et al., 1990) (see Section 5.2.1.15.2.1.1).

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10. Supplemental Material

10.1 Literature

See attached data storage devices.

10.2 Site Visit Images

See attached data storage devices.

10.3 Data Sets

See attached data storage devices.