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northwest hydraulic consultants

May 14, 2010

David Okita, General Manager
Solano County Water Agency
P.O. Box 349
Elmira, CA 95625-0349

Regarding: FINAL Study Report: *Investigation of Sources of Turbidity, Sediment and Aquatic Vegetation in Putah South Canal*; *Second Annual Report*; May 14, 2010, NHC Project No. 50564

Dear Mr. Okita:
Enclosed for your files and library is a bound copy of the Final (Second Annual) *Investigation of Sources of Turbidity, Sediment and Aquatic Vegetation in Putah South Canal* Study Report along with a CD that contains the native WORD version of the report and a PDF version of the complete report with all five appendices. We have also provided a second bound copy and CD for SID. All of the Water Agency's review comments on the Draft Report are addressed in this Final 2010 Study Report. This final deliverable completes Phases 1 and 2 of the PSC Turbidity, Sediment and Vegetation Study.

Thank you for the opportunity to work with you and your staff on this challenging and important project. Please call me if you have questions regarding these materials or any further needs.

Sincerely,
Northwest Hydraulic Consultants, Inc.

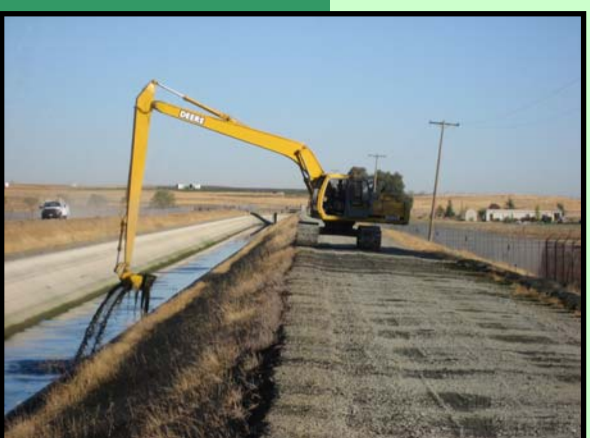
Robert C. MacArthur

Robert C. MacArthur, Ph.D., P.E.
Principal

cc: Alex Rabidoux

Enclosure: Two bound copies and two CDs of FINAL Study Report



INVESTIGATION OF SOURCES OF TURBIDITY, SEDIMENT, AND AQUATIC VEGETATION IN PUTAH SOUTH CANAL

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May 14, 2010

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List of Abbreviations

ADCP	Acoustic Doppler Current Profiler
AEI	Aquatic Environments Inc
APS	Applied Polymer Systems Inc
ARS	Agricultural Research Service
BMP	Best Management Practice
BOD	Biological Oxygen Demand
CAL-EPA	California Environmental Protection Agency
CRWQCB	California Regional Water Quality Control Board
cfs	cubic feet per second
DO	Dissolved Oxygen
DOC	Dissolved Organic Carbon
DPR	Department of Pesticide Regulation
d/s	downstream
EPA	Environmental Protection Agency
ft	feet
ft/s	feet per second
GIS	Geographic Information System
GPS	Global Positioning System
LCD	Liquid Crystal Display
MCL	maximum contaminant levels
M&I	municipal and industrial
MP	milepost (distance from Headworks along Putah South Canal)
MW	megawatt
mg/L	milligrams per liter
µg/L	micrograms per liter
NBR	North Bay Regional
NHC	Northwest Hydraulic Consultants Inc
NPDES	National Pollutant Discharge Elimination System
NSF	National Science Foundation
NTU	Nephelometric Turbidity Units
NWS	National Weather Service
O&M	operation and maintenance
PSC	Putah South Canal
ROW	Right of Way
SCWA	Solano County Water Agency
SID	Solano Irrigation District
SSC	suspended sediment concentration
THM	Trihalomethanes
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TRM	Turf Reinforcement Mat
TSS	Total Suspended Solids
USACE	U.S. Army Corps of Engineers
USDA	U.S. Department of Agriculture
USBR	U.S. Bureau of Reclamation
USGS	U.S. Geological Survey
u/s	upstream
WTP	Water Treatment Plant
WY	water year (12-month period from October 1 to September 30, designated by the calendar year in which it ends).

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EXECUTIVE SUMMARY

This is the second annual summary report prepared by Northwest Hydraulic Consultants (NHC) regarding the investigation of the sources of turbidity, sediment and aquatic vegetation in the Putah South Canal. NHC, along with Hydro Science and Taber Consultants (Taber), were hired by the Solano County Water Agency (SCWA) to investigate causes, sources, and magnitude of turbidity and sediment in the Putah South Canal (PSC) and to develop recommendations for reducing sediment deposition and growth of aquatic vegetation in the canal. This second annual report updates and expands the first report (NHC, 2008) based on present recent findings, and provides an up to date stand-a-lone summary of the main methods, results and recommendations developed during the period October 2006 through June 2009.

The PSC is part of the Federal Solano Project, which was constructed in the 1950's by the U.S. Bureau of Reclamation (USBR) to meet water demands of agriculture, municipal, industrial, and military facilities within Solano County in California. The Solano County Water Agency (SCWA) is responsible for operation and maintenance of the Solano Project on behalf of the USBR. The SCWA in turn has a long-term contract with the Solano Irrigation District (SID, referred to in this report as the "Solano Project operators") to implement the operation and maintenance activities associated with the Project. The Solano Project consists of four major facilities: Monticello Dam, Putah Diversion Dam, Putah South Canal, and the Terminal Reservoir. The PSC is a concrete-lined open channel extending south along the eastern toe of the English Hills through the Cities of Vacaville and Fairfield to the Terminal Reservoir in Green Valley. The PSC serves municipal, industrial, agricultural and military customers and frequently transitions from rural to urban settings. The total length of the canal is divided into 12 reaches or controlled checks. Along the canal, there are 5 operational spills (2 inactive), 11 plant intakes (1 inactive), and approximately 55 pumped or gravity turnouts/laterals consisting of combinations of open channels and/or pipe conveyance infrastructure.

Municipal and industrial (M&I) water users along the PSC withdraw raw water from the canal and treat it in order to meet current drinking water standards. There have been dramatic and sometimes sudden increases in turbidity in the canal water during winter storm periods. These turbidity pulses create operational problems for the water treatment plants (WTPs) and increase costs for treating the water supply distributed to their customers. When possible the WTPs will close their intakes and temporarily forego excessively turbid water. However, with increasing urban development and population growth throughout Solano County there is increasing demand for potable water supply. Increasing demand places greater constrains on the WTPs abilities to by-pass turbid water. Some plants, such as the Waterman WTP only have the system storage capacity to by-pass PSC water for 24 hours until they need to accommodate less desirable quality water to meet user demands. This leads to increased operational and water treatment costs.

Turbid water can enter the canal during storm events from lateral sources along the canal and through the Headworks located at the Putah Diversion Dam at the head of the canal. Sediment entering the PSC settles and deposits along the bottom of the canal. Sediment deposition promotes growth of aquatic weeds and algae, which impacts water quality in the canal and, in turn, promotes more sediment deposition. For maintenance purposes, Solano Project operators de-water and clean the entire Putah South Canal once a year. Canal cleanout requires extensive labor, heavy equipment, and vast logistical planning and coordination. Canal cleanout operations interrupt water supply to treatment plants and affect water turbidity and water quality in canal reaches located downstream from active cleanout locations.

The major goals of this study were to:

1. Assess geomorphic and hydrologic processes contributing to increases in turbidity in the canal.
2. Identify and quantify major sources of turbidity and sediment entering the canal; identify seasonal differences and causes.
3. Assess the relative annual contribution of sediment from the different sources.
4. Determine composition and characteristics of materials leading to turbidity and sediment deposition problems.
5. Assess issues and concerns regarding aquatic vegetation growing in the PSC.
6. Identify issues related to water quality and water user concerns.
7. Develop recommendations and cost effective solutions for mitigating periodic high turbidity, sediment and aquatic vegetation accumulation problems in the canal.

Project tasks included monitoring annual cleanout of the PSC, winter storm monitoring (turbidity and suspended sediment concentrations), identification of sources of sediment, preparation of an erosion hazard index procedure, hydraulic measurements in the canal and Lake Solano, assessment of annual sediment budgets, water user surveys, completion of a preliminary aquatic vegetation assessment, installation and monitoring of several Best Management Practices (BMPs) to reduce sediment loading into the canal, and preparation of recommendations for capital improvements, operations, maintenance and additional pilot studies. Following is a summary of the major results.

Putah South Canal Cleanout Monitoring

Cleanout of the PSC is conducted once a year during the fall (October and early November) when irrigation water demand is low and before the winter rains begin. PSC cleanout monitoring was conducted during the fall of 2006, 2007, and 2008 to observe sediment removal and cleaning operations, document depositional patterns and local sources of sediments, identify regions where the most severe deposits occur, measure approximate thickness and volumes of sediment deposits before and after cleanout and relate location of deposits to canal hydraulics. Bed material deposits were collected along the canal to determine grain-size composition and organic content of the sediment deposits and to determine the material's physical characteristics (density, moisture content). The spatial extent and approximate amount of aquatic weeds in the canal was documented. The measured pre- and post-cleanout volumes of sediment deposits in the PSC are essential components used to develop the annual sediment budgets for the canal.

Results from the 2006, 2007, and 2008 cleanout monitoring revealed that there is a significant on-going sedimentation problem in the PSC and a significant aquatic vegetation problem as well. Furthermore, it is likely that sediment and vegetation processes and problems are closely related to each other. Sediments enter the canal from Lake Solano and from local lateral sources including local runoff, open lateral drainages, and bank failures primarily during the winter runoff period. Due to the low currents in the canal and due to the presence of many flow control structures, inflowing suspended sediments (silts and clays) gradually deposit on the bottom as flow moves along the canal. Coarse sediments (sands and gravels) normally deposit in the vicinity of the supply source (e.g. bank failure site or open drainage).

Sediment deposition is highly non-uniform along the canal and depends on local sources of sediment and on local hydraulic conditions in each check and on how well the check was cleaned during the previous fall cleanout. Sediments tend to accumulate in backwater areas, particularly in the downstream reaches of each of the checks, upstream of flow control structures, inside water intakes, along the inside toe of canal bends, in depressions in the bottom of the canal, and at the outlets of siphons. The thickness of sediment deposits on the bottom of the PSC generally increases in the downstream direction. The maximum measured thickness of fine sediment deposits was on the order of 2 ft in the canal and up to 2-4 ft inside intake structures. Maximum height of coarse sediment piles was up to about 3 ft in several locations after major storm events. Sediment deposits mostly consist of silt, clay, and organic matter. Occasional deposits of sand and gravel occur below bank failure sites, locations where gravel from road maintenance activities is cast or slips into the canal, and at outlets of local open drainages. Sedimentation processes in the PSC promote the growth of aquatic weeds and algae, which impacts water quality in the canal. Growth of aquatic weeds also affects the location and depth of fine sediment deposits in the canal and makes canal cleanout more difficult.

Total volumes of sediment deposits in the PSC immediately prior to the 2006, 2007, and 2008 cleanouts were estimated at 13,000 yd^3, 4,000 yd^3, and 6,500 yd^3, respectively. Total residual volumes of sediment left in the canal after the 2006, 2007, and 2008 cleanouts were approximately 3,000 yd^3, 500 yd^3, and 2,000 yd^3, respectively. Residual sediments constituted on the order of 10-30% of the pre-cleanout volumes. Because of the highly non-uniform distribution and floc-like character of sediment deposits in the PSC, the estimated volumes of sediment deposits presented in this report should be regarded as approximate, order of magnitude estimates with possible variations as much as 20-30%.

The volumes of sediment deposits calculated for 2006 and 2007 may represent extreme, atypical conditions. The 2005/2006 winter was extremely wet, while the 2006/2007 winter was very mild, with no significant rain events affecting the study area. As a result, significantly more sediment accumulated in the canal during water year 2006 compared to water year 2007 (water year, or WY, is the 12-month period from October 1 to September 30, designated by the calendar year in which it ends). The 2007/2008 winter was moderately wet, with a few intense storm events, and was more representative of average winter conditions. The long-term average sediment deposition in the canal is likely to be between the estimated 2006 and 2007 volumes and closer to the 2008 volume. Canal cleanout monitoring results provide an important basis for understanding the effects of different annual hydrologic conditions, various sediment sources, variable material characteristics and overall sedimentation processes occurring in the PSC.

Winter Storm Monitoring

Baseline winter conditions at the Headworks and in the PSC were measured and real-time storm event data were collected during three significant winter storm events and a “first flush” storm event that occurred early in the winter rainy season. Winter monitoring was conducted during WY 2007 and WY 2008. Storm event monitoring involved measuring and tracking sediment turbidity plumes entering the PSC from Lake Solano and other lateral sources and following those plumes as they propagated down the canal. Water turbidity and suspended sediment concentration (SSC) were measured at a number of locations along the PSC, as well as in Pleasants Creek and Putah Creek above Lake Solano.

During winter non-storm baseline conditions, water flowing in the PSC is relatively clear, with turbidity values typically ranging between 2-20 NTU and SSC approximately 1-13 mg/L. During storm events, turbidity and SSC values in the PSC and other streams in the study area can increase dramatically by one to two orders of magnitude, depending on the intensity, duration, and location of the storm. During storm events that were monitored, the maximum measured turbidity was 3,220 NTU in the PSC, approximately 4,000 NTU in Pleasants Creek, and 1,590 NTU in Putah Creek above Lake Solano. The maximum SSC values were 2,080 mg/L in the PSC, 4,680 mg/L in Pleasants Creek, and 1,220 mg/L in Putah Creek above Lake Solano. Turbidity and suspended sediment concentrations during the extreme storm that occurred on December 31, 2005 were likely higher than these maxima according to data collected at some of the water treatment plants along the PSC.

Winter monitoring data confirms that Pleasants Creek is by far the largest contributor of turbidity and sediment into Lake Solano during winter storm events. Turbid waters from Lake Solano enter the PSC through the Headworks and slowly propagate down the canal as a turbidity plume (a parcel of water with increased turbidity and SSC). A turbidity plume can move through the entire 33 miles of the canal, gradually attenuating as fine suspended sediments settle out along the canal. The propagation speed of typical winter turbidity plumes in the PSC is approximately 0.2-0.4 ft/s, depending on canal flow conditions. Suspended sediment concentrations in the turbidity plumes are distributed relatively uniformly (vertically and laterally), which is likely due to the very small size of the sediment in suspension as well as mixing effects generated by the canal walls, wind mixing and from numerous structures in the canal.

Significant volumes of turbid water and sediment can periodically enter the canal during large storms from multiple lateral sources which include bank failures, road cast, open drainages, overland runoff, canal overtopping, and spillage of turbid waters from flume crossings. The contribution from individual lateral sources is episodic and depends on the severity and phasing of a given storm event or sequence of storm events.

Results from the winter monitoring program were used to develop a relationship between turbidity and SSC. This relationship can be used to convert turbidity readings to SSC and to estimate sediment loads in the canal.

Field measurements revealed periodic accuracy problems with some of the SCWA automated turbidity probes. During several of the high turbidity events, the turbidity probes at the Sweeney Check and the Eldredge Plant systematically underestimated turbidity by approximately 100-300 NTU, while the automated turbidity probe installed at the Terminous Check consistently overestimated turbidity in the PSC by about 100 NTU. The other SCWA turbidity probes performed reasonably well. NHC accounted for this in their analyses so these conditions do not affect the reliability of the results and conclusions presented in this Final Report.

Identification of Lateral Sources of Sediment and Preparation of Erosion Hazard Index Procedure

Principal objectives of the project were to identify primary sources of sediment and turbidity that enter the canal and to assess the relative annual contributions from these sources. Results from the field inventory of lateral sediment sources were used to develop an erosion hazard index procedure that was applied on a reach-by-reach basis to identify locations along the canal with insignificant, low, moderate, high, and severe erosion and sediment production potential. A GIS database was developed to show where sources of lateral erosion occur and to provide erosion hazard ratings for different reaches of the canal. This database can be used by SCWA to identify reaches along the canal that warrant the application of erosion control BMPs. Chapter 4 discusses the methods used to identify sediment sources and explains the results from these activities.

BMP Pilot Studies to Evaluate Control of Lateral Sediment Sources

Best Management Practices (BMPs) are measures used to control nonpoint source erosion and sediment delivery to the PSC. For the Putah South Canal, an initial set of BMPs were developed and implemented. Monitoring results from these initial sites show good success and provide needed information to develop plans for additional BMP applications. The initial BMP measures were designed (1) to control erosion from the earthen upper banks along the canal which extend from the edge of the canal's concrete lining up to the access roads along each side of the canal, (2) to reduce or eliminate sediment loading from open drains, and (3) to reduce or eliminate direct runoff from access roads that enters the canal. Recommendations for additional BMP measures were developed and discussed with SCWA and the Project Operators. Chapter 5 presents the 2009 fiscal year erosion control work products including the developmental aspects for the pilot test program and a summary of the monitoring results from the first set of BMP test applications.

ADCP Measurements

Flow hydraulic characteristics were measured using an Acoustic Dopler Current Profiler (ADCP) at selected locations in the Putah South Canal, in Lake Solano and the Headworks. Flow monitoring sites included a straight reach of the canal and a canal bend located upstream from the Weyand Intake (MP 5.6), a straight reach of the canal upstream from the Waterman WTP Intake (MP 23.5), Lake Solano in the vicinity of the diversion dam and the Headworks, and inside the Headworks forebay. The flow patterns measured in the non-vegetated reaches of the PSC at the Weyand Intake are common to open channel flows. The highest velocity was located in the central, deepest portion of the canal in the straight reaches and was shifted toward the outer bank along bends in the canal. During the measurements, water discharge ranged from 195 to 245 cfs, with maximum measured canal velocities of approximately 0.8-1 ft/s. Vertical velocity profiles fit a typical “log law” velocity distribution.

ADCP flow measurements in a heavily vegetated reach of the PSC at the Waterman WTP revealed the dramatic effect that aquatic vegetation has on flow distribution in the canal. Thick vegetation (forests of aquatic weeds) growing on the bottom of the trapezoidal canal significantly slow the flow in the central portion of the canal and result in highly non-uniform velocity distributions in the canal. Velocities in the lower 1/2 to 1/3 of the water column in the vegetated portion of the canal were near zero. The highest velocities in heavily vegetated reaches were observed in free-flowing zones near the water surface along the canal edges. Partial removal of the vegetation increased stream velocities in the central portion of the flow and resulted in more uniform vertical and lateral velocity distributions. Maximum velocities measured at the Waterman WTP were approximately 0.6-0.8 ft/s.

The ADCP measurements in Lake Solano revealed converging and accelerating flows at the entrance to the Headworks. During the measurements, outflow from the lake into the PSC was approximately 620-630 cfs. Measured depth-averaged velocities ranged from 0.25-0.75 ft/s in the lake at the diversion dam to 0.75-1.25 ft/s for flows approaching the trash screens. The highest velocities (greater than 3 ft/s) were observed in the narrowest section of the Headworks forebay near the sluice gates. A large eddy was detected in the north-east corner of the forebay, which indicated that only 1/2 to 3/5 of the entrance cross section at the Headworks was effectively conveying flows into the canal on the day of the measurements. Briefly opening the right-most gate in the diversion dam slightly accelerated near-bottom flow velocities approaching the dam. Based on this observation, it was concluded that periodic flow releases (flow pulses) from the diversion dam gates nearest to the Headworks could help clean bottom sediment deposits from the entrance to the Headworks.

Assessment of Annual Sediment Budget

Annual sediment budgets were developed for the PSC for WYs 2006, 2007, and 2008 using available flow and turbidity data, results of suspended sediment sampling, and measured pre- and post-cleanout volumes of sediment deposits in the canal. According to the calculations, during WY 2006 (an extremely wet year) a total of between 5,300-12,800 tons of sediment was supplied into the canal, of which approximately 900 tons (7-17%) were derived from Lake Solano and between 4,400-11,900 tons (83-93%) were derived from lateral sources. Of the sediment supplied into the canal during WY 2006, approximately 700 tons (5-13%) exited the canal with water outtakes, 100 tons (1-2%) were conveyed into Terminal Reservoir, and between 4,500-12,000 tons (85-94%) deposited in the canal.

During WY 2007 (a dry year), altogether between 940-1,440 tons of sediment was introduced into the canal, of which approximately 540 tons (38-57%) came from Lake Solano and 400-900 tons (43-62%) were derived from lateral sources. Of the sediment supplied into the canal in WY 2007, an estimated 420 tons (29-45%) exited the canal with water outtakes, 20 tons (1-2%) were conveyed into Terminal Reservoir, and approximately 500-1,000 tons (53-69%) deposited in the canal.

During WY 2008 (a moderately wet year), a total of between 2,900-6,900 tons of sediment was introduced into the PSC. Of this total amount, about 900 tons (13-31%) entered the canal from Lake Solano and between 2,000-6,000 tons (69-87%) were derived from lateral sources. Of the sediment supplied into the PSC in WY 2008, about 800 tons (12-28%) were extracted with water outtakes, 100 tons (1-3%) were conveyed into Terminal Reservoir, and between 2,000-6,000 tons (69-87%) deposited in the canal.

Due to the lack of precision with which the floc-like sediment and organic material deposits can be measured in the canal, natural variability of sediment transport processes, episodic character of sediment inputs into the canal, limited number of sampling locations, and significant length of the canal, the estimated sediment amounts should be regarded as approximate order of magnitude estimates. Even though the measurements are not precise, the estimated annual budget information provides valuable project planning and management information.

The results obtained indicated that of the two major sources of sediment considered in this study (Lake Solano and lateral sources, which include local runoff, overbank flows, open drainages, canal panel failures, and bank sloughing), lateral sources were most significant during WYs 2006 and 2008. During WY 2007, sediment supply from Lake Solano and lateral sources was comparable. It should be noted however, that WYs 2006 and 2007 may have been atypical for the study area. WY 2006 was extremely wet, with record high rainfall and runoff throughout Solano County. On the contrary, WY 2007 was very dry, with no significant rainfall events in the study area. WY 2008 was a more moderate year, yet the results were skewed by an extreme storm event on January 4, 2008. Nevertheless, the results obtained for WY 2008 are believed to be more representative of average rainfall and runoff conditions in the study area.

According to the three years of data and estimates developed for the annual amount of sediment entering the PSC from Lake Solano, approximately half or less of the annual load is derived during winter storm events (when the flow in the canal is low and sediment concentrations are high) and the remaining amount is derived during summer irrigation periods (when the flow in the canal is high and suspended sediment concentrations are low). This seasonal distribution of sediment loading from Lake Solano into the PSC needs additional research to check if summer turbidity readings are influenced by aquatic vegetation growth in the lake and in the canal.

In summary, the study results clearly demonstrate how significant both major sources (Lake Solano and lateral sources) are for supplying annual sediment loads into the PSC. Although use of different bulk densities (a likely range) to convert volumetric measurements of sediment deposits in the PSC into weight units changes the relative contribution of different sediment sources, there is an apparent dependency of sediment supply into the canal on local rainfall and runoff conditions. The more it rains in winter and the greater the rainfall intensity, the more sediment is supplied into the canal from Lake Solano and the greater the contribution from lateral sediment sources. Sediment delivery from lateral sources dramatically increases if overbank flooding occurs along the PSC alignment. During extremely wet years, total annual sediment delivery into the canal significantly increases and can be approximately 5,000-13,000 tons. During such wet years, the relative contribution of sediment from Lake Solano into the canal is 10-20% of the total annual load and the contribution from lateral sources is approximately 80-90%. During dry years, annual sediment supply into the canal may reduce to less than 1,000 tons/yr, with roughly equal supply coming from Lake Solano and lateral sources. During average years, annual sediment inflow into the PSC is likely to be on the order of 2,000-7,000 tons, with approximately 20-40% of sediment coming from Lake Solano and 60-80% from lateral sources.

Identification and Analysis of Sediment and Turbidity Sources

NHC determined that the magnitude of turbidity and sediment entering the PSC as well as the sources of sediment and turbidity responsible for these constituents can be highly variable in space (location) and time (seasonally and annually). NHC also determined that these factors are highly dependent upon the intensity and duration of local and regional rainfall occurring in the watersheds upstream from Lake Solano as well as those smaller local watersheds that drain toward the canal from the west. The two primary sources of sediment and turbidity in the PSC are: (1) inflows that enter the PSC from Lake Solano, and (2) from the sum of all lateral sources, including canal bank surface erosion, canal bank mass failures, inputs from direct drains, inflows from overtopping flows at stream crossings or other points, and atmospheric deposition. During the course of these studies, NHC examined information and data related to rainfall, runoff, and turbidity and found that each of the three water years studied (WYs 2006, 2007, and 2008) was somewhat unique from a hydrologic perspective and none of the three years may be representative of “typical annual hydrologic conditions.” Annual sediment budget estimates developed by NHC for WYs 2006, 2007, and 2008 show the large variability in annual sediment inputs caused by the occurrence of significantly different annual hydrologic conditions. NHC estimated approximately 5,300-12,800 tons of total sediment loading (from all sources) occurred in WY 2006, 940-1,440 tons in WY 2007, and 2,900-6,900 tons in WY 2008. Based on results from the three annual sediment budget analyses, lateral sources contributed 83-93%, 43-62%, and 69-87% of the sediment load during WYs 2006, 2007, and 2008, respectively. Unfortunately, with only three complete water years of data available, there is insufficient long-term information to accurately describe the likely range and nature of the annual sediment yields generated from each sediment source along the canal for different hydrologic conditions. Based on the present results and data, the range of the average annual sediment contribution from lateral sources can be on the order of 60-90% of the total loading to the canal, with remaining 10-40% coming from Lake Solano depending on annual hydrologic conditions.

Thus, it appears that lateral sediment sources are dominant during major flood events which produce overtopping flows and canal bank failures (soil slips and landslides). Although overtopping events that spill stormwater directly into the canal are relatively rare, they likely represent the majority of the total lateral source of sediment loading on a decadal time scale. Above the Serpas Check, canal bank sloughing and landslides are estimated to be the second largest lateral source, followed by surface erosion from the canal banks, which is largely limited to those areas maintained in a barren condition through the application of herbicides. Below the Serpas Check, the two direct drains in Suisun Valley can routinely discharge sediment laden runoff directly into the canal from approximately 90 acres of cultivated land. Other sources of sediment include periodic overtopping events from Ledgewood and/or Suisun Creeks. Duration and persistence of turbid conditions in the canal downstream from the Serpas Check is related to the winter-long delivery of turbid runoff from direct drains as the single largest chronic source of turbidity followed by barren canal banks that are sprayed annually with herbicides.

Assessment of Issues and Concerns Regarding Aquatic Vegetation in Putah South Canal

Issues and concerns regarding aquatic vegetation in the Putah South Canal are discussed in Chapter 9. Based on initial observations and preliminary sampling of aquatic vegetation in the PSC, 4 to 5 species of aquatic plants (some native, some exotic) successfully grow, reproduce, and contribute most of the rooted biomass along the majority of the canal system. Filamentous algae also contribute significant biomass both in suspension and as attached (colonial filaments) along the sides and bottom of the canal. Seasonal production of biomass is generated along the canal, but is augmented by imports from Lake Solano and drainage basins immediately upstream from the Headworks. Seasonal senescence (die-back) of this biomass contributes to the overall organic load in the canal and when combined with fine sediments probably increase the hypoxic conditions in the sediment deposits. Even if all of the vegetation were successfully removed within the canal in one season, new propagules (viable plant fragments, shoots, tubers, turions and seeds) of both macrophytes and algae would continue to infest the canal from the upstream sources. This suggests that a fully integrated source management strategy is needed that includes both in-canal actions (physical removal and/or herbicides), as well as source management of exotic (non-native) plants in Lake Solano and considerations to install improved vegetation screening equipment at the Headworks. The magnitude of the upstream sources and their seasonal contributions need to be assessed further. NHC will complete a full year of "vegetation biomass loading measurements at the Headworks and USGS gaging station this fall. These data along with monthly flow diversion records at the Headworks should provide important information that can be used to design new high capacity vegetation screens and automated screen cleaning facilities for the Headworks.

Issues Related to Water Quality and Water User Concerns

Issues related to water quality and water user concerns are discussed in Chapter 10. Investigations conducted to date related to water quality issues and water user concerns suggest the following:

- The periodic occurrence of winter plumes of highly turbid water passing through the canal is caused by significant storm events. Occurrence of these events may cause some

WTPs to shut down for short periods of time. Treatment of high turbidity water increases plant treatment costs.

- Problems associated with interruptions to WTPs water supply and water quality treatment problems often arise because the treatment plants may not have an alternate source of acceptable raw water or sufficient storage in their systems to survive source interruptions that last more than 24 hours at a time.
- Aquatic vegetation is becoming a principal source of water quality and canal and intake maintenance problems within the PSC relative to the WTPs.
- Introduced sediment of all sizes greatly exacerbates water quality problems by increasing the growth of algae and aquatic macrophytes. Mixtures of sediment deposits and decaying plant materials create accumulations of black organic sludge-like materials in the canal with very poor water quality characteristics that are very difficult to remove or treat.
- Thick mature patches of aquatic macrophytes encourage further capture and settling of fine sediments from the water column and provide a location where inorganic sediments combine with vegetation and other organic detrital materials. These thick mats of sediment and organic bottom materials become anaerobic during the summer and fall and are sources of hydrogen sulfide, other detrimental water quality constituents and impart odors and tastes into the water that must be removed in water treatment plants, especially during annual canal cleanout operations. Thick growth of aquatic vegetation can reduce water treatment plant intake efficiency and lead to increased maintenance needs.
- Traditional mechanical canal cleaning methods are not capable of removing the fluid-like black floc and much of the fine sediments and organic sludge that are the primary sources of the water quality problems experienced during cleanout.
- The fluid-like floc and fine organic bottom deposits (sludge materials) are generated each year as new "crops" of aquatic vegetation are produced, die, settle to the bottom, and decay or decompose into other forms of organic bio-mass that may harbor mixed biological populations of microorganisms.
- Water quality characteristics of these fluid-like floc and sludge materials are very poor and are leading to increased annual water treatment costs.
- Polymers are commonly used in water and wastewater treatment plants throughout California and are commonly applied during potable water treatment processes. There are numerous NSF/EPA approved polymers that are acceptable for use in potable water supply treatment processes. The Waterman and NBR WTPs use polymers in their water treatment processes.
- Polymers accelerate settling of suspended materials in water and help reduce concentrations of other water quality constituents such as nutrients and metals.
- Results from bench scale laboratory experiments conducted by NHC indicate that polymers greatly accelerate settling of fine suspended sediments and floc-like materials and increase their settled bulk density.
- Field trials are needed to assess the possibility and costs of full scale application of polymers as settling aids during cleanout in the PSC.
- Polymers in combination with commercially available gravity belt sludge thickening equipment show good promise as sludge enhancement and water separation methods and

may provide an alternative for removing and treating the black residual sludge materials left from annual cleanout operations. Field testing of this equipment is recommended.

Recommendations for Managing Sediment and Vegetation

Recommendations for sediment and vegetation management are discussed in Chapter 11. The recommendations are grouped by category: (1) capital improvements; (2) operations; (3) maintenance; (4) recommendations requiring easements or landowner agreements; and (5) pilot studies or additional studies needed for prescription development. Additional analysis will be needed to assess the feasibility, design requirements and cost-benefits of many of the suggested improvements and modifications. Table 11.1 summarizes "primary" recommended Putah South Canal capital improvements and re-operation recommendations. Also listed are pilot studies that are most likely to contribute to reducing sedimentation and aquatic vegetation growth in the canal, as well as means for providing alternative water supply and additional backup water storage. Improvements are grouped in this table by their main purpose (sediment control, aquatic vegetation control, and supplemental water supply) and are approximately ranked according to their bulk installation cost, operation and management cost, and expected effectiveness and benefits. Additional recommendations are presented in this chapter but are not included in Table 11.1 because they are not considered to be "primary recommendations."

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1. INVESTIGATION OF SOURCES OF TURBIDITY, SEDIMENT, AND AQUATIC VEGETATION IN PUTAH SOUTH CANAL

1. Introduction

1.1. Background

This is the second annual summary report prepared Northwest Hydraulic Consultants (NHC) regarding their investigation of the sources of turbidity, sediment and aquatic vegetation in the Putah South Canal. NHC, along with Hydro Science and Taber Consultants (Taber) were hired by the Solano County Water Agency (SCWA) to investigate causes, sources, and magnitude of turbidity and sediment in the Putah South Canal (PSC) and to develop recommendations for reducing sediment deposition and growth of aquatic vegetation in the canal. This second annual report updates and expands the first report (NHC, 2008) based on present recent findings and provides an up to date stand-a-lone summary of the main methods, results and recommendations developed during the period October 2006 through June 2009.

NHC is the prime consultant responsible for overall project management, organization of field investigations, data collection and analysis. Hydro Science is a sub-consultant assisting with geomorphic studies, inventory of local sources of turbidity and sediment, and collection and analysis of field data and recommendations for best management practices (BMPs). Taber Consultants is a sub-consultant who assisted with sediment sampling, geotechnical services, laboratory sediment analyses, and other field investigations.

1.2. Project Setting

The PSC is a concrete-lined open channel that delivers water from Lake Solano to agricultural, municipal, and industrial users along a 33 mile alignment of the canal through rural and urban environments in Solano County, California (Figure 1.1). The PSC is part of the Federal Solano Project, which was constructed in the 1950's by the U.S. Bureau of Reclamation (USBR) to meet water demands of agriculture, municipal, industrial, and military facilities within Solano County in California (NHC 1998). The Solano County Water Agency (SCWA) is responsible for operation and maintenance of the Solano Project on the USBR's behalf. The SCWA in turn has a long-term contract with the Solano Irrigation District (SID, referred to as the Solano Project operators) to implement the operation and maintenance activities associated with the Project.

The Solano Project was designed to irrigate approximately 96,000 acres of land. Principal crops are corn, wheat, sugar beets, tomatoes, fruits, nuts, and irrigated pasture. The project is also a major municipal and industrial water supply for over 411,000 people in the cities of Vallejo, Vacaville, Fairfield, Benicia, and Suisun City, supplying about 32,000 ac-ft annually.

The Federal Solano Project consists of four major facilities: Monticello Dam, Putah Diversion Dam, Putah South Canal, and the Terminal Reservoir. Monticello Dam (Figure 1.2) impounds water from Upper Putah Creek creating Lake Berryessa with a maximum storage capacity of 1.6 million acre-ft. Lake Berryessa has three outlet features: a 54-inch hollow-jet valve, the 11.5 MW Monticello Power Plant, and a 72-ft diameter reinforced concrete pipe spillway known as the "Glory Hole". Controlled "active" releases up to an approximate maximum flow of 600 cfs from the hollow-jet valve and Monticello Power Plant, each, are made based on fixed operating rules. Uncontrolled "passive" spills occur through the Glory Hole spillway with a maximum design capacity of 45,000 cfs.

The Putah Diversion Dam (Figures 1.3 and 1.4) is located approximately 6 miles downstream of Monticello Dam. The dam is a gated concrete weir structure with an earthfill embankment wing. The dam is 29 ft high, and has a crest length of 910 ft. The Putah Diversion Dam regulates water in Lake Solano parsing flow releases between Putah South Canal diversions to SCWA service areas and releases to Lower Putah Creek. The portion of Putah Creek between Monticello Dam and Putah Diversion Dam is known as the "Inter-Dam Reach". This reach consists of approximately 4 miles of stream and 2 miles of lake environments. The Inter-Dam Reach is a steep-gradient riffle-run system at Monticello Dam transitioning to pool-glide system approaching Lake Solano. Lake Solano is about 1.5 miles long, narrow, and relatively shallow reservoir with a capacity of 750 acre-ft. The bed material in the creek is composed of gravel and sand. Sediments in the lake are composed primarily of fine silts, clays, sands, and organic materials.

The Putah Diversion Dam develops enough head at the PSC Headworks to maintain gravity flow into the PSC. The Headworks is located on the south bank of Lake Solano immediately upstream of the diversion dam (Figure 1.5). Flow into the PSC is regulated by two parallel bottom-up tainter gates (Figure 1.6). The PSC is a 33-mile long concrete-lined open channel (Figure 1.7) extending south along the eastern toe of the English Hills through the Cities of Vacaville and Fairfield to the Terminal Reservoir in Green Valley. The canal has a diversion capacity of 956 cfs with a terminal capacity of 116 cfs. The PSC serves municipal, industrial, and agricultural customers and frequently transitions from rural to urban settings. During the spring and summer months approximately 75% of the water deliveries provided through the PSC are for irrigation and agricultural uses. Municipal and industrial (MI) water users along the PSC withdraw raw water year round from the canal and treat it in order to meet current drinking water standards. The total length of the canal is divided up into 12 reaches or controlled checks (see Table 1.1). Along the canal, there are 5 operational spills (2 inactive), 11 plant intakes (1 inactive), and approximately 55 pumped or gravity turnouts/laterals consisting of combinations of open channel and/or pipe conveyance infrastructure. The plant intakes are summarized in Table 1.2. Canal section properties are given in Table 1.3. The longitudinal profile of the canal is shown in Figure 1.8. Canal longitudinal slope ranges from 0.00010 to 0.00015. Longitudinal distribution of typical winter and summer flows in the PSC are shown in Figure 1.9. Mean daily winter and summer outtakes from different reaches of the PSC during water year 2008 and design storage capacity of each check are shown in Figure 1.10 (water year, or WY, is the 12-month period from October 1 to September 30, designated by the calendar year in which it ends).

Geology of the Solano Project watershed consists primarily of marine sedimentary rocks that exhibit a high degree of erodibility. Erosion rates range from near zero to very high, dependent on the steepness of the terrain, underlying rock, degree of weathering, soil types, land use, vegetation, and hillslope orientation. Soils are composed of moderate to highly erodible sandy and silty materials, with some clay and boulders that have fallen from steep, weathered mountain slopes. Important water and sediment contributors to Lake Solano include Pleasants Creek (Figure 1.11), as well as Canyon Creek, Thompson Creek, Bray Creek, and Proctor Draw. During severe rainfall/runoff events, large boulder and debris loads enter Putah Creek from many of its steep lateral drainages, occasionally obstructing the main channel. Pleasants Creek is the largest tributary conveyor of sediment and exhibits a deeply incised channel with unstable eroding banks (Summers 1980, NHC 1998). Sediments transported by the stream are deposited in Lake Solano, reducing its storage capacity and impacting project operation and maintenance, water delivery, and water quality/clarity (Figures 1.3, 1.12, 1.13). No significant dredging of Lake Solano has been done, other than localized debris and sediment removal in the vicinity of the Headworks in the 1990's (NHC 2008) and no significant watershed or sediment source control programs have been implemented other than local bridge replacement and bank erosion control projects in Pleasants Valley.

1.3. Problem Statement

Sudden and dramatic increases in turbidity in the canal water can occur during winter storm periods (Summers 1980, SID 1981, NHC 1998, Archibald and Starr 2006). Turbid water can enter the canal during storm events through the PSC Headworks and from lateral sources along the canal. These turbidity pulses create problems in the operational efficiency of the water treatment plants (WTPs) and increase costs for treating the water supply distributed to their customers. When possible the plants will close their intakes and temporarily forego excessively dirty water. However, with increasing urban development and population growth throughout Solano County (as of 2007 its population was estimated at 411,680; with 4.34% growth since 2000) there is increasing demand for potable water supply as well as a continued need for irrigation water for agricultural use. Increasing demand places greater constraints on the WTPs abilities to by-pass turbid canal waters. Some plants, such as the Waterman WTP in Fairfield only have the system storage capacity to by-pass PSC water for 24 hours until they need to accommodate less desirable quality water to meet user demands. This leads to increased operational and water treatment costs.

To monitor water turbidity, SCWA installed 5 continuous monitoring stations along the Putah South Canal (shown in Figure 1.1). The upstream most station is located at the Headworks, serving as an early warning system for the treatment plant operators. In addition to the turbidity stations along the canal, the SCWA installed one turbidity monitoring station on Pleasants Creek near Lake Solano and one on Putah Creek just upstream from Lake Solano. Continuous turbidity monitoring (every 4 hrs) is also routinely conducted at the water treatment plants.

Sediment entering the PSC settles and deposits on the bottom of the canal. Sediment deposition promotes the growth of aquatic weeds and algae, which impacts water quality in the canal and, in turn, promotes more sediment deposition within rapidly growing stands of aquatic weeds. Thick growths of aquatic vegetation can clog irrigation turnouts, plug drip emitters, reduce water treatment plant intake efficiency, and lead to increased operations and maintenance costs.

For maintenance purposes, Solano Project operators de-water and clean the entire Putah South Canal once a year. Canal cleanout requires extensive labor, heavy equipment, and vast logistical planning and coordination. Canal cleanout operations interrupt water supply to treatment plants and affect turbidity and water quality in sections of the canal located downstream from active vegetation and sediment cleanout locations. The efficiency of the cleaning process is limited by the inability to completely drain the canal and because bottom deposits are easily suspended into a slurry-like fluid when disturbed which makes mechanical removal very difficult. Formerly, Solano Project operators utilized wasteways along the canal to completely drain and flush the canal, but increased environmental concerns have since discontinued their use.

1.4. Study Goals

The major goals of the study were to:

1. Assess geomorphic and hydrologic processes contributing to increases in turbidity in the canal.
2. Identify and quantify major sources of turbidity and sediment entering the canal; identify seasonal differences and causes.
3. Assess the relative annual contribution of sediment from the different sources.
4. Determine composition and characteristics of materials leading to turbidity and sediment deposition problems.
5. Assess issues and concerns regarding aquatic vegetation growing in the PSC.
6. Identify issues related to water quality and water user concerns.
7. Develop recommendations and cost effective solutions for mitigating periodic high turbidity, sediment and aquatic vegetation accumulation problems in the canal.

Major tasks for the project included monitoring of the annual cleanout of the Putah South Canal, winter storm monitoring (turbidity and suspended sediment concentrations), identification of sources of sediment, preparation of an erosion hazard index procedure, hydraulic measurements in the canal and Lake Solano, development of annual sediment budgets, water quality surveys, and aquatic vegetation assessments. The main results and data obtained during the course of this study are presented in this report.

Table 1.1. Controlled checks in Putah South Canal.

No.	Check	Milepost (MP)*	Storage capacity (acre-ft)	Cumulative storage (acre-ft)
1	Sweeney	6.15	132.9	132.9
2	Gibson	9.64	64.5	197.4
3	Highway 80	12.05	53.3	250.7
4	Alamo	13.76	30.8	281.5
5	Union	15.82	33.6	315.1
6	McCoy	18.80	44.4	359.5
7	Burton	21.19	21.5	381.0
8	Serpas	23.51	20.6	401.6
9	Mankas	25.94	24.3	425.9
10	Suisun	27.48	14.2	440.1
11	Rockville	30.02	15.2	455.3
12	Terminous	32.33	12.1	467.4

*Milepost, or MP, is distance from Headworks along Putah South Canal.

Table 1.2. Plant intakes in Putah South Canal.

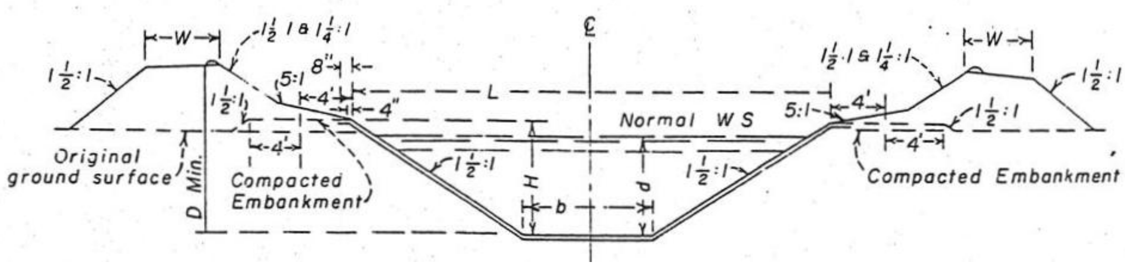
No.	Plant intake	Milepost (MP)
1	Eldredge Pumping Plant	11.80
2	City of Vacaville	12.84
3	California State Prison-Solano	14.77
4	North Bay Regional WTP	16.85
5	Cement Hill WTP	19.61
6	Paradise Valley Pumping Plant	20.56
7	Gregory Hill WTP (inactive)	23.50
8	Waterman WTP	23.50
9	Ledgewood Creek Winery	25.11
10	Green Valley Conduit	32.33
11	Terminal Reservoir Outlet	33.53

Table 1.3. Canal section properties (data from SCWA).

Lined Sect. No.	Type Sect.	Length Mi. to Mi.	TABLE OF CANAL SECTION PROPERTIES CANAL DIMENSIONS							
			b Bottom Width	d Water Depth	H Lining Height	L Top Lining Width	Minimum Earth Frbd.	Minimum D Canal Depth	Minimum Width W Lt. Bk.	Minimum Width W Rt. Bk.
1	Concrete Lined	0.39 6.15	12'	10.28	11.79'	47.37'	3.0'	14.79	14'	14'
2	Concrete Lined	6.15 13.79	10'	8.66'	10.08'	40.24'	1.6'	11.68'	14'	9'
3	Concrete Lined	13.79 18.81	10'	7.52'	8.75'	36.25'	1.6'	10.35'	14'	9'
4	Concrete Lined	18.81 27.52	7'	6.40	7.42'	29.26'	1.6'	9.02'	14'	9'
5	Concrete Lined	27.52 32.33	5'	5.30'	6.00'	23.00'	1.6'	7.60'	14'	9'

Lined Sect. No.	HYDRAULIC PROPERTIES A	V	h_v	Q	r	n	s
1	281.9	3.39	.178	956	5.74	.014	.00010
2	199.09	3.69	.211	735	4.83	.014	.00015
3	160.03	3.44	.184	550	4.31	.014	.00015
4	106.24	3.01	.141	320	3.53	.014	.00015
5	68.65	2.62	.107	180	2.85	.014	.00015

Spec. #	Mi. to Mi.
DC 4555	00 to 6.19
DC 4733	6.19 to 18.82
DC 4881	18.82 to 27.52
DC 4986	27.52 to 32.58



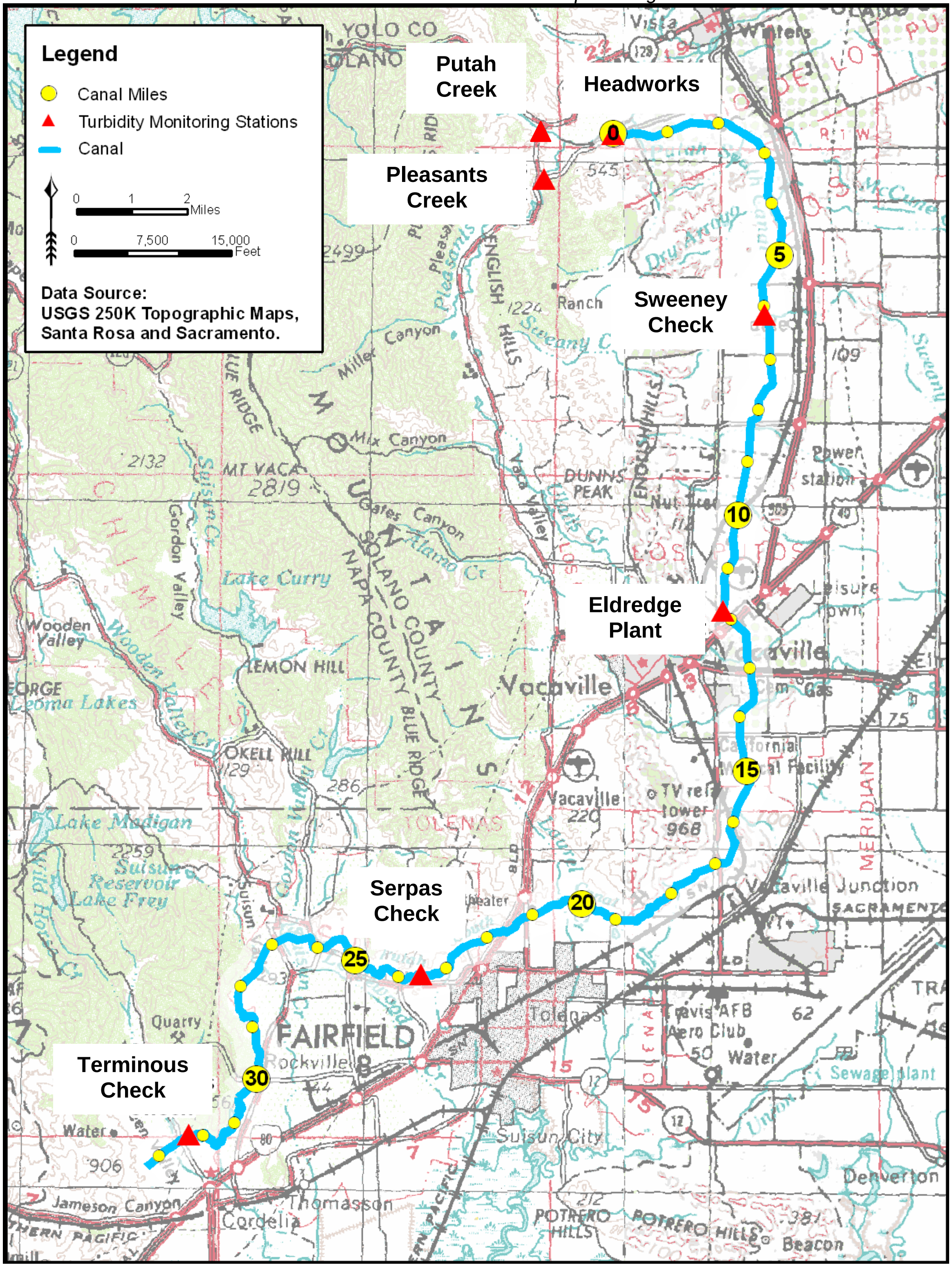


Figure 1.1. Map of Putah South Canal, Solano County, California.

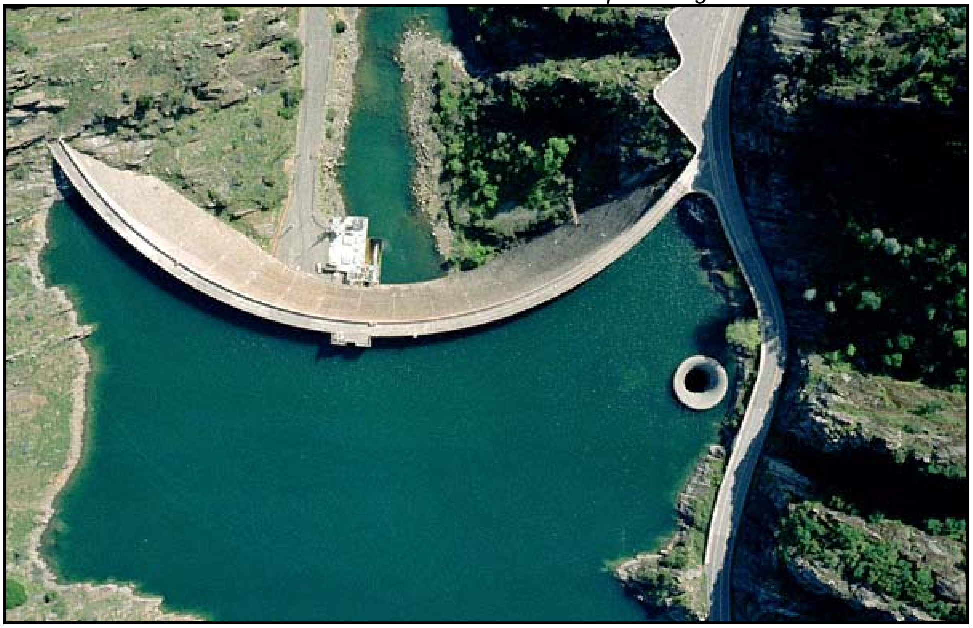


Figure 1.2. Monticello Dam and Lake Berryessa. Photo from http://www.scwa2.com.

Figure 1.3. Putah Diversion Dam, Solano Lake, and Putah South Canal inlet structure. Photo from http://www.scwa2.com. Note sediment deposits in Lake Solano near canal inlet.

Figure 1.4. Downstream face of Putah Diversion Dam. Flow left to right. Photo of September 19, 2006.

Figure 1.5. Headworks structure at inlet to Putah South Canal. View upstream. Note sediment and algae deposited on fish/trash screen. Photo of September 19, 2006.

Figure 1.6. Tainter gates at inlet to Putah South Canal. Photo of September 19, 2006.

Figure 1.7. Putah South Canal, Sweeney Check. View upstream.
Photo of December 27, 2006.

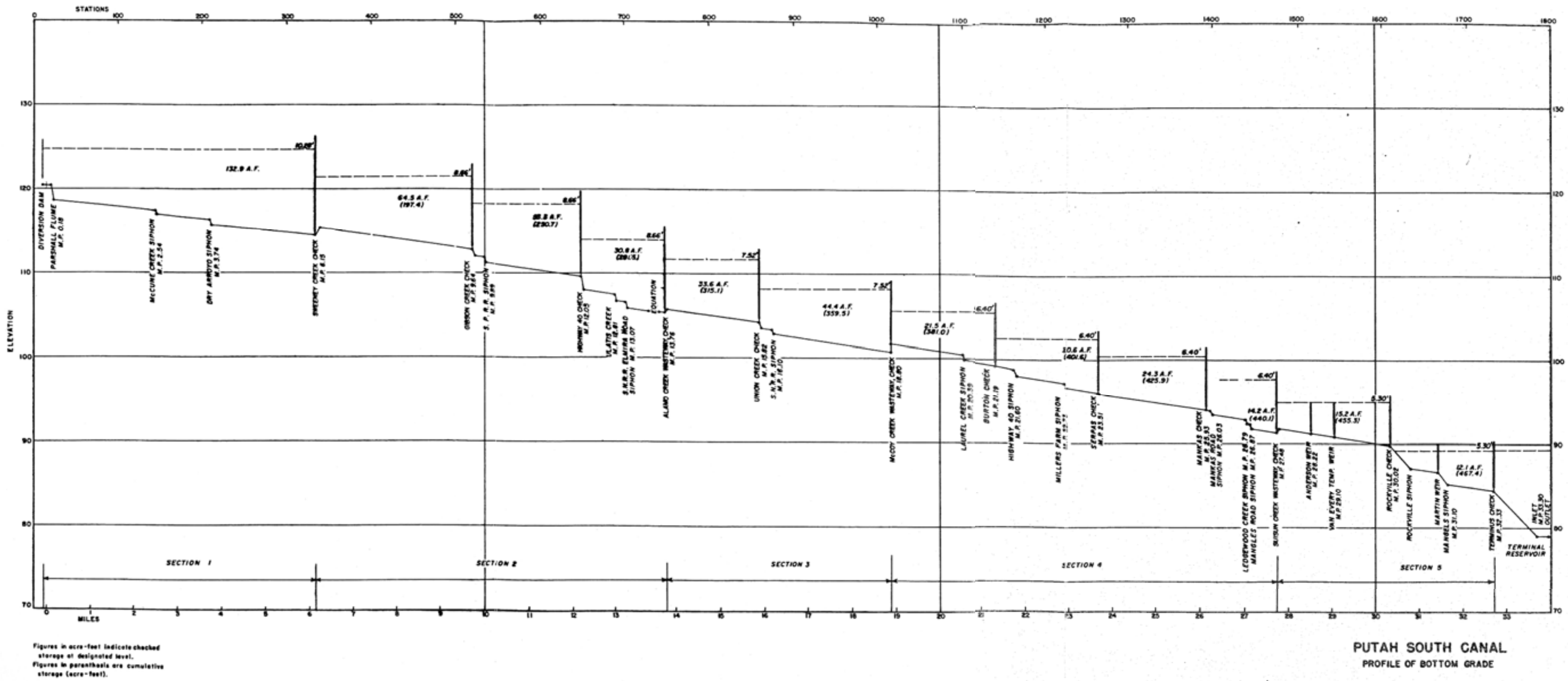


Figure 1.8. Longitudinal profile of Putah South Canal (provided by SCWA).

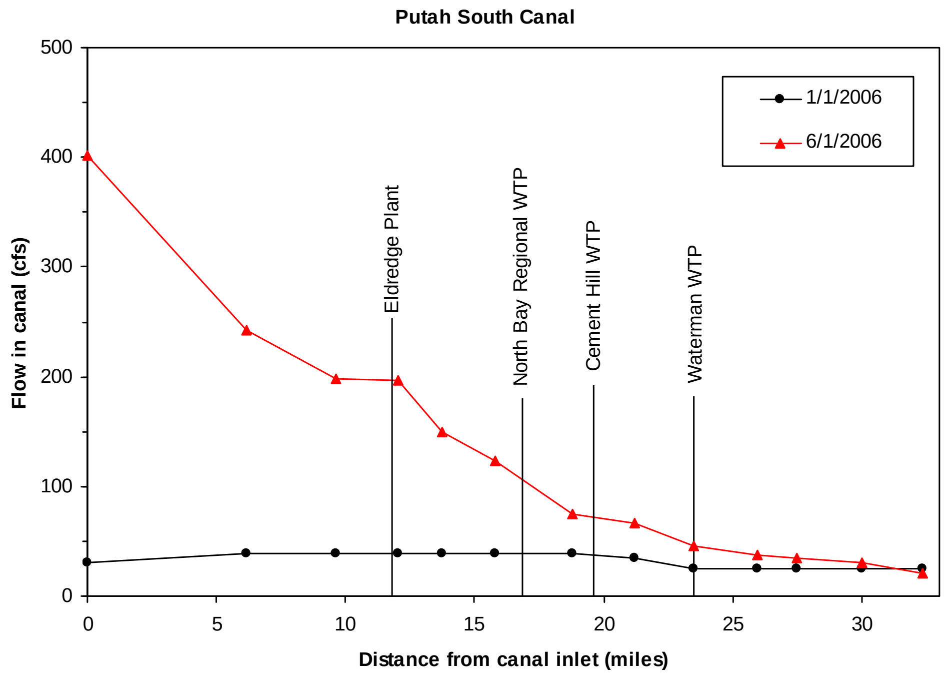


Figure 1.9. Longitudinal distribution of winter and summer flows in Putah South Canal (SID data for water year 2006).

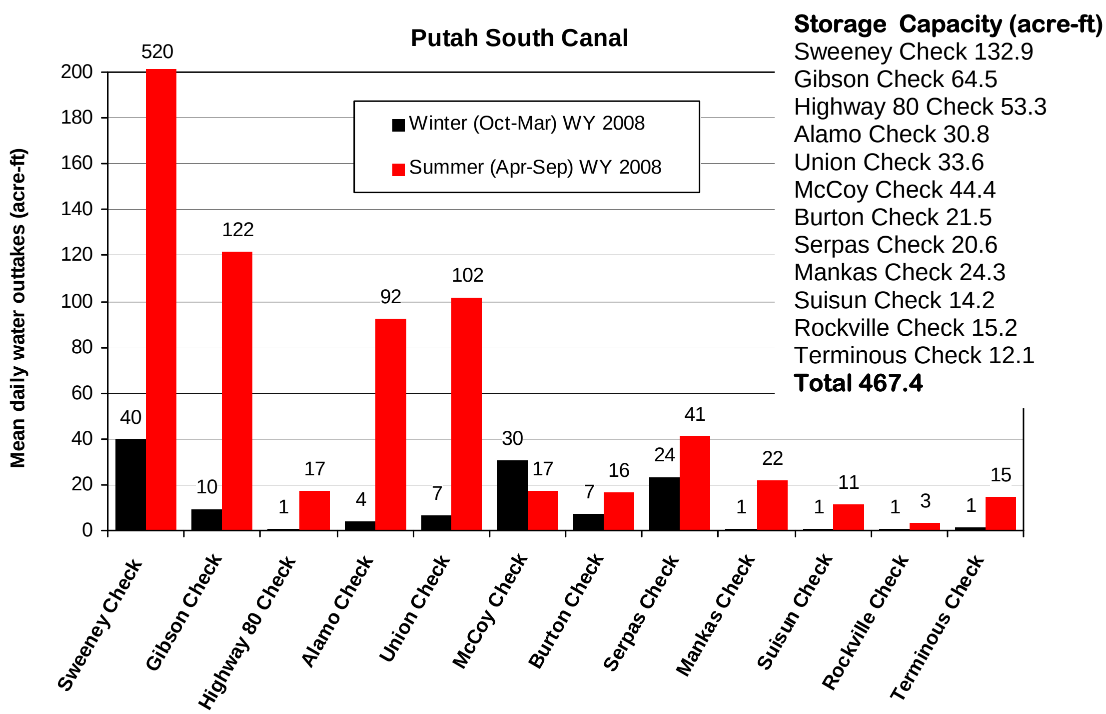


Figure 1.10. Mean daily winter and summer water outtakes from Putah South Canal (SID data for water year 2008) and design storage capacity for each check.

Figure 1.11. Sediment deposits in delta of Pleasants Creek in 1995.
Photo from NHC (1998) report.

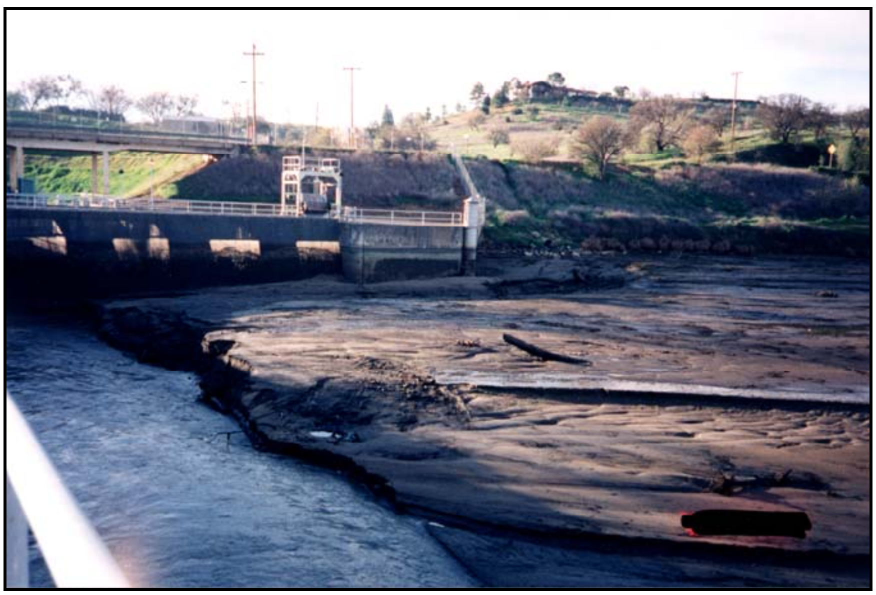


Figure 1.12. Sediment deposits in Lake Solano at entrance to Putah South Canal.
Photo of February 26, 1997 (from NHC 1998 report).

Figure 1.13. Sediment removal at inlet of Putah South Canal on February 7, 1995 (photo from NHC 1998 report).

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2. PUTAH SOUTH CANAL CLEANOUT MONITORING

2.1. Objectives and Methods

The purposes of the canal cleanout monitoring were to observe sediment removal and cleaning operations, document depositional patterns and local sources of sediments, and identify regions with the most severe deposits. Additional purposes were to document the spatial extent of aquatic weeds, measure approximate thickness and volumes of sediment deposits before and after the cleanout, relate location of deposits to canal hydraulics, sample bed material deposits along the canal, determine grain-size composition and organic content of the sediment deposits, and determine the material's physical characteristics (density, moisture content). Measured pre- and post-cleanout volumes of sediment deposits in the Putah South Canal (PSC) are essential components used in the assessment of annual sediment budget of the canal.

Cleanout of the PSC is conducted once a year during fall periods (when water demand is reduced) before the start of the winter rainy season. Essentially, the canal is drained and deposited sediment, organic detritus and debris are mechanically removed reach by reach. Cleanout methods include removal of sediment using front loaders and bobcats (Figures 2.1 and 2.2), removal of weeds and sediment using an excavator (Figure 2.3), pushing sediment down the canal using a tractor (Figure 2.4), and manual removal of deposits from water intakes (Figure 2.5). Canal maintenance also includes repair of failed canal panels and collapsed earthen banks (Figure 2.6).

Monitoring of the canal de-watering and cleanout was conducted during the fall of 2006, 2007, and 2008. Sampling and probing of in-canal sediment deposits and assessments of sediment coverage were conducted at each marked milepost, as well as at major flow control structures, water intakes, and locations of significant sediment deposits. All the measurements were conducted before the sediments and weeds were removed from the canal. The spatial extent of aquatic weed coverage in the canal was estimated visually. In addition, the average thickness of the weed layer on the bottom was approximated either by probing or visual inspection during the 2008 cleanout observations to roughly estimate volume of weed growth in the canal.

To document canal conditions after the cleanout was completed, post-cleanout measurements of residual sediment deposits in the canal were conducted after the 2006, 2007, and 2008 cleanouts and before the start of the winter rainy season. The measurements were conducted by probing the thickness of residual sediment deposits from bridges, culvert crossings, and canal banks, and visually assessing the amount of aquatic vegetation in the canal. Thickness of the weed layer was visually estimated during the 2008 post-cleanout observations.

The measured pre- and post-cleanout sediment thickness data were used to calculate approximate volumes of sediment accumulated in the canal. Because of the highly non-uniform distribution and floc-like character of sediment deposits, the calculated sediment volumes presented in this report should be regarded as approximate, order of magnitude estimates. An attempt was made to roughly determine the volume of aquatic weed materials in the canal using the 2008 cleanout monitoring data. This volume is also an order of magnitude estimate.

The main results from the 2006, 2007, and 2008 cleanout monitoring are summarized below.

2.2. 2006 Cleanout Monitoring Results

Sediment deposition in the canal was affected by the extremely wet 2005/2006 winter, with record high rainfall and runoff that occurred throughout Solano County. Widespread overbank flooding occurred along the canal during the December 31, 2005 storm event. As a result, unusually high volumes of sediment were deposited in the canal.

Monitoring of the canal de-watering and cleanout was conducted from October 18 to November 9, 2006. Selected ground photographs of the drained canal taken during the 2006 cleanout are shown in Figures 2.7-2.21. Altogether, 50 samples of bed material deposits were collected from the canal in 2006, of which 10 representative samples were selected and analyzed in a laboratory. A photograph of a bed material sample before and after drying is shown in Figure 2.22. The remaining samples collected from the canal provided visual estimates of the composition of the bottom deposit found in different locations and settings along the canal. Post-cleanout measurements of residual sediment deposits in the canal were conducted on January 24 and 25, 2007.

Longitudinal variations of the average thickness of sediment deposits and weed growth patterns prior to and after the fall 2006 cleanout are shown in Figures 2.23 and 2.24, respectively. Estimated volumes of sediment deposits in each check prior to and after the 2006 cleanout are shown in Figure 2.25. Locations of sediment samples collected during the cleanout observations are shown in Figure 2.23. Longitudinal variations of silt and clay content, organic content, and dry density of sediment deposits sampled during the fall of 2006 are shown in Figure 2.26.

The canal cleanout monitoring revealed a highly non-uniform pattern of sediment deposits and aquatic vegetation in the canal. Sediment deposition in the canal is site-specific and depends on local source contributions and local hydraulic conditions in each check and on how well the check was cleaned during the previous fall cleanout. According to the 2006 cleanout observations, upstream reaches of the checks in general appeared to be relatively clean (Figures 2.7-2.10). Fine sediments tended to accumulate in backwater areas, particularly in the downstream reaches of the checks, immediately upstream of flow control structures, inside water intakes, and on the inside of canal bends (Figures 2.11-2.14). In the vicinity of a few long siphons (with inlets located at mileposts, or MP, 21.60, 30.02, and 31.10), sediments were washed away from inlet reaches and deposited at outlets of the siphons (Figure 2.15). Significant amounts of sediments were derived from local bank failures during heavy rains (Figures 2.16-2.18). Sediments were also supplied into the canal with lateral inflow from local open drainages from small catchments, particularly in the Rockville Check (Figure 2.19).

The amount of sediment deposited in the canal generally increased in the downstream direction (Figures 2.23). Maximum thickness of sediment deposits increased from around 4-8 inches in the upstream checks to 6-18 inches in the downstream checks of the canal. The thickest deposition of about 2 ft was observed in the lower portion of the Union Check at MP 15.80. Estimated pre-cleanout volumes of sediment deposits ranged from approximately 300 yd^3 in the Alamo Check to over 2,000 yd^3 in the Sweeney Check (Figure 2.25). Total volume of deposits in the entire canal prior to the fall 2006 cleanout was estimated to be on the order of 13,000 yd^3. According to Solano Project operators, the uppermost three checks were not cleaned in the fall of 2005. Therefore, sediments measured in these checks in the fall of 2006 had accumulated over a two-year period, while in all the other checks sediments were accumulated over one-year period.

Sediment deposits in the PSC mostly consist of silt, clay, and organic matter (Figure 2.26). These fine sediments are easily suspended when disturbed, which makes cleaning of the canal very difficult. Coarse-grained sediment (sand and gravel) are supplied into the canal mainly from bank failures and from open local drainages. According to the data measured in the fall of 2006, content of silt and clay in sediment deposits increased in the downstream direction from approximately 40-60% in the uppermost checks to 80-100% in the lower portion of the canal. Dry density of sediments reduces from 31-68 lb/ft^3 in the upper part to 14-23 lb/ft^3 in lower portions of the canal. The average dry density of in-canal deposits was 27 lb/ft^3. Organic content ranged from 4% to 13% and generally increased in the downstream direction. The measured organic content refers to sediments and does not include weeds growing in abundance on top of sediment deposits.

Deposition of fine sediments in the canal promotes growth of aquatic weeds (Figures 2.20-2.21). The growth of aquatic weeds, in turn, captures more fine sediment and promotes more sediment deposition. In the fall of 2006, the distribution of weeds in the canal generally followed the sediment deposition pattern. There was an apparent direct correlation between fine sediment deposits and weed growth in the canal – the more the fine sediment, the more the weeds. Weed growth tended to increase in the downstream direction (Figure 2.23). At many locations, particularly upstream of flow control structures, aquatic weeds occupied the entire width of the canal.

The sediments observed in the canal in the fall of 2006 were mostly derived during the extremely intense storm event of December 31, 2005. During this rare event, overbank flow occurred in many locations along the canal, carrying large volumes of sediment into the canal from inundated agricultural fields and urban areas. Overbank flow eroded earthen banks and dumped significant amounts of sediment into some sections of the canal. Therefore, the depositional patterns and volumes of sediment accumulated in many reaches of the canal during 2005/2006 are not typical annual conditions and should be regarded as extreme. During average flow conditions, deposition in the canal is likely to be less significant.

Cleanout of the PSC conducted in the fall of 2006 removed most of the sediment deposits and weeds from the canal (Figure 2.24). The upstream half of the canal was clean and contained very little sediment and no aquatic weeds. However, some residual sediments and weeds were observed in the downstream reach of the canal (extending from the Burton Check to the

Terminous Check) after the cleanout was completed. The thickness of residual sediment deposits in the downstream reach was up to 4-7 inches. Residual deposits remaining in the canal were composed mostly of fine sediment (silt and clay), with some gravel particles scattered at outlets from open drainages in the Rockville Check. Most severe post-cleanout weed growth was observed in the Rockville and Terminous Checks, where aquatic weeds occupy most of the canal area.

Estimated volumes of residual sediment deposits left in the PSC after the 2006 cleanout ranged from zero or negligible in the upstream checks to approximately 600 yd^3 in the Terminous Check (Figure 2.25). The total volume of residual sediment remaining in the canal was estimated to be approximately 3,000 yd^3, which constituted around 23% of the initial (pre-cleanout) volume of sediment deposits.

2.3. 2007 Cleanout Monitoring Results

The 2006/2007 winter was very mild, with no significant rainfall events occurring in the study area. As a result, no canal overtopping occurred and significantly less sediment was deposited in the canal than occurred during the extremely wet 2005/2006 winter.

Monitoring of the canal cleanout was conducted from October 16 to November 15, 2007. Selected ground photographs of the drained canal taken during the 2007 cleanout are shown in Figures 2.27-2.34. Altogether, 15 samples of bed material deposits were collected from the canal in 2007 to provide visual estimates of the composition of the sediment deposits in the canal. Post-cleanout measurements of residual sediment deposits in the canal were conducted on December 12, 2007 and covered the canal from the Headworks to Suisun Valley Road (just upstream of the Suisun Check). Due to an early arrival of the rains during the third week in December 2007, the remaining post-cleanout amounts of sediment and vegetation in the reach extending downstream of MP 26.87 were assumed to be similar to that in the adjacent monitored reach.

Longitudinal variations of sediment thickness and weed growth in the canal prior to and after the fall 2007 cleanout are shown in Figures 2.35 and 2.36, respectively. Locations of sediment samples collected during the 2007 cleanout observations are shown in Figure 2.35. Estimated volumes of sediment deposits in each check prior to and after the 2007 cleanout are shown in Figure 2.37.

Much less sediment was deposited in the canal in 2007 than in 2006. The sediment deposition pattern was highly non-uniform, showing a slightly increasing trend in the downstream direction. Maximum thickness of sediment deposits was around 4-12 inches in the upstream checks and between 2-24 inches in the downstream checks of the canal. The thickest deposits of 2 ft were observed in the downstream portion of the Suisun Check at MP 27.32 and in the middle portion of the Rockville Check at MP 28.40. Fine sediment generally accumulated in backwater areas, at water intakes, and in the vicinity of flow control structures. In the upstream checks (Sweeney, Gibson, and Highway 80), long stretches of relatively clean canal were followed by large accumulations of fine sediments, organic material, and weeds. In the downstream checks, sediment layers were more uniformly distributed along the canal and were often observed as thin layers of sediment located underneath accumulated organic material and dense weeds. Many of the large deposits found in the canal were comprised of black, highly organic, easily suspendable floc-like mud, overgrown by dense aquatic vegetation. This was especially noticeable in the McCoy, Serpas, and Suisun Checks. Many of the sediment spikes shown in Figure 2.35 in the lower checks were due to these large deposits of the organic mud and vegetation. Sediment thicknesses were observed to be considerably less in the Mankas, Rockville, and Terminous Checks; however, canal bottoms were commonly observed to be completely covered with aquatic vegetation in these areas.

In the fall of 2007, estimated pre-cleanout sediment volumes ranged from approximately 100 yd^3 in the Terminous Check to almost 700 yd^3 in the Sweeney Check (Figure 2.37). Total 2007 pre-cleanout volume of sediment deposits in the entire canal was estimated at approximately 4,000 yd^3, which was roughly one third of the volume observed prior to the 2006 cleanout (Figure 2.38). The 2006/2007 winter was very mild and, as a result, little sediment was deposited in the canal. A significant portion of the sediment observed in the canal in the fall of 2007 was derived from the residual deposits left in the canal after the 2006 cleanout. The volume of sediment measured in the fall of 2007 is likely to be below the average.

While observing that a significantly smaller amount of sediment had deposited in the PSC in 2007, the amount of weeds in the canal had noticeably increased compared to 2006 (compare Figures 2.23 and 2.35). For example, relatively low weed growth was observed in the Alamo and Union Checks in 2006. However, in 2007 much of the canal in these areas was completely covered with aquatic weeds. Apparently aquatic vegetation growth depends not only on sediment deposition, but also on some other factors such as water temperature, light, flow velocity, and vegetation supply from Lake Solano. Weed growth generally increased in the downstream direction of the canal as water depths and flow velocity decreased and water temperature increased.

Cleanout of the PSC conducted in the fall of 2007 removed most of the sediment deposits and weeds from the canal (Figure 2.36). The upstream half of the canal was observed to be relatively clean containing very little or no sediment and no aquatic weeds. However, along most of the canal, difficult to remove algae attached to the side walls was left relatively intact following cleanout. Some residual sediments and weeds remained in the downstream reaches of the canal extending from the Burton Check to the Terminous Check. The observed thickness of residual sediment deposits in the downstream reach was up to 0.5-1 inches. The total residual volume of sediment left in the canal after the fall 2007 cleanout was estimated at approximately 500 yd^3 (or about 13% of the pre-cleanout volume).

2.4. 2008 Cleanout Monitoring Results

The 2007/2008 winter was moderately wet year, yet the results were skewed by an extreme storm event on January 4, 2008. Nevertheless, the results obtained for WY 2008 are believed to be more representative of average rainfall and runoff conditions in the study area. Overbank flooding occurred along the upper reaches of the canal during the extremely intense localized January 4, 2008, storm event. This resulted in significant sediment inflow into the PSC from Lake Solano and from lateral sources.

Monitoring of the canal cleanout was conducted from October 17 to November 6, 2008. Selected ground photographs of the canal taken during the 2008 cleanout are shown in Figures 2.38-2.56. No sediment samples were collected from the canal this time. Post-cleanout measurements of residual sediment deposits in the canal were conducted on November 20 and 26, 2008.

Longitudinal variations of average thickness of sediment deposits and weed growth prior to and after the fall 2008 cleanout are shown in Figures 2.57 and 2.58, respectively. Estimated volumes of sediment deposits in each check prior to and after the 2008 cleanout are shown in Figure 2.59. Estimated 2006, 2007, and 2008 pre-cleanout sediment volumes are compared in Figure 2.60. Approximately estimated volumes of weeds prior to and after the 2008 cleanout are shown in Figure 2.61.

As in previous years, sediment deposition observed during the 2008 cleanout monitoring showed a highly non-uniform deposition pattern that generally increased in thickness in the downstream direction (Figure 2.57). Fine sediment (silt and clay) tended to accumulate in backwater reaches with slower moving water upstream of flow control structures and at some bridges (Figure 2.47), shaded areas inside intake structures (Figures 2.50, 2.51, and 2.54), areas of flow separation on the inside of canal bends (Figure 2.51) and flow divergence downstream of siphons and narrow gates (Figure 2.45), and in depressions in the bottom of the canal located in the lower sections of the Sweeney, Alamo, McCoy, and Suisun Checks (Figures 2.46, 2.49, and 2.53). Coarse sediments (sand and gravel) were mainly observed at locations of bank failure (Figures 2.38, 2.42, and 2.43) and at open outfall drainages (Figure 2.55). Significant amounts of sediment deposits were found in the Sweeney Check at MP 2.56 (McCune Creek Crossing, Figure 2.39) and at MP 5.65 (Figure 2.42) and in the Gibson Check at MP 6.21 (Figure 2.43), where intense bank erosion was caused by spilling overbank flows during a very intense storm of January 4, 2008. Piles of sediment at these locations were up to 2-3 ft high. Also, significant sediment accumulations (up to 9-13 inches thick) were observed in the Sweeney Check at the entrance to Weyand Canal at MP 5.62 (Figure 2.41), in the Alamo Check in the vicinity of MP 13 (Figure 2.46), in the McCoy Check between MP 18 and MP 19, in the Suisun Check in the vicinity of MP 27 (Figure 2.53), and in the Terminous Check between MP 31 and MP 32 (Figure 2.56). Thickness of mud deposits inside intake structures was up to 2-4 ft (e.g. in the Sweeney Check at MP 2.00, in the Burton Check at MP 19.37 and MP 21.11, and in the Suisun Check at MP 27.48 – see Figures 2.50 and 2.54).

Estimated pre-cleanout volumes of sediment deposits ranged from less than 100 yd^3 in the Mankas Check to almost 2,000 yd^3 in the McCoy Check (Figure 2.59). Total pre-cleanout volume of sediment deposits in the canal was approximately 6,500 yd^3. This amount is less than the total volume of 13,000 yd^3 measured in the fall of 2006 (after an extraordinarily wet year), but higher than the volume of 4,000 yd^3 measured in the fall of 2007 (after an unusually dry year). The 2007/2008 winter was moderately wet, with a few intense storm events, and therefore the volume of sediment accumulation measured in the canal in the fall of 2008 is likely to be more representative of average annual conditions than those measured in the previous two years. Comparison of pre-cleanout volumes measured in each check in 2006, 2007, and 2008 (Figure 2.60) shows no systematic pattern of sediment deposits along the canal. Sediment deposition in individual checks depends on a variety of factors including sediment inflow from upstream reaches, local rainfall intensity and duration, local runoff, occurrence of overbank flows, local source contributions, and how well the check was cleaned during the previous fall cleanout.

In 2008, weed growth was observed in most checks. However, the aerial distribution and amount of aquatic vegetation had highly non-uniform patterns (Figure 2.57). The most severe weed growth was observed in the lower portions of the Alamo, McCoy, and especially Terminous Checks (Figures 2.46, 2.48, and 2.56). In general, weed growth followed the sediment deposition pattern. However, in some reaches despite the occurrence of significant sediment deposits, weeds growth was low (e.g. in the Suisun and Rockville Checks). This could be related to the grain size of bottom sediments and other conditions affecting weed growth. The estimated pre-cleanout volumes of weeds ranged from less than 5 yd^3 in the Mankas and Suisun Checks to over 400 yd^3 in the Alamo and McCoy Checks (Figure 2.61). The total volume of weeds in the canal was approximately 2,000 yd^3. The total weed volume was about 30% of the total volume of sediment deposits in the canal. This indicates that aquatic weed growth is a significant factor affecting canal capacity, as well as water quality.

The 2008 cleanout removed most of the sediment deposits and weeds from the upper reaches of the canal (Figure 2.58). However, some difficult to remove fine sediments and weeds remained after the cleanout in the middle and downstream reaches of the canal, particularly in the lower sections of the McCoy, Suisun, and Terminous Checks. The measured thickness of residual sediment deposits was up to 2-4 inches in the McCoy Check, up to 3-6 inches in the Suisun Check, and up to 8-12 inches in the Terminous Check. The total volume of residual sediment was approximately 2,000 yd^3 (or about 31% of the pre-cleanout volume of sediment deposits). Residual weeds were observed mainly in the McCoy and Terminous Checks. The fraction of the canal bottom covered with residual weeds in these two checks was up to 20% and 80%, respectively. The estimated total volume of residual weeds remaining in the canal was on the order of 100 yd^3.

2.5. Summary of Cleanout Monitoring Results

Canal cleanout monitoring conducted in 2006, 2007, and 2008 revealed that not only is there a significant on-going sedimentation problem in the PSC, but a significant vegetation problem as well. Furthermore, it is likely that sediment and vegetation issues are closely related to each other. Sediments are supplied into the canal from Lake Solano and from local sources including local runoff, open lateral drainages, and bank failures. Due to the low currents in the canal and due to the presence of many flow control structures, inflowing suspended sediments (silt and clay) gradually deposit on the bottom as flow moves along the canal. Coarse sediments (sand and gravel) normally deposit in the vicinity of the supply source (e.g. bank failure site or open drainage).

The sediment deposition pattern in the canal is highly non-uniform and depends on local hydraulic conditions in each check, local sources of sediment and how well the check was cleaned during the previous fall cleanout. Sediments tend to accumulate in the backwater areas, particularly in the downstream reaches of the checks, upstream of flow control structures, inside water intakes, on the inside of canal bends, in depressions in the bottom of the canal, and at the outlets of siphons. The thickness of sediment layers on the bottom of the PSC generally increases in the downstream direction. The maximum measured thickness of fine sediment deposits was on the order of 2 ft in the canal and up to 2-4 ft inside intake structures. Maximum height of coarse sediment piles was approximately 3 ft.

Sediment deposits mostly consist of silt, clay, and organic matter. Occasional deposits of sand and gravel occur at bank failure sites, locations where gravel from road maintenance activities is cast or slips into the canal, and at outlets of local open drainages. Sedimentation processes in the PSC promotes aquatic weed and algae growth, which impacts water quality in the canal, especially during canal cleanouts. Growth of aquatic weeds also affects the location and depth of fine sediment deposition in the canal.

Total volumes of sediment deposits in the PSC immediately prior to the 2006, 2007, and 2008 cleanouts were approximately 13,000 yd^3, 4,000 yd^3, and 6,500 yd^3, respectively. Total residual volumes of sediment left in the canal after the 2006, 2007, and 2008 cleanouts were approximately 3,000 yd^3, 500 yd^3, and 2,000 yd^3, respectively. Residual sediments constituted on the order of 10-30% of the pre-cleanout sediment volumes. Because of the highly non-uniform distribution and floc-like character of some sediment deposits in the PSC, the estimated volumes of sediment deposits presented in this report should be regarded as approximate, order of magnitude estimates with possible errors as much as 20-30%.

The estimated total volume of sediment deposits calculated for 2006 and 2007 represent extreme, atypical conditions. The 2005/2006 winter was extremely wet, while the 2006/2007 winter was very mild, without significant rainfall events in the study area. As a result, significantly more sediment accumulated in the canal in 2006 compared to 2007. The 2007/2008 winter was moderately wet, with a few intense storm events, and was more representative of the average winter conditions. The long-term average sediment deposition in the canal is likely to be between the estimated 2006 and 2007 volumes and closer to the 2008 volume. Canal cleanout monitoring results provide an important basis for understanding the effects of different annual hydrologic conditions, various sediment sources, variable material characteristics and overall sedimentation processes occurring in the PSC.

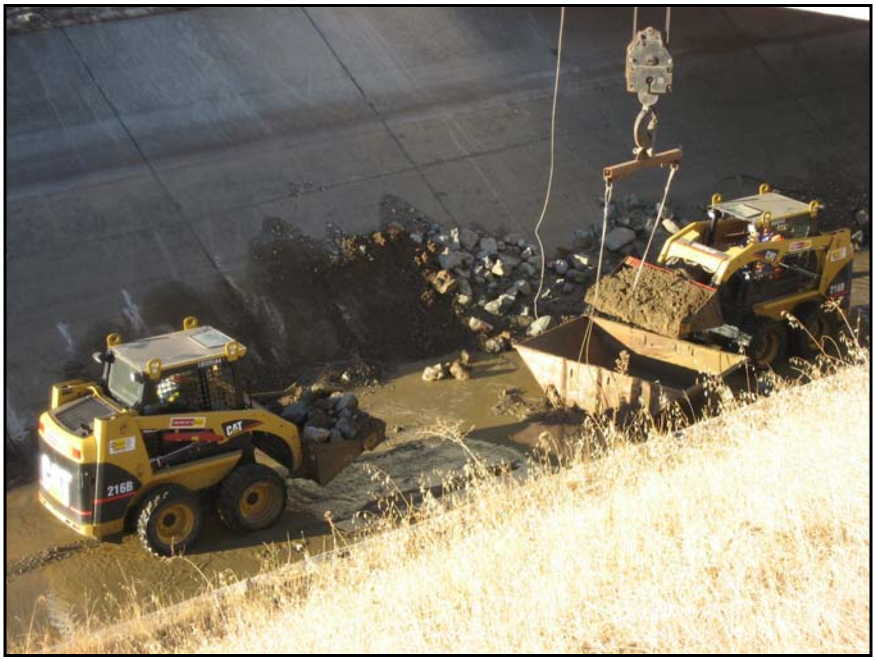

Figure 2.1. Removal of sediment from Sweeney Check at MP 0.5.
Photo of October 18, 2006.

Figure 2.2. Cleanout of Alamo Check at MP 12.84.
Photo of October 30, 2006.

Figure 2.3. Removal of weeds and sediment from Sweeney Check at MP 6.15.
View upstream. Photo of October 19, 2006.

Figure 2.4. Pushing sediment down Union Check at MP 14.80.
Photo of November 3, 2006.

Figure 2.5. Manual removal of sediment from intake in Suisun Check at MP 26.87. Flow right to left. Photo of October 31, 2006.

Figure 2.6. Repair of failed panels in Union Check at MP 14.0. Flow right to left. Photo of November 3, 2006.

Figure 2.7. Clean upstream reach of Sweeney Check at MP 0.36. View downstream. Photo of October 18, 2006.

Figure 2.8. Clean upstream reach of Gibson Check at MP 8.58. View downstream. Photo of October 19, 2006.

Figure 2.9. Clean upstream reach of Highway 80 Check at MP 10.23. View downstream. Note algae growing on canal sides. Photo of October 19, 2006.

Figure 2.10. Clean upstream reach of Serpas Check at MP 21.42. View downstream. Photo of November 9, 2006.

Figure 2.11. Mud and weeds in downstream portion of McCoy Check at MP 18.80. View upstream. Photo of November 6, 2006.

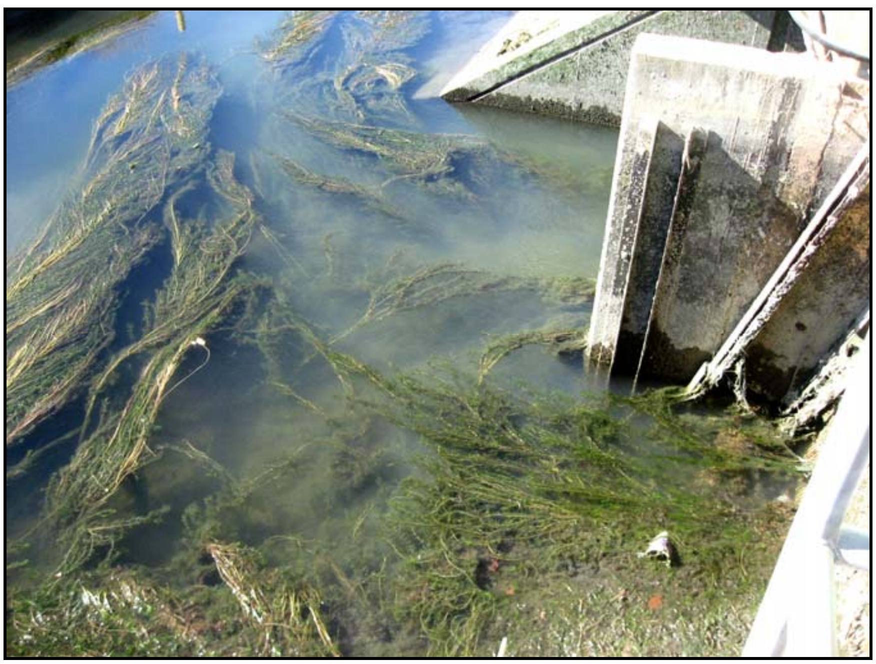

Figure 2.12. 2-ft thick deposit of mud and weeds in Serpas Check at Waterman Plant intake at MP 23.50. View downstream. Photo of November 9, 2006.

Figure 2.13. Mud deposits at intake in Suisun Check at MP 26.87. Flow right to left. Photo of October 31, 2006.

Figure 2.14. Mud and weeds at siphon in Terminous Check at MP 32.33. View downstream. Photo of November 1, 2006.

Figure 2.15. Sediment deposition at siphon outlet in Terminous Check at MP 31.29. Flow left to right. Photo of November 1, 2006.

Figure 2.16. Pile of sand/gravel from bank failure in Sweeney Check at MP 3.44. Flow right to left. Photo of October 18, 2006.

Figure 2.17. Failed earthen bank and canal panels in Union Check at MP 14.0.
Flow right to left. Photo of October 30, 2006.

Figure 2.18. Sediment from failed bank in Terminous Check at MP 31.0. Flow left to right.
Photo of November 1, 2006.

Figure 2.19. Pile of sand and gravel from local open drainage in Rockville Check at MP 29.54.
Flow right to left. Photo of October 31, 2006.

Figure 2.20. Mud and weeds in downstream portion of Sweeney Check at MP 6.15.
Flow right to left. Photo of October 18, 2006.

Figure 2.21. Mud and weeds in downstream portion of Gibson Check at MP 9.46. Flow right to left. Photo of October 19, 2006.

Figure 2.22. Sediment from Putah South Canal before and after drying.

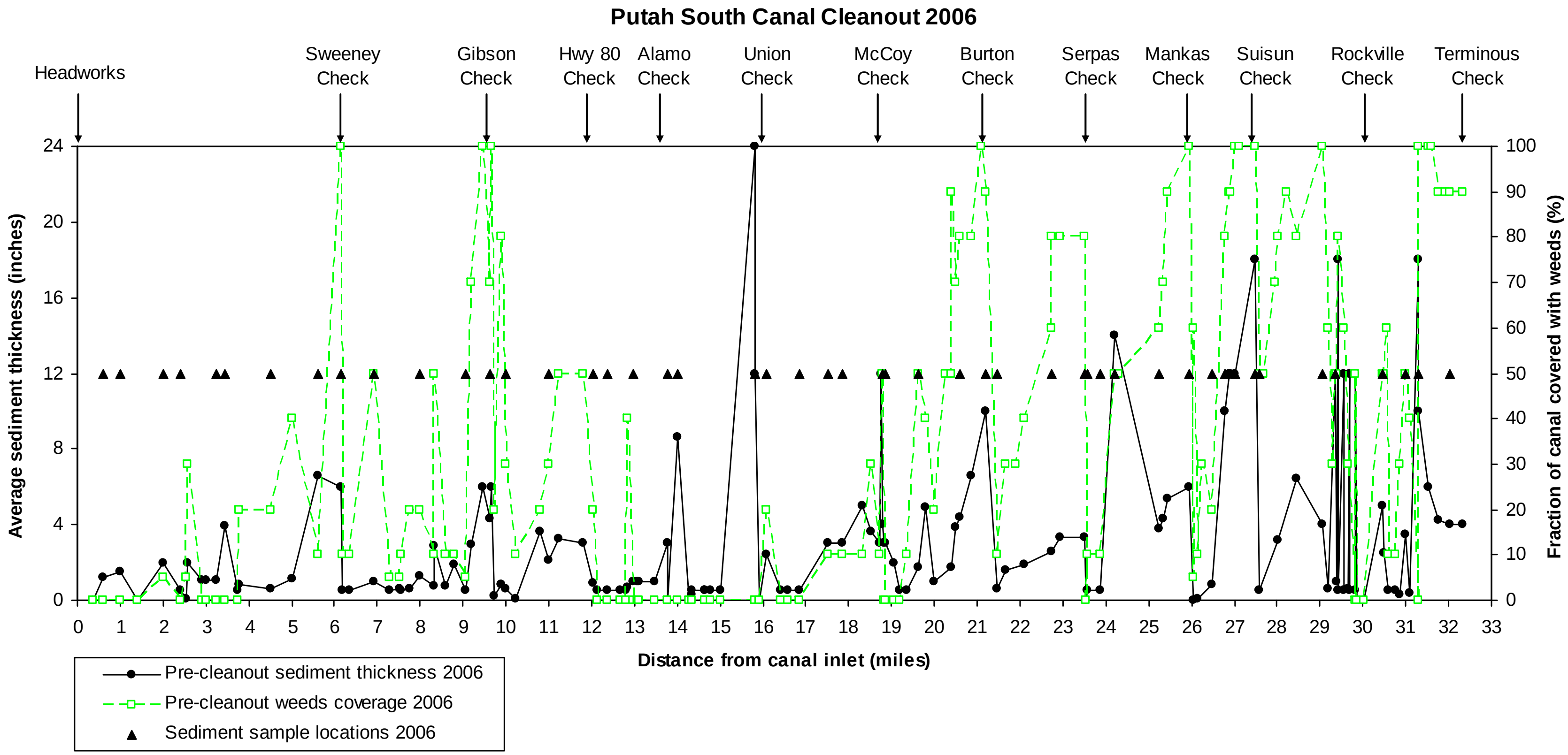

Figure 2.23. Longitudinal variations of average thickness of sediment deposits and weed growth prior to fall 2006 cleanout.

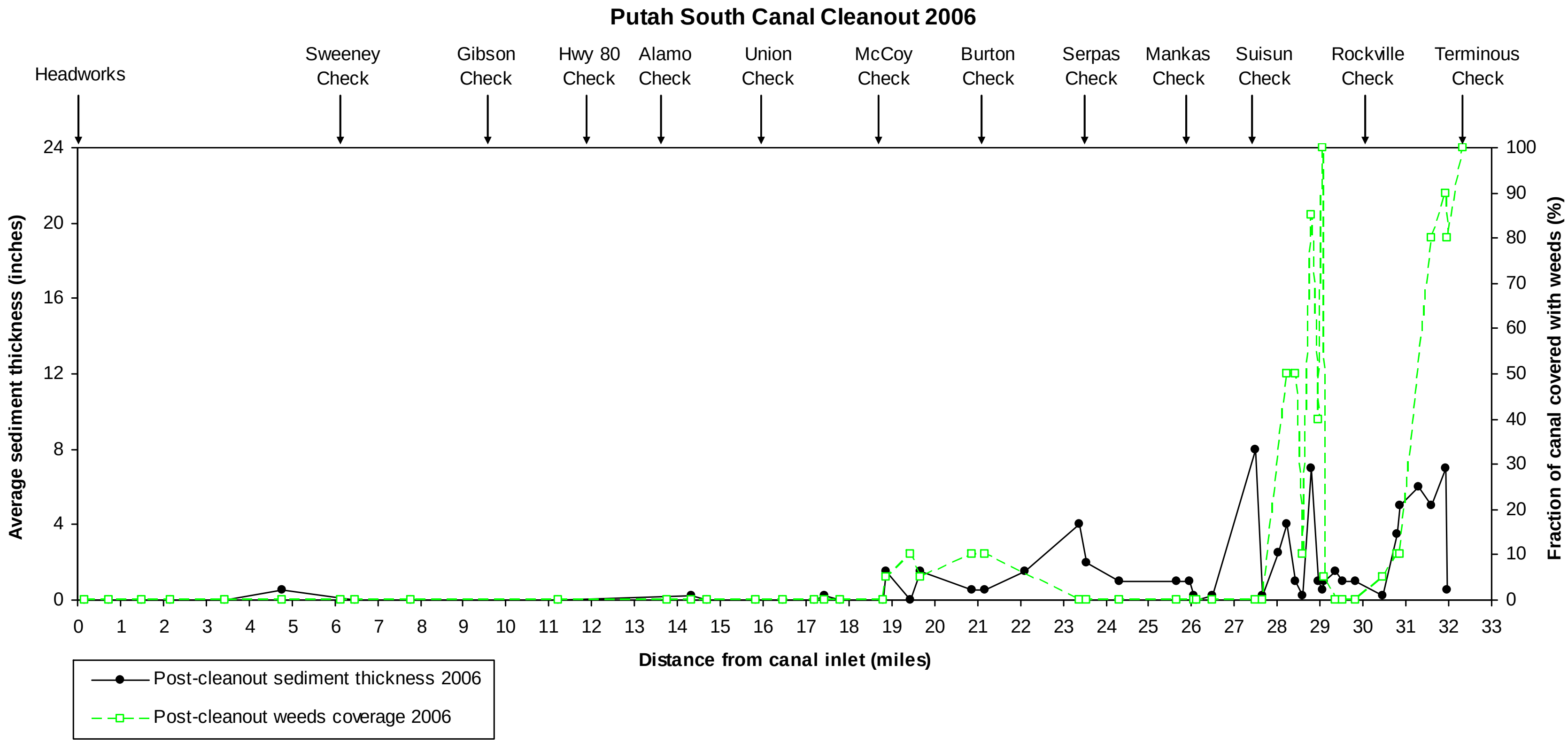

Figure 2.24. Longitudinal variations of thickness of residual sediment deposits and weed growth after fall 2006 cleanout.

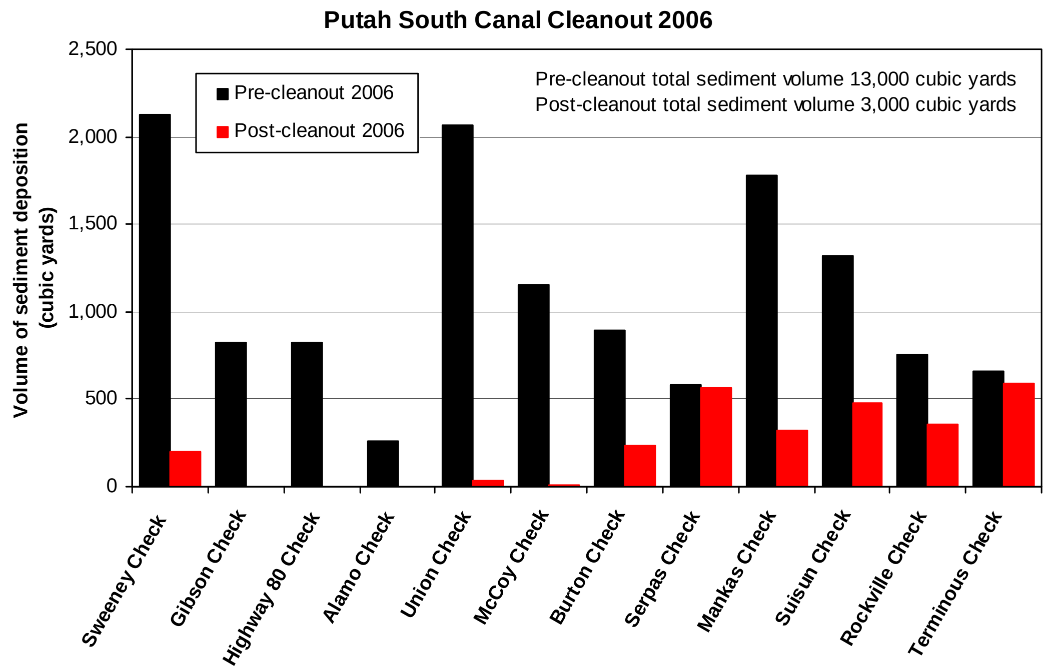

Figure 2.25. Estimated volumes of sediment deposits in each check before and after fall 2006 cleanout.

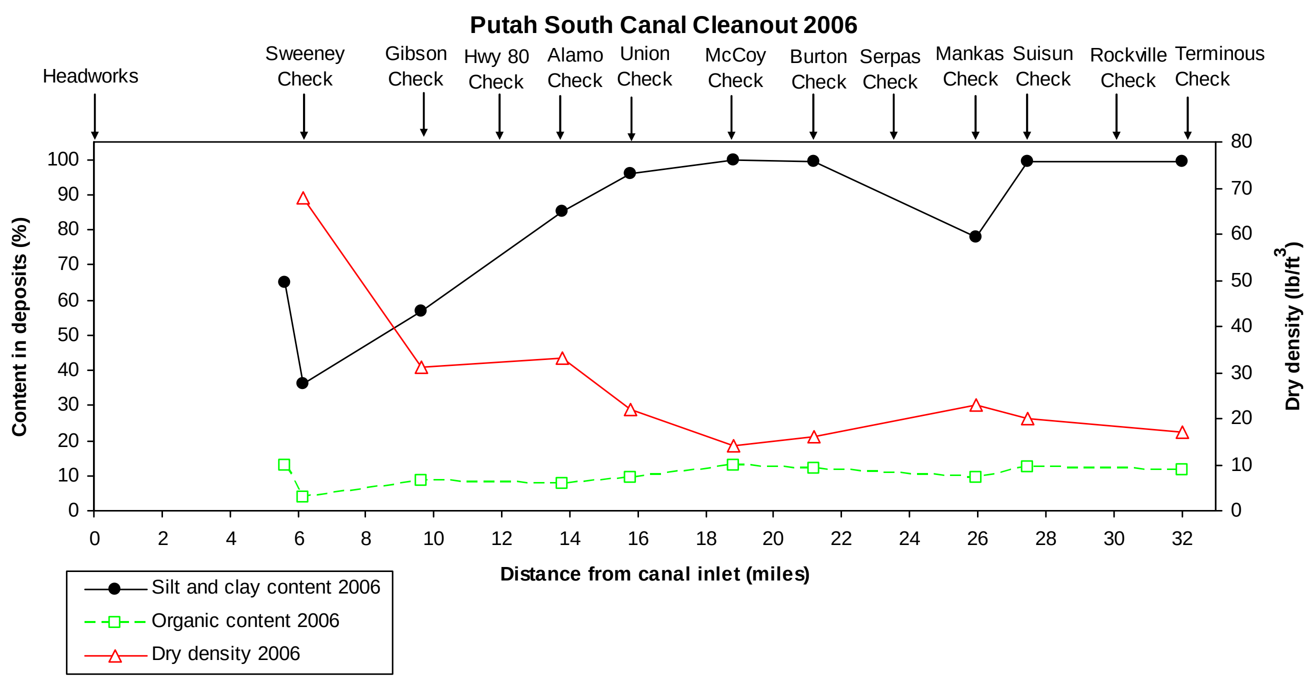

Figure 2.26. Longitudinal variation of bed material properties (according to measurements taken during fall 2006 cleanout).

Figure 2.27. Relatively clean canal bottom upstream of Gibson Check gate at MP 9.64.
Flow right to left. Photo of October 19, 2007.

Figure 2.28. Mud and weed accumulation in Highway 80 Check at MP 9.66.
View downstream. Photo of October 19, 2007.

Figure 2.29. Mud and weeds completely covering bottom in Highway 80 Check at MP 11.10. View downstream. Photo of October 23, 2007.

Figure 2.30. Clean canal bottom in Highway 80 Check at MP 11.57. Flow right to left. Photo of October 23, 2007.

Figure 2.31. Accumulation of mud and organic deposits at intake structure upstream of Alamo Check gate at MP 13.76. Flow left to right. Photo of October 29, 2007.

Figure 2.32. Weed growth in Mankas Check at MP 25.35. View upstream. Photo of October 22, 2007.

Figure 2.33. Large patch of mud and vegetation in Suisun Check at MP 28.45. Flow right to left. Photo of November 2, 2007.

Figure 2.34. Eroding road and embankment above canal in Gibson Check at approximately MP 9. View downstream. Photo of October 18, 2007.

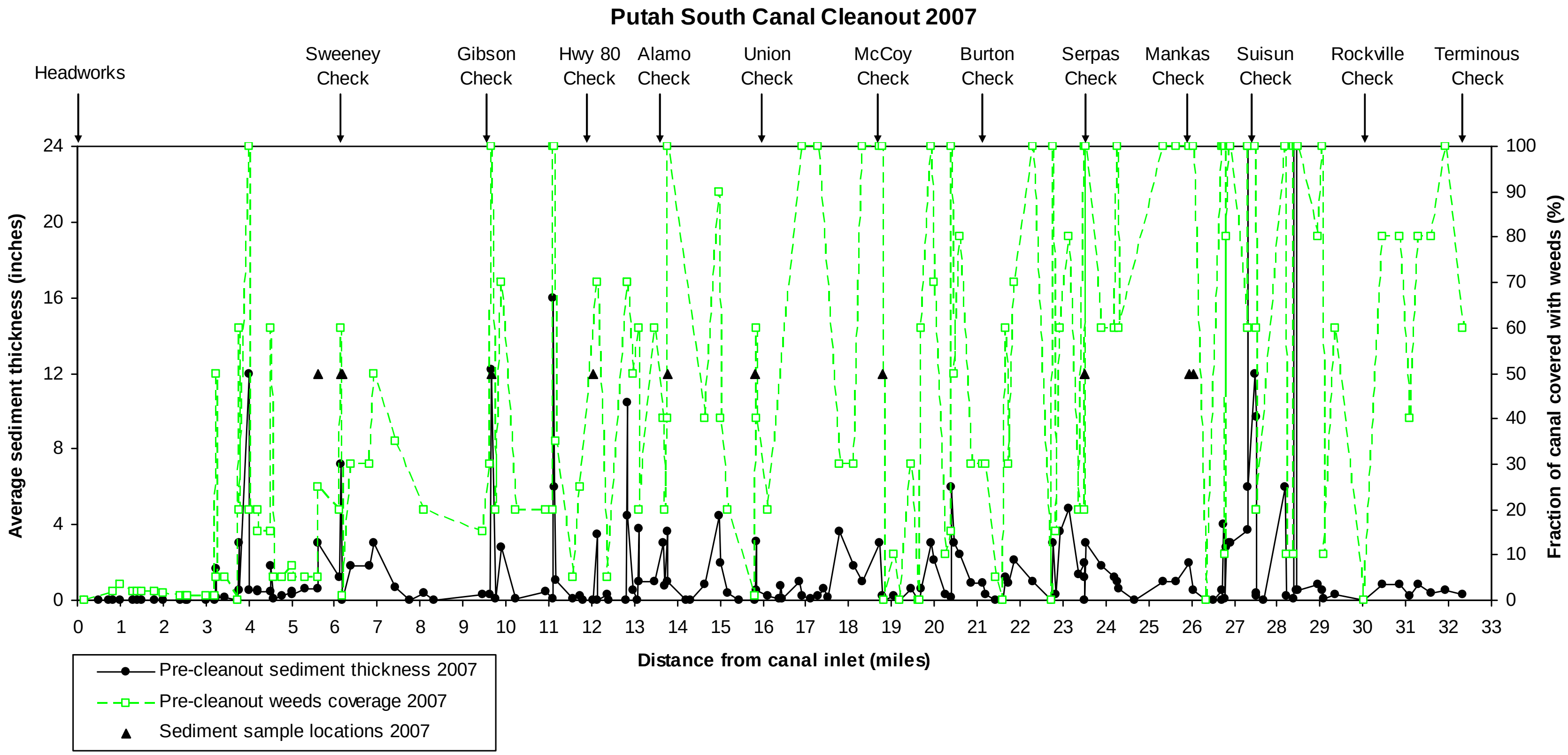

Figure 2.35. Longitudinal variations of average thickness of sediment deposits and weed growth prior to fall 2007 cleanout.

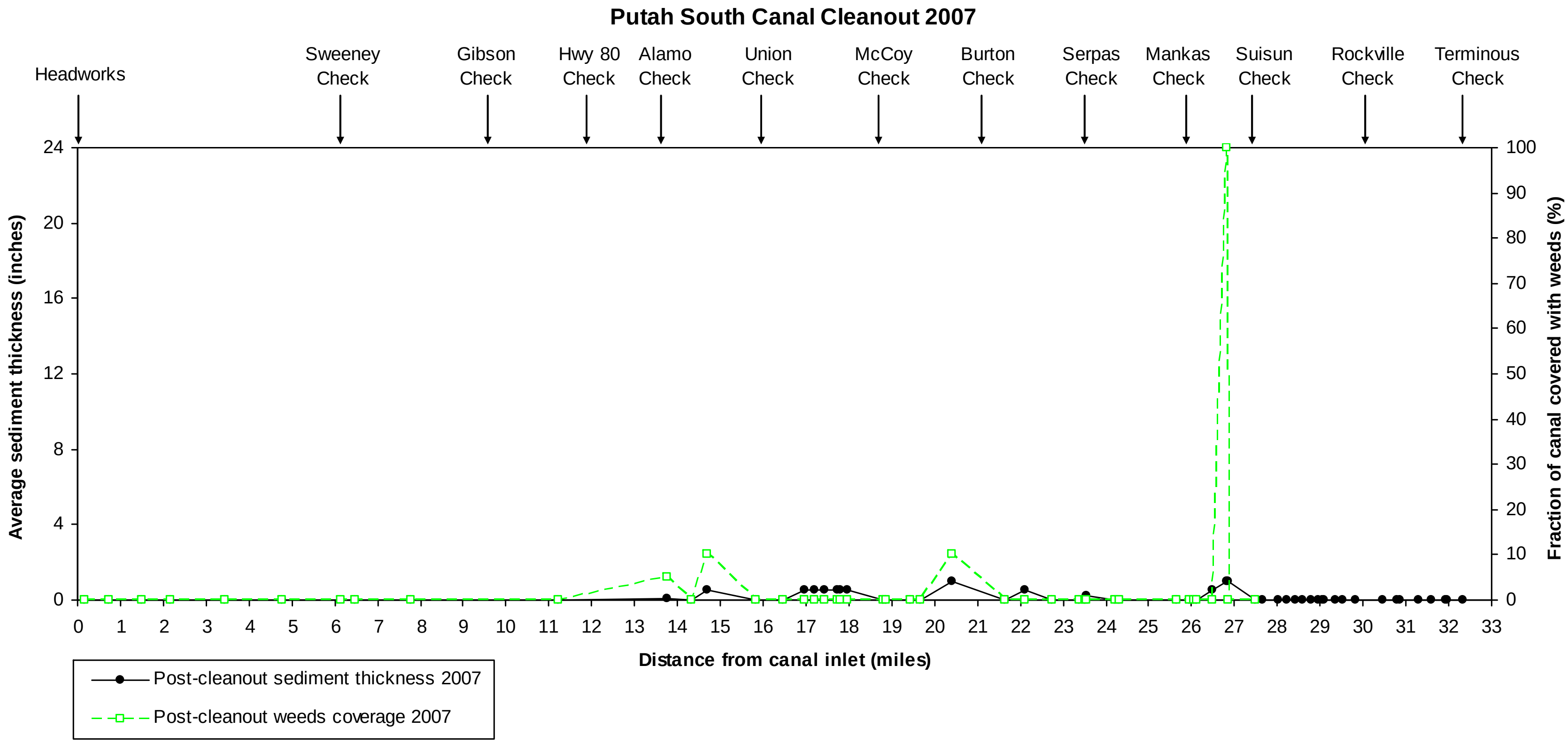

Figure 2.36. Longitudinal variations of thickness of residual sediment deposits and weed growth after fall 2007 cleanout.

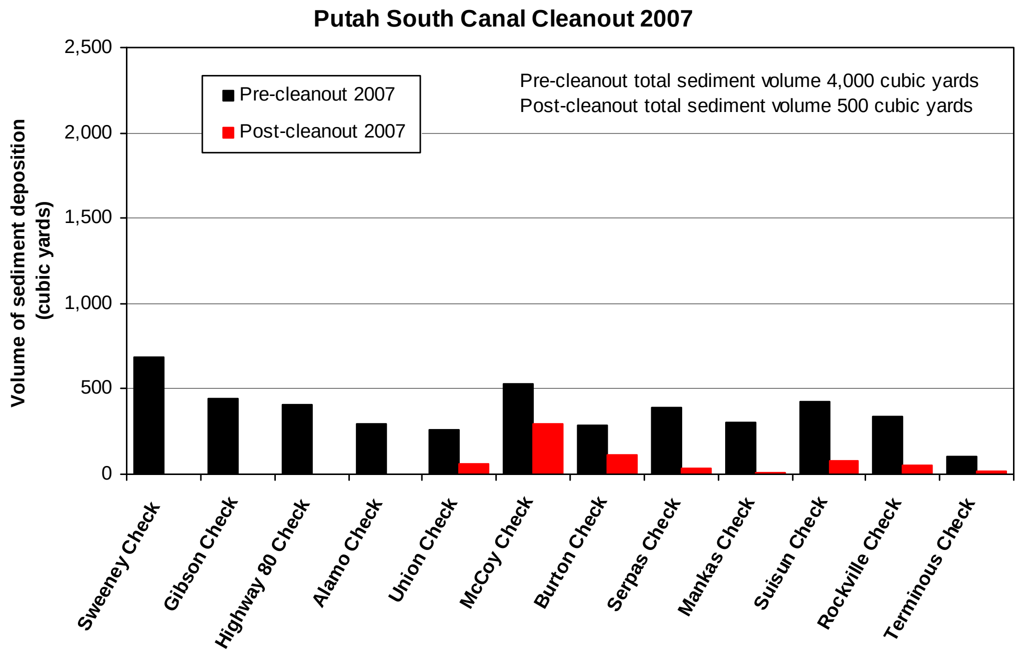

Figure 2.37. Estimated volumes of sediment deposits in each check before and after fall 2007 cleanout.

Figure 2.38. Pile of gravel from bank failure in Sweeney Check at MP 0.4. Flow left to right. Photo of October 17, 2008.

Figure 2.39. Eroded bank and damaged panels in Sweeney Check at McCune Creek Crossing at MP 0.47. View upstream. Photo of October 17, 2008.

Figure 2.40. Clean canal in Sweeney Check at MP 1.50. View upstream. Photo of October 17, 2008.

Figure 2.41. Sediment deposition in Sweeney Check at intake at MP 5.62.
Flow right to left. Photo of October 17, 2008.

Figure 2.42. Sediment deposition from eroded right bank in Sweeney Check at MP 5.65.
Flow right to left. Note repaired section of right bank. Photo of October 17, 2008.

Figure 2.43. Sediment deposition from eroded right bank in Gibson Check at MP 6.21.
View upstream. Note repaired section of right bank. Photo of October 17, 2008.

Figure 2.44. Thick mates of weeds in Highway 80 Check at MP 11.90.
View upstream. Photo of October 17, 2008.

Figure 2.45. Mud and weed accumulation in Alamo Check at MP 12.84. Flow right to left. Photo of October 20, 2008.

Figure 2.46. Mud and weed in Alamo Check at MP 13.76. View downstream. Photo of October 20, 2008.

Figure 2.47. Mud and weed upstream of Union Check gate at MP 15.82.
View downstream. Photo of October 27, 2008.

Figure 2.48. Sediment and weeds in McCoy Check at NBR WTP intake at MP 16.85.
Flow right to left. Photo of October 29, 2008.

Figure 2.49. Sediment removed from McCoy Check at MP 18.80.
Photo of November 6, 2008.

Figure 2.50. Almost 2 ft of sediment deposit in intake at MP 19.37 in Burton Check.
Photo of October 31, 2008.

Figure 2.51. Sediment and weeds in Serpas Check at Waterman WTP at MP 23.50.
View upstream. Photo of November 6, 2008.

Figure 2.52. Deposits on canal panels in Mankas Check at MP 25.63. View downstream.
Photo of October 23, 2008.

Figure 2.53. Weeds and 0.5 ft thick sediment deposits in Suisun Check at MP 26.95. View downstream. Photo of October 23, 2008.

Figure 2.54. Over 2 ft thick sediment deposits in intake structure immediately upstream of Suisun Check gate at MP 27.48. Flow right to left. Photo of October 23, 2008.

Figure 2.55. 0.5 ft thick deposit of sand from open drainage in Rockville Check at MP 29.54. View upstream. Photo of October 23, 2008.

Figure 2.56. Thick sediment deposits and weed growth in Terminous Check at MP 31.60. View downstream. Photo of October 23, 2008.

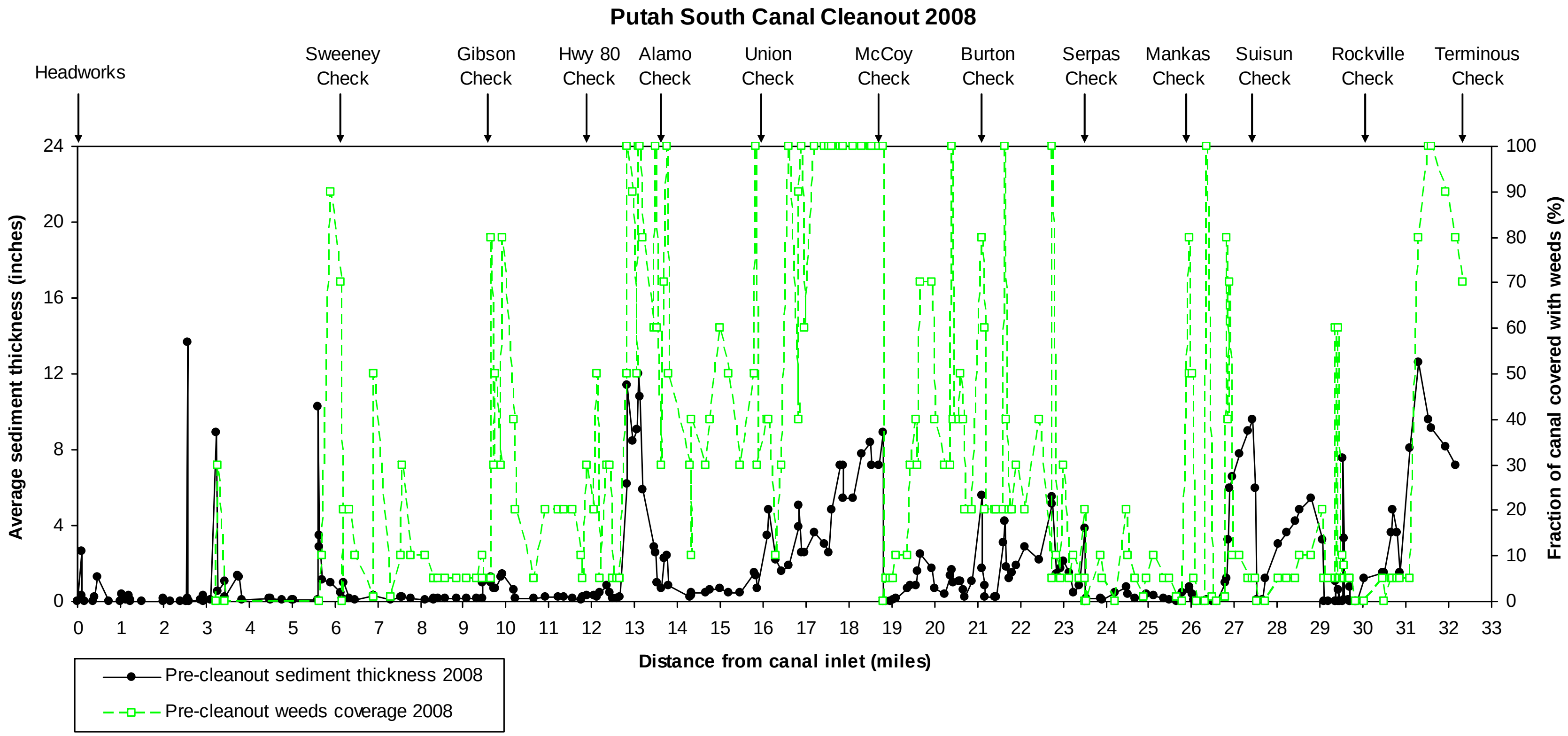

Figure 2.57. Longitudinal variations of average thickness of sediment deposits and weed growth prior to fall 2008 cleanout.

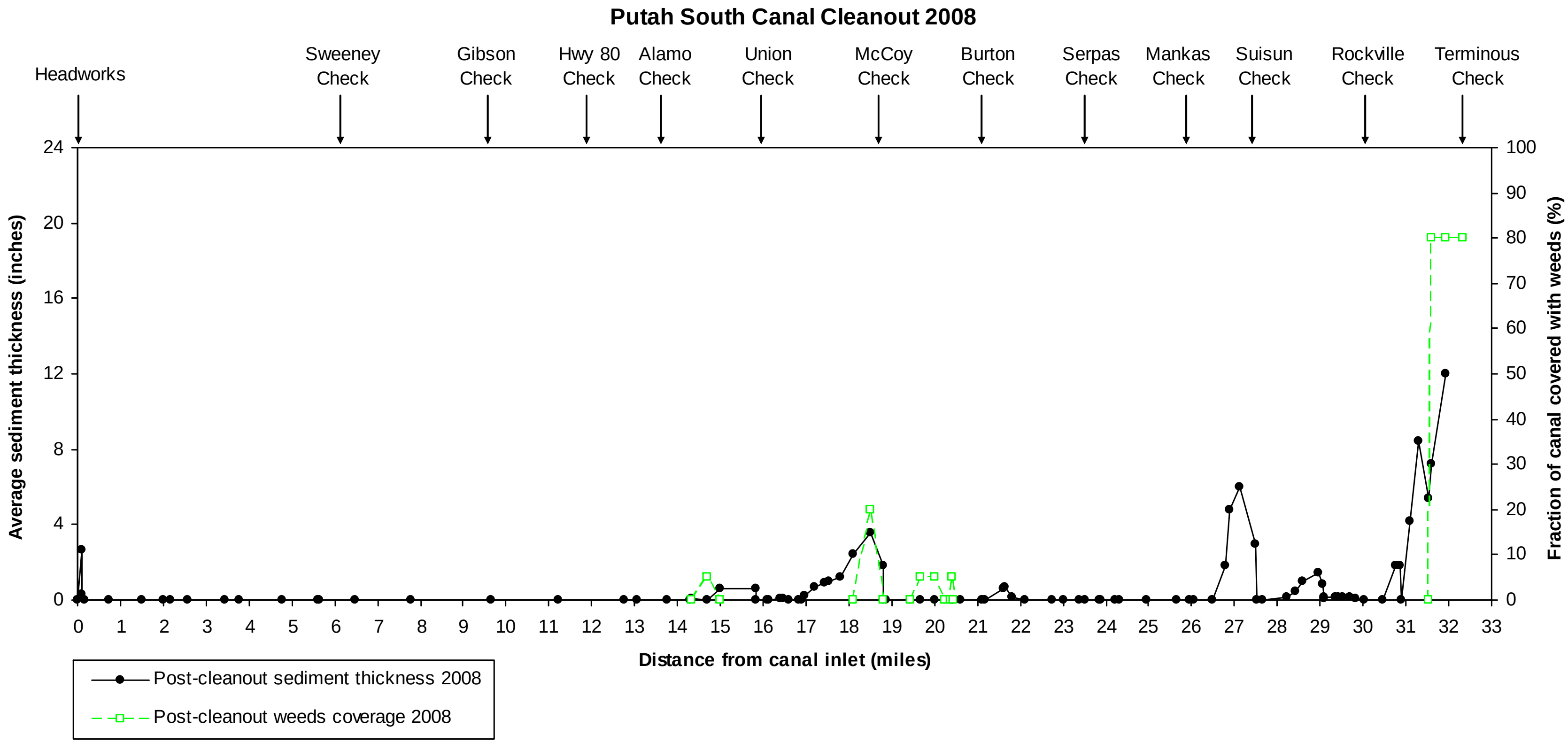

Figure 2.58. Longitudinal variations of thickness of residual sediment deposits and weed growth after fall 2008 cleanout.

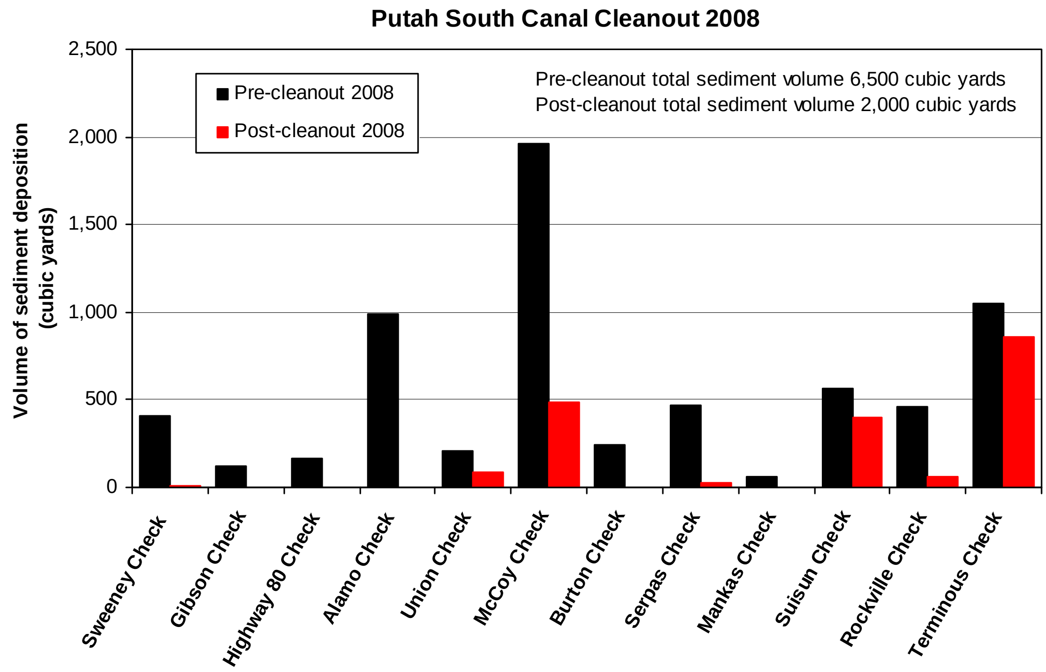

Figure 2.59. Estimated volumes of sediment deposits in each check before and after fall 2008 cleanout.

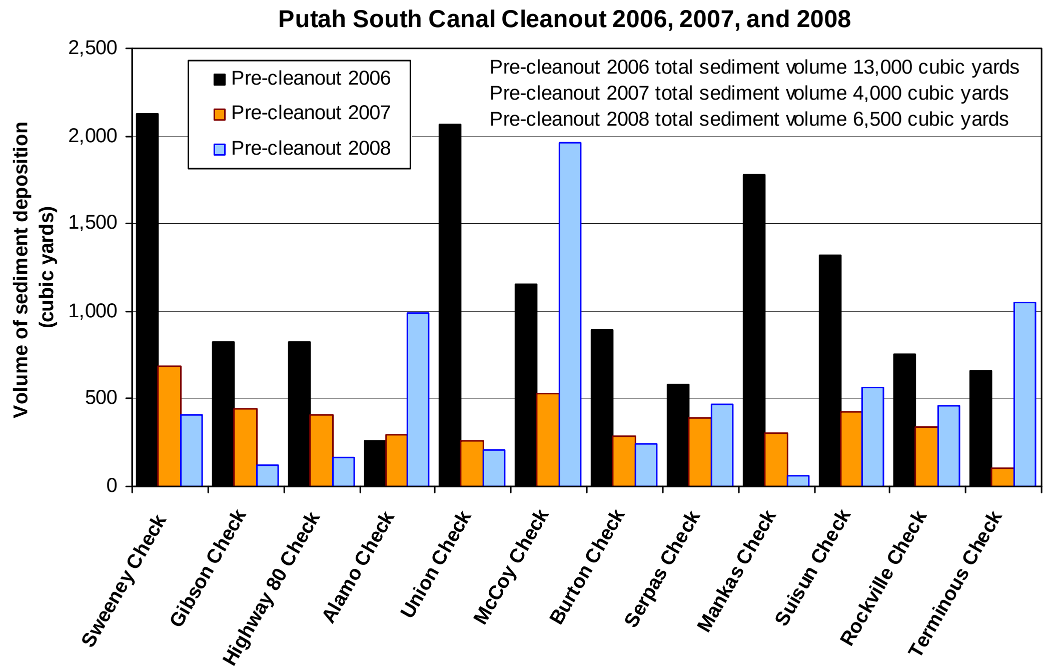

Figure 2.60. Comparison of estimated pre-cleanout volumes of sediment deposits in 2006 (wet year), 2007 (dry year), and 2008 (moderate year).

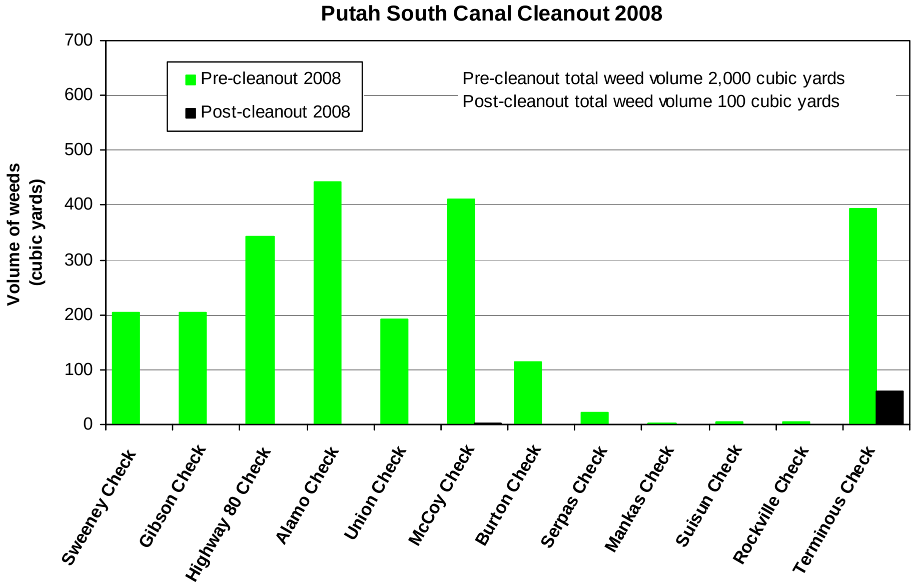

Figure 2.61. Estimated volumes of weeds in each check before and after fall 2008 cleanout.

3. WINTER STORM MONITORING

3.1. Objectives and Methods

The main objectives of the winter storm monitoring were to measure turbidity and observe propagation characteristics (temporal and spatial) of turbidity plumes entering the Putah South Canal (PSC) from Lake Solano during winter rain storm events. Tasks included collection of episodic, section-average turbidity and suspended sediment concentration data in the vicinity of the SCWA turbidity stations and major WTPs, validation of SCWA real-time turbidity data, and development of a relationship between measured water turbidity and suspended sediment concentration (SSC) in the canal (this relationship is needed to convert turbidity data into sediment loads and to develop PSC sediment budget). NHC also determined if vertical and lateral gradients in turbidity exist within the canal, and observed and measured (where possible) the contribution of sediment into the canal from lateral sources.

Five winter monitoring stations were established along the canal at approximately 5-8 mile intervals at the following locations:

(1) The Headworks (MP 0.00),
(2) Flume crossing downstream of the Sweeney Check (MP 6.47),
(3) Road bridge upstream of the Eldredge Plant (MP 11.23),
(4) Road bridge upstream of the NBR WTP (MP 16.47),
(5) Road bridge upstream of the Waterman WTP (MP 23.38), and
(6) Road bridge upstream of the Terminous Check (MP 31.60).

These NHC winter monitoring stations were located near SCWA turbidity monitoring stations and major WTPs. Two additional winter monitoring stations were established on Putah Creek at Pleasants Valley Road (upstream end of Lake Solano) and on Pleasants Creek at Putah Creek Road. Figure 3.1 shows a schematic of the Putah South Canal with the locations of the winter monitoring sites, and locations of SCWA's continuous turbidity monitoring stations and selected WTPs.

Winter storm monitoring was conducted during the winter seasons of WYs 2007 and 2008. Turbidity and SSC measurements were conducted from bridge and culvert crossings. Turbidity measurements were conducted using an Analcites NEP160 portable turbidity meter (accurate to +/- 0.5 Nephelometric Turbidity Units, or NTU, according to the manufacturer specifications). Point measurements of turbidity were taken at 1 to 2 ft depth increments at a number of verticals (ranging from 5 to 12, depending on the flow width) established across the canal/stream. Point turbidity data were then averaged to obtain section-average water turbidity. Turbidity measurements were also taken at each of the SCWA turbidity stations in order to verify their automated real-time readings. Depth-integrated samples of water laden with suspended sediment were taken using a DH-48 suspended sediment sampler at the same verticals. Water samples were then combined and analyzed in a laboratory to obtain section-average suspended sediment concentration. In addition to these detailed measurements, grab samples of sediment-laden water were taken from a few open lateral drainages to determine suspended sediment concentrations of water derived to the canal from these lateral sources. The main results from the winter storm monitoring are discussed below.

3.2. WY 2007 Winter Monitoring Results

WY 2007 was characterized by a very mild winter with a few insignificant storm events in the study area. Field measurements of turbidity and SSC in the canal, Putah Creek, and Pleasants Creek were conducted during and immediately after a single rain event occurred in the area on December 27, 2006. This rain event increased turbidity in Pleasants Creek, but did not cause detectable increases in turbidity in the PSC. Turbidity and SSC data were measured during December 27-28, 2006 and are summarized in Table 3.1. Measured section-average turbidity in the PSC was within 2-9 NTU. No vertical or lateral gradients in turbidity within the canal were detected. Section-average SSC in the PSC ranged from 0.88 mg/L at the Headworks to 55.5 mg/L at MP 31.60 upstream of the Terminous Check. Turbidity and SSC data measured at MP 6.47 downstream of the Sweeney Check were influenced by muddy waters leaking from the flume crossing the canal. SSC values measured at MP 23.38 upstream of the Waterman WTP and at MP 31.60 upstream of the Terminous Check were likely overestimated because of the presence of 4-5 inches of residual floc-type sediment deposits remaining on the bottom of the canal after the fall 2006 cleanout and captured by the suspended sediment sampler during the measurements. In Pleasants Creek, turbidity was 50 NTU, while SSC was only 8.85 mg/L. Due to the very small depth in the creek (less than 0.5 ft), suspended sediments were sampled mostly from the upper part of the water body, which likely underestimated the SSC in Pleasants Creek. In Putah Creek above Lake Solano, section-average turbidity was 4 NTU and SSC was 0.85 mg/L. Due to the very light rain in the area, the data collected during December 27-28, 2006 are regarded as representative of baseline winter conditions rather than effects one would experience during storm events.

Another attempt to measure the effect of winter storms on turbidity in the PSC was undertaken during the rain event of February 9, 2007. However, this event was very small and did not generate an increase of turbidity in the PSC. Turbidity was measured at the Headworks and Sweeney Check and was within 4-5 NTU. Due to the very low turbidity readings and visibly very clear water in the PSC, Putah Creek, and Pleasants Creek, it was decided not to continue field operations on that date.

3.3. WY 2008 Winter Monitoring Results

The winter of WY 2008 was characterized by a few very strong storm events in the study area resulting in significant increases in water turbidity and SSC in the PSC. A total of three storm events were monitored during the winter season of WY 2008. These monitored events included the "first flush" storm event of January 4, 2008 and storm events that occurred on January 25, 2008 and February 24, 2008. Main results from the monitoring of each of these winter storm events are discussed in the following sections.

3.3.1. "First flush" event of January 4, 2008

The storm event of January 4, 2008 was the first significant storm event in the WY 2008 winter rainy season. This "first flush" event turned out to be a very significant storm event. During and following the January 4, 2008 storm, the PSC experienced significant sediment loading from Lake Solano and especially from lateral sources along the canal (which included road cast and open drainages, overland runoff, and high flows in creeks that overwhelmed the capacity of flume/culvert crossings). The storm started at 2:45 am and lasted for approximately 14.5 hrs. The peak 15-minute rainfall depth was 0.52 inches and the 24-hr accumulated rainfall depth was 8.5 inches (Figure 3.2). Return periods for this event were estimated by the SCWA using the SCWA (1999) hydrology manual and ranged from 36 to 10,000+ years (see Table 3.2). Daily average total inflow to Lake Solano on January 4, 2008 was 898 cfs with outflows of 932 cfs to Putah Creek and 20 cfs to the PSC (USBR 2008). Flow passing through the Lake Solano diversion dam is shown in Figure 3.3. Flow in Putah Creek downstream from Lake Berryessa was only 45 cfs (USBR 2008, USGS 2008). This indicates that much of the inflow to Lake Solano was attributed to the Interdam tributaries such as Pleasants Creek which ramped up significantly in response to the intense storm. Putah Creek below Pleasants Valley Road is shown in Figure 3.4 and Pleasants Creek at Putah Creek Road is shown in Figure 3.5.

At approximately 11:00 am the Headworks was shut down in response to flows from McCune Creek that were overwhelming the flume overpass at MP 0.47 (Figures 3.6 and 3.7). The capacity of the flume and culvert system below the road embankments was exceeded and highly turbid water from McCune Creek was uncontrollably pouring into the canal. Sweeney Creek also overtopped its banks spilling its turbid water into the canal and eroding earthen banks downstream of the Sweeney Check at multiple locations (Figures 3.8-3.10). Additional inflows of turbid runoff occurred in the downstream reaches of the canal from multiple open drainages (Figures 3.11 and 3.12).

Turbidity data and suspended sediment samples were collected at the winter monitoring stations on the PSC, Putah Creek, and Pleasants Creek on January 4, 2008 through January 11, 2008. Additional turbidity and grab sample measurements were also collected on the McCune Creek overchute at MP 0.47 during the time it was overtopping, downstream of the Sweeney Check at Midway Road at MP 8.32, at a local tributary flowing into McCune Creek, and at an open drain at MP 29.54. Section-average data collected during and following the January 4, 2008 storm event are summarized in Table 3.1. Field turbidity data measured at the SCWA turbidity probes are compared with the SCWA automated turbidity readings in Table 3.3.

The highest turbidity and SSC values observed during the storm event were detected in Pleasants Creek. The turbidity in Pleasants Creek exceeded the measurement capacity of the portable turbidity meter. During the measurements, portable turbidity meter readings were climbing and when they reached about 3,500 NTU, there was a jump to 4,000 NTU followed by an error message. The results were interpreted as 4,000 +/-500 NTU, which is close to the SCWA real-time measurement of 3,910 NTU. The measured SSC in Pleasants Creek was 4,680 mg/L. At the same time, turbidity in Putah Creek at Pleasants Valley Road was approximately 1,590 NTU and SSC was 1,220 mg/L. Similar turbidity and SSC values (1,580 NTU and 1,290 mg/L, respectively) were measured in McCune Creek at MP 0.47. Measured turbidity values in the smaller streams in the study area were on the order of 800 to 1,100 NTU and SSC was approximately 400 to 500 mg/L. The field measurements confirmed that Pleasants Creek is by far the largest contributor of turbidity and sediment into Lake Solano during intense storm events.

According to the field observations, turbid waters that entered the PSC partially from Lake Solano and mainly from lateral sources in the upper reaches of the canal, slowly propagated down the canal as a turbidity plume (parcel of water with increased turbidity and SSC). This turbidity plume entered at the Headworks (MP 0.00) and traveled all the way to the Terminous Check (MP 32.33), gradually attenuating as suspended fine sediments settled out along the canal. Propagation of the turbidity plume along the PSC according to available SCWA continuous turbidity records and the measured field data is shown in Figure 3.13. Data gaps exist in the SCWA turbidity records for the Headworks (from January 3, 2008 3:10 pm to January 9, 2008 12:10 am). Turbidity at the Sweeney Check exceeded the calibrated range of the SCWA turbidity probe (from January 5, 2008 4:00 pm to January 6, 2008 11:30 am). According to measured data, the peak turbidity of the plume ranged from 3,220 NTU at the Headworks on January 4, 2008 at 3:00 pm (NHC measurement) to 741 NTU at the Terminous Check on January 10, 2008 at 10:15 pm (SCWA real-time measurement). Some of the measured field data (mainly pertaining to the upper reaches of the canal and high turbidity flows) indicated a slight vertical gradient in turbidity values (turbidity readings were higher near the bottom of the canal). However, in general, fine sediments were relatively uniformly distributed both vertically and across the canal. Maximum measured SSC ranged from 2,080 mg/L at the Headworks to 132 mg/L at the Terminous Check. The observed propagation speed of the turbidity plume as it moved through the system was 0.3-0.4 ft/s. Peak turbidity and propagation speed of the plume are summarized in Table 3.4.

There were multiple discrepancies for readings of turbidity between the field measurements and the SCWA continuously operated turbidity probes. The discrepancies were site specific, and varied in significance (see Table 3.3). The Pleasants Creek and Headworks turbidity probes, which serve as a warning system of approaching turbid waters, compared favorably with the field measurements. The Sweeney Check turbidity data were also in good agreement. During high turbidity flows, the SCWA turbidity probe at the Eldredge Plant consistently read turbidity values about 100 NTU less than those measured in the field. The Serpas Check turbidity probe compared favorably with the field measurements and the Terminous Check turbidity probe generally overestimated water turbidity (by 100+ NTU).

3.3.2. Storm event of January 25, 2008

The January 25, 2008 storm started at 1:00 pm and lasted for 12.5 hrs. The peak 15-minute rainfall depth was 0.06 inches and the total accumulated depth of rainfall over a three day period was 2.6 inches (Figure 3.14). In response to this storm, daily inflow to Lake Solano increased the following day to 719 cfs; daily outflow from Lake Solano to Putah Creek increased to 799 cfs, and daily inflow to the PSC was maintained constant at 45 cfs. During and following this storm event PSC experienced inflows of highly turbid water at the Headworks entering from Lake Solano (Figure 3.15).

In anticipation of this event, field measurements of pre-storm conditions were undertaken on Pleasants Creek at Putah Creek Road and in the PSC at the Headworks (MP 0.00) and at the USGS gaging Weir (MP 0.18) on January 23, 2008. Field monitoring of the effects of this event was initiated early in the morning on January 26, 2008. At that time peak turbidity had already passed the Headworks and was within the first 3 miles of the canal. PSC turbidity monitoring was conducted at the established winter monitoring stations and continued until February 1, 2008. To obtain additional information on the turbidity plume characteristics, measurements of water turbidity and SSC were also collected in the PSC at the Weir at MP 0.18, at a bridge crossing at MP 0.72, and downstream of the siphons located at MP 2.56 and MP 3.77. Section-average turbidity and SSC data collected prior to and following the storm of January 25, 2008 are summarized in Table 3.1. Comparison of field turbidity measurements at the SCWA turbidity stations and SCWA turbidity readings is provided in Table 3.3. Ground photos of the canal during the measurements are given in Figures 3.16-3.23.

Prior to the storm, measured water turbidity in the canal was approximately 15-20 NTU and SSC was 10-15 mg/L. During and following the storm of January 25, 2008, the turbidity plume entered the PSC from Lake Solano and propagated through the entire 33 miles of the canal. Propagation of the turbidity plume along the PSC as detected by the SCWA turbidity stations and field measurements is shown in Figure 3.24. Characteristics of the monitored turbidity plume are shown in Table 3.4. As the plume moved along the PSC, the peak turbidity decreased from 1,470 NTU at the Headworks to approximately 300-500 NTU in the downstream reaches of the canal. Measured SSC values in the plume decreased from approximately 300-600 mg/L in the upper reaches to 100 mg/L in the downstream reaches of the canal. The propagation speed of the turbidity plume in the system was 0.3-0.4 ft/s. Some of the measured turbidity data sets demonstrated a slight vertical gradient in turbidity values (higher turbidity readings near the bottom of the canal), but in general fine sediments were relatively uniformly distributed within the water body at the monitoring locations.

Comparison the field turbidity data and SCWA turbidity probes readings showed significant discrepancies in the measured turbidity values for the Sweeney Check, Eldredge Plant, and Terminous Check. During the monitored high turbidity event, the SCWA turbidity probes at the Sweeney Check and Eldredge Plant systematically underestimated (by 300+ NTU) while the automated turbidity probe installed at the Terminous Check consistently overestimated (by about 100 NTU) turbidity in the PSC. The other SCWA turbidity probes performed reasonably well.

3.3.3. Storm event of February 24, 2008

An intense isolated rain storm in the study area caused a sharp spike in the flow and elevated turbidity in Pleasants Creek in the afternoon of February 24, 2008. To prevent turbid waters entering the PSC, the gates at the Headworks were shut down at about 3:30 pm on that day. However, due to drawdown effects at the Sweeney Check, the gates were reopened on February 25, 2008 at about 6:00 am. Field monitoring of the PSC was initiated in the morning of February 25, 2008 and was aimed at observing the propagation of the second turbidity plume that entered the canal after the gate reopening. When the NHC field monitoring teams arrived, the plume was located in the first check of the canal. The monitoring included measurements of turbidity in the first check of the canal at the Headworks (MP 0.00), Weir (MP 0.18), Sweeney Check (MP 6.15), and a number of bridge, flume, and siphon crossings located within the first check that were easily and safely accessible. To obtain near-instantaneous longitudinal turbidity profiles of the second plume, emphasis was placed on rapid collection of turbidity data only. No suspended sediment samples were taken during these field works.

Section-average turbidity measured in the PSC during February 25, 2008 is shown in Table 3.1. Field turbidity measurements at the SCWA turbidity stations and SCWA turbidity readings are compared in Table 3.3. Variations of turbidity in Pleasants Creek and at the PSC Headworks (MP 0.00) during and after the February 24, 2008 storm are shown in Figure 3.25. Peak turbidity readings in Pleasants Creek and at the Headworks on February 24, 2008 were 2,070 NTU and 458 NTU, respectively, with a lag time between the peaks of about 4 hours. After the PSC gates were shut down, turbidity at the Headworks reduced to approximately 100 NTU. Following the gate reopening on February 25, 2008 turbidity at the Headworks jumped up to 248 NTU and then began to gradually recede as the second plume propagated down the canal. Ground photos of the canal showing propagation of the second plume after the gate reopening are given in Figures 3.26-3.28.

Longitudinal distribution of turbidity in the second plume is shown in Figure 3.29. The data used to construct this figure were collected within 1.5 hrs. Therefore, given the relatively slow propagation speed of the plume (around 0.2-0.4 ft/s, or 0.1-0.3 mi/hr, according to the previous measurements), the profile shown can be regarded as near-instantaneous. Section-average turbidity increased in the downstream direction in the uppermost portion of the canal from 187 NTU at the Weir at MP 0.18 to 263 NTU at the siphon at MP 2.56. Downstream of this siphon, the turbidity significantly dropped to 10-20 NTU and remained nearly constant all the way to the downstream end of the Sweeney Check at MP 6.15. Overall, suspended fine sediments in the canal were relatively well mixed in most areas with no significant cross-sectional or vertical gradients in the turbidity readings. Turbidity measurements taken just upstream of the leading edge of the plume demonstrated an obvious vertical gradient in turbidity (higher readings were near the water surface as the plume approached and near the bed as the plume passed), which was likely attributed to wind mixing effects.

Turbidity measurements taken in the field closely matched measurements recorded by the SCWA turbidity probes at the Headworks (MP 0.00) and Sweeney Check (MP 6.15).

3.4. Relationship between Water Turbidity and Suspended Sediment Concentration

One of the main objectives of the winter storm monitoring was to develop a relationship between measured water turbidity and SSC (suspended sediment concentration) in the canal. All of the turbidity and SSC data collected during winter monitoring of WY 2007 and WY 2008 are plotted in Figure 3.30. The data measured in Pleasants Creek and Putah Creek are also shown in this figure for comparison. The data set measured in the canal covers a wide range of turbidity and SSC values: the measured turbidity values for the PSC range from 2 to 3,220 NTU and SSC values range from less than 1 to 2,080 mg/L. For Pleasants Creek and Putah Creek, maximum measured turbidity was 4,000 and 1,590 NTU, respectively, and maximum measured SSC was 4,680 and 1,220 mg/L, respectively.

To complement the collected data set, a unique data point collected at the NBR WTP from the canal during an extremely severe storm event that occurred in WY 2006 was also used in the analysis. A single water sample was taken at the NBR WTP (by plant's staff) on December 31, 2005 during the severe New Year's Eve storm event. The measured suspended sediment concentration for this sample was 3,014 mg/L. The corresponding turbidity for this sample was 6,610 NTU. This data point is plotted in Figure 3.30. Significant overbank flooding into the canal occurred in the Alamo Check during this event which is likely to have contributed to the high sediment and turbidity values obtained from the NBR water sample.

The winter monitoring data measured in the PSC and supplemented by the NBR WTP data were used to develop a relationship between turbidity and SSC in the PSC. The relationship is shown in Figure 3.30 and is approximated by the following equation:

$$\text{SSC (mg/L)} = 0.55\ \text{NTU}^{0.98} \qquad (3.1)$$

where SSC = suspended sediment concentration (in mg/L) and NTU = turbidity (in NTU).
The correlation coefficient for this relationship is 0.99 and root mean square error is 118 mg/L. Equation 3.1 can be used to convert any turbidity data measured in the PSC into SSC, which in turn can be used to calculate suspended sediment loads in the canal. It should be remembered, however, that the turbidity-sediment relationship in Figure 3.30 is a statistical approximation based on a limited data set and therefore should be regarded as approximate. Some deviation of calculated values from individual measurements is possible (although unlikely to be very significant).

3.5. Summary of Winter Monitoring Results

Baseline winter conditions and three winter storm events (including "first flush" event early in the winter rain season) were monitored during WY 2007 and WY 2008. Monitoring of the storm events involved tracking of turbidity plumes entering the PSC from Lake Solano and other lateral sources and propagating down the canal. Water turbidity and SSC (suspended sediment concentration) were measured at a number of locations along the PSC, as well as in Pleasants Creek and Putah Creek above Lake Solano.

During baseline winter conditions, waters in the PSC are very clean, with turbidity values typically between 2-20 NTU and SSC around 1-13 mg/L. During storm events, turbidity and SSC values in the PSC and in other streams in the study area may increase dramatically (by one to two orders of magnitude, depending on the intensity, duration, and location of the storm). During the monitored storm events, maximum measured turbidity was 3,220 NTU in the PSC, about 4,000 NTU in Pleasants Creek, and 1,590 NTU in Putah Creek above Lake Solano. Maximum measured SSC value was 2,080 mg/L in the PSC, 4,680 mg/L in Pleasants Creek, and 1,220 mg/L in Putah Creek above Lake Solano.

Winter monitoring confirmed that Pleasants Creek is by far the largest contributor of turbidity and sediment into Lake Solano during winter storm events. From Lake Solano, turbid waters then enter the PSC and slowly propagate down the canal as a turbidity plume (parcel of water with increased turbidity and SSC). This turbidity plume moves through the entire 33 miles of the canal, gradually attenuating as suspended fine sediments settle down. Propagation speed of the plume in the PSC is approximately 0.2-0.4 ft/s. Suspended sediments in turbidity plumes are relatively uniformly distributed vertically and laterally, which is likely due to the very small size of the sediment as well as mixing effects from numerous structures in the canal.

Significant volumes of turbid water and sediment also enter the canal from multiple lateral sources which include bank failures, road cast, open drainages, overland runoff, and spillage of turbid waters from flume crossings. The contribution from individual lateral sources is episodic and depends on the severity and spacing of a given storm event.

Results from the winter monitoring were used to develop a relationship between turbidity and SSC. This relationship can be used to convert turbidity readings to SSC and to estimate sediment loads in the canal. Quantitative assessment of the PSC sediment budget and contribution of sediment into the PSC from various sources is provided in Chapter 7 of this report.

Field measurements revealed accuracy problems with some of the SCWA automated turbidity probes. During the monitored high turbidity events, the SCWA turbidity probes at the Sweeney Check and Eldredge Plant systematically underestimated (by approximately 100-300 NTU) while the automated turbidity probe installed at the Terminous Check consistently overestimated (by about 100 NTU) turbidity in the PSC. The other SCWA turbidity probes performed reasonably well.

Table 3.1. Section-average turbidity and suspended sediment concentration data measured in Putah South Canal during winter seasons of WY 2007 and WY 2008.

Location	PSC milepost	Date & Time	Turbidity (NTU)	Suspended sediment concentration (mg/L)
Storm of 12/27/2006				
Pleasants Creek at Putah Creek Rd	-	12/27/2006 12:20	50	8.85
Putah Creek at Pleasants Valley Rd	-	12/27/2006 14:15	4	0.85
PSC Headworks	0.00	12/27/2006 11:00	4	0.88
PSC d/s Sweeney Check	6.47	12/27/2006 15:30	9	5.36
PSC u/s of Eldredge Plant	11.23	12/27/2006 16:20	3	3.62
PSC u/s of NBR WTP	16.47	12/28/2006 9:40	4	1.98
PSC u/s of Waterman WTP	23.38	12/28/2006 11:00	2	6.77
PSC u/s of Terminous Check	31.60	12/28/2006 12:00	4	55.5
Storm of 1/4/2008				
McCune Creek Flume	0.47	1/4/2008 11:20	1,580	1,290**
Tributary to McCune Creek	-	1/4/2008 11:20	847	460**
Pleasants Creek at Putah Creek Rd	-	1/4/2008 12:30	4,000*	4,680
Putah Creek at Pleasants Valley Rd	-	1/4/2008 14:00	1,590	1,220
PSC Headworks	0.00	1/4/2008 16:00	3,220	2,080
PSC at Midway Rd	8.32	1/4/2008 15:20	385	240
PSC u/s of Eldredge Plant	11.23	1/4/2008 14:35	25	15
PSC d/s Sweeney Check	6.47	1/5/2008 10:00	185	88
PSC u/s of Eldredge Plant	11.23	1/5/2008 10:50	251	109
PSC u/s of Terminous Check	31.60	1/5/2008 12:50	22	12
Open drainage in PSC	29.54	1/5/2008 16:00	1,030	425**
PSC u/s of Eldredge Plant	11.23	1/8/2008 9:55	395	158
PSC u/s of NBR WTP	16.47	1/8/2008 10:45	731	369
PSC u/s of Waterman WTP	23.38	1/8/2008 11:40	18	6
PSC u/s of Waterman WTP	23.38	1/9/2008 11:00	682	285
PSC u/s of Terminous Check	31.60	1/11/2008 10:05	328	132

* NHC turbidity meter readings were climbing and when they reached about 3,500 NTU, there was a jump to 4,000 NTU followed by an error message. Results should be interpreted as 4,000 +/-500 NTU.

** Grab sample.

Table 3.1. (continued).

Location	PSC milepost	Date & Time	Turbidity (NTU)	Suspended sediment concentration (mg/L)
Storm of 1/25/2008				
Pleasants Creek at Putah Creek Rd	-	1/23/2008 9:00	118	46
PSC Headworks	0.00	1/23/2008 9:50	20	13
PSC Weir	0.18	1/23/2008 10:45	17	12
PSC Headworks	0.00	1/26/2008 8:05	828	432
PSC Weir	0.18	1/26/2008 10:18	680	447
PSC Bridge	0.72	1/26/2008 10:40	870	550
PSC d/s Siphon	2.56	1/26/2008 11:15	980	554
PSC d/s Siphon	3.77	1/26/2008 11:40	583	337
PSC d/s Sweeney Check	6.47	1/27/2008 9:40	921	375
PSC u/s of Eldredge Plant	11.23	1/28/2008 13:25	753	288
PSC u/s of NBR WTP	16.47	1/28/2008 9:40	431	105
PSC u/s of Waterman WTP	23.38	1/30/2008 13:17	343	84
PSC u/s of Terminous Check	31.60	2/1/2008 14:50	323	104
Storm of 2/24/2008				
PSC Weir	0.18	2/25/2008 9:35	187	-
PSC Bridge	0.72	2/25/2008 10:00	197	-
PSC Bridge	1.50	2/25/2008 10:10	221	-
PSC Flume Crossing	2.16	2/25/2008 10:23	216	-
PSC Siphon	2.56	2/25/2008 10:35	263	-
PSC Flume Crossing	3.44	2/25/2008 10:45	11	-
PSC Flume Crossing	4.76	2/25/2008 10:57	18	-
PSC Sweeney Check	6.15	2/25/2008 11:10	10	-
PSC Sweeney Check	6.15	2/25/2008 12:50	14	-
PSC Flume Crossing	4.76	2/25/2008 13:05	15	-
PSC Flume Crossing	3.44	2/25/2008 13:16	165	-
PSC Siphon	3.74	2/25/2008 13:40	27	-
PSC Intake	3.25	2/25/2008 13:46	200	-
PSC Siphon	2.56	2/25/2008 14:10	193	-
PSC Bridge	1.50	2/25/2008 14:20	181	-
PSC Bridge	0.72	2/25/2008 14:30	176	-
PSC Weir	0.18	2/25/2008 14:45	162	-
PSC Headworks	0.00	2/25/2008 14:55	152	-

Table 3.2. Rainfall intensities and return periods for January 4, 2008 storm event as measured at Sweeney rain gage (provided by SCWA).

Time interval	Rainfall depth (inches)	Return period (yrs)
15 min	0.52	100
30 min	0.95	36
1 hr	1.53	121
2 hr	3.05	10,000
3 hr	4.38	10,000+
6 hr	6.91	10,000+
12 hr	8.07	10,000+
1 day	8.60	8,776

Table 3.3. Comparison of field turbidity data and SCWA real-time turbidity readings.

Location	PSC milepost	Day & Time	Field turbidity (NTU)	SCWA turbidity (NTU)	Difference (%)
Storm of 1/4/2008					
Pleasants Creek at Putah Creek Rd	-	1/4/2008 12:45	4,000*	3,910	2
PSC Headworks	0.00	1/4/2008 15:30	3,220	**	-
PSC at Sweeney Check	6.15	1/5/2008 10:00	184	174	5
PSC at Eldredge Plant	11.80	1/4/2008 14:30	25	28	12
PSC at Eldredge Plant	11.80	1/5/2008 10:45	251	174	31
PSC at Eldredge Plant	11.80	1/8/2008 10:00	395	267	32
PSC at Serpas Check	23.51	1/5/2008 12:00	17	14	18
PSC at Serpas Check	23.51	1/8/2008 11:45	15	54	260
PSC at Serpas Check	23.51	1/9/2008 11:00	620	558	10
PSC at Terminous Check	32.33	1/5/2008 12:45	22	71	223
PSC at Terminous Check	32.33	1/11/2008 10:00	328	508	55
Storm of 1/25/2008					
PSC Headworks	0.00	1/23/2008 9:50	20	23	15
PSC Headworks	0.00	1/26/2008 8:10	828	859	4
PSC at Sweeney Check	6.15	1/23/2008 11:30	11	14	27
PSC at Sweeney Check	6.15	1/26/2008 12:00	23	16	30
PSC at Sweeney Check	6.15	1/27/2008 12:30	820	444	46
PSC at Eldredge Plant	11.80	1/23/2008 11:55	10	3	70
PSC at Eldredge Plant	11.80	1/26/2008 12:24	21	15	29
PSC at Eldredge Plant	11.80	1/28/2008 13:25	590	234	60
PSC at Serpas Check	23.51	1/30/2008 13:07	326	343	5
PSC at Terminous Check	32.33	2/1/2008 14:50	323	409	27
Storm of 2/24/2008					
Sweeney Check	6.15	2/25/2008 11:10	10	14	40
Sweeney Check	6.15	2/25/2008 12:50	14	14	0
Headworks	0.00	2/25/2008 14:55	152	184	21

* NHC turbidity meter readings were climbing and when they reached about 3,500 NTU, there was a jump to 4,000 NTU followed by an error message. Results should be interpreted as 4,000 +/-500 NTU.

** Data gap in SCWA readings.

Table 3.4. Propagation characteristics of turbidity plumes along Putah South Canal during WY 2008 winter monitoring.

Canal site	PSC milepost	Date & Time	Peak turbidity (NTU)	Travel distance (miles)	Travel time (hrs)	Travel speed (ft/s)
Storm of 1/4/2008						
NHC Headworks	0.00	01/04/2008 15:30	3,220	6.15	33.5	0.27
SCWA Sweeney Check	6.15	01/06/2008 1:00	>500*	5.65	30.2	0.27
SCWA Eldredge Plant	11.80	01/07/2008 7:15	475	11.71	57.2	0.30
SCWA Serpas Check	23.51	01/09/2008 16:30	794	8.82	29.8	0.43
SCWA Terminous Check	32.33	01/10/2008 22:15	741			
Storm of 1/25/2008						
SCWA Headworks	0.00	1/25/2008 22:10	1,470	6.15	38.3	0.24
SCWA Sweeney Check	6.15	1/27/2008 12:30	444	5.65	30.8	0.27
SCWA Eldredge Plant	11.80	1/28/2008 19:15	323	11.71	51.0	0.34
SCWA Serpas Check	23.51	1/30/2008 22:15	452	8.82	36.8	0.35
SCWA Terminous Check	32.33	2/1/2008 11:00	548			

*** Turbidity exceeded calibrated range of turbidity probe.**

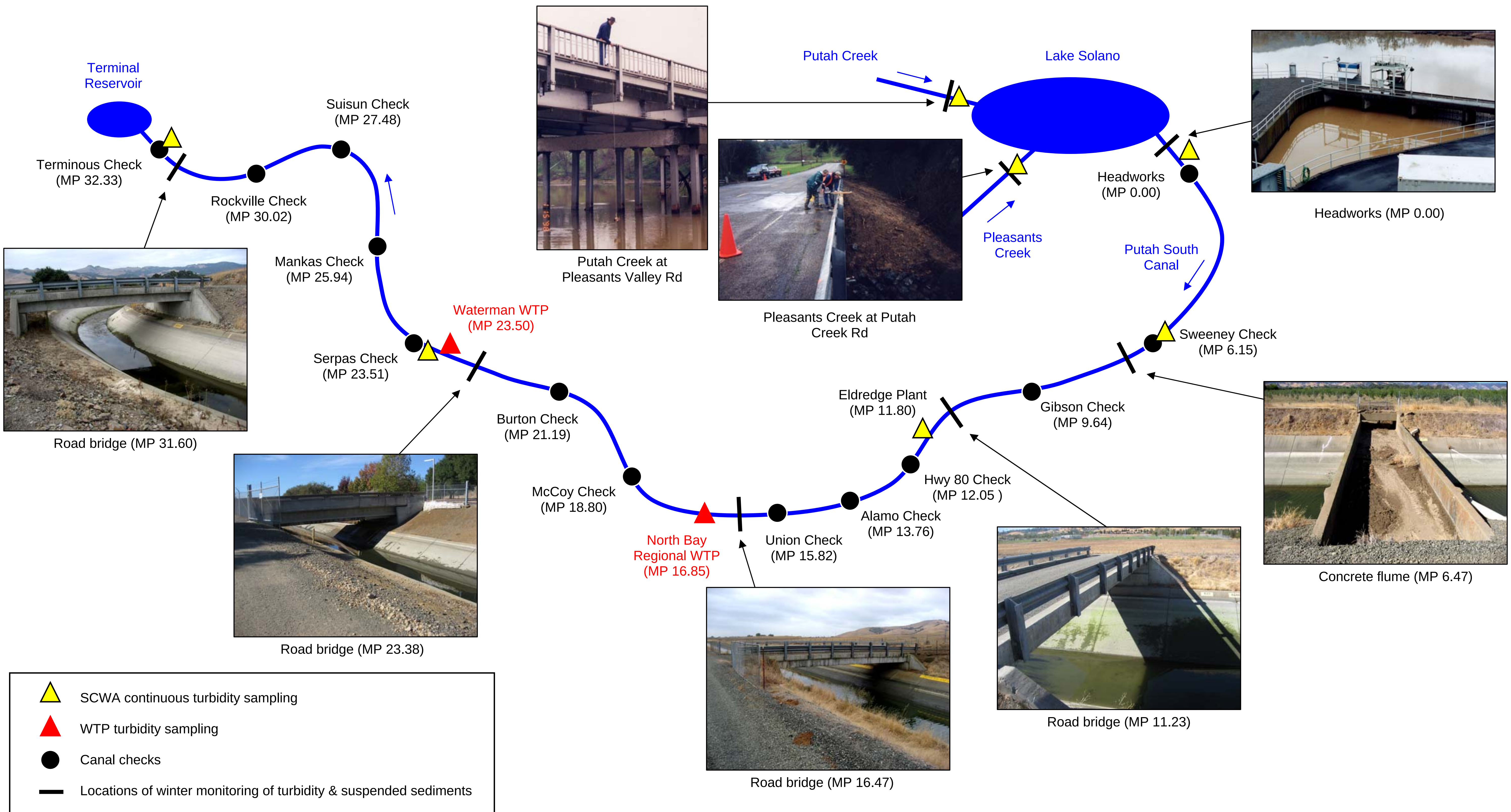

Figure 3.1. Putah South Canal schematic showing location of winter monitoring sites.

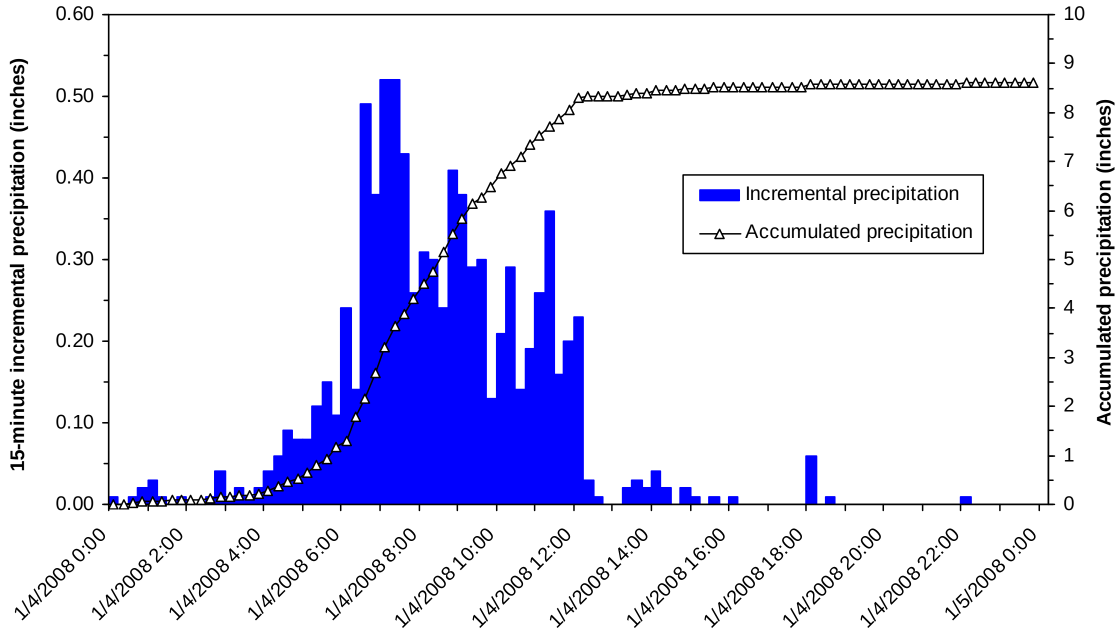

Figure 3.2. Precipitation record from SCWA rain gage at Sweeney Check on January 4, 2008.

Figure 3.3. Putah Creek downstream of diversion dam on Lake Solano on January 4, 2008 at 3:00 pm.

Figure 3.4. Putah Creek below Pleasants Valley Road on January 4, 2008 at 2:00 pm.
View downstream.

Figure 3.5. Pleasants Creek at Putah Creek Road Bridge on January 4, 2008 at 12:30 pm.
Flow right to left.

Figure 3.6. McCune Creek crossing over Putah South Canal at MP 0.47 on January 4, 2008 at 11:00 am. Flow in creek from left to right.

Figure 3.7. McCune Creek crossing over Putah South Canal at MP 0.47 on January 4, 2008 at 11:00 am. Flow in creek from right to left.

Figure 3.8. Overflow from Sweeney Creek into Putah South Canal downstream of Sweeney Check at MP 6.15 on January 4, 2008 at 2:00 pm. Flow in canal from right to left.

Figure 3.9. Overbank flow into Putah South Canal downstream of Sweeney Check on January 4, 2008 at 2:00 pm. View downstream.

Figure 3.10. Bank erosion caused by overbank flows into Putah South Canal downstream of Sweeney Check. Photo of January 5, 2008. Flow right to left.

Figure 3.11. Local drainage spilling turbid storm water into canal from open pipe at MP 29.54 on January 5, 2008. Flow right to left.

Figure 3.12. Local drainage spilling turbid storm water into canal at MP 29.69 on January 5, 2008. Flow right to left.

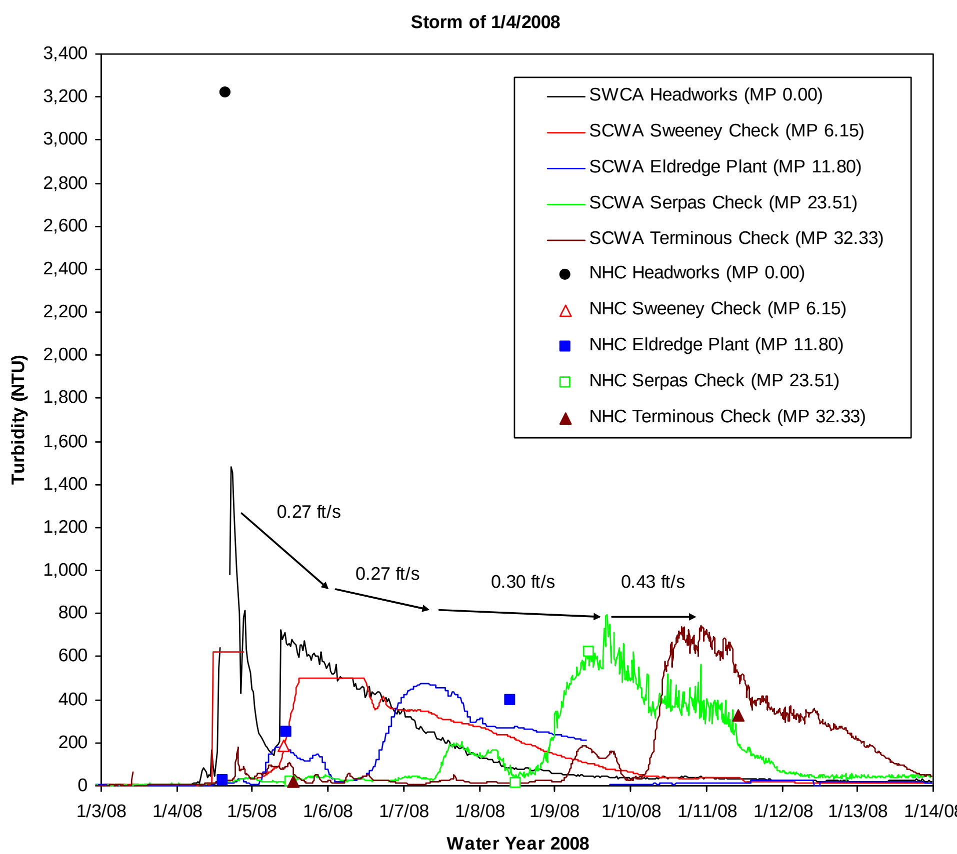

Figure 3.13. Propagation of turbidity plume along Putah South Canal during and following January 4, 2008 storm event. Data gaps exist in SCWA data for Headworks (from January 3, 2008 3:10 pm to January 9, 2008 12:10 am). Arrows and velocities denote travel speed of turbidity plume.

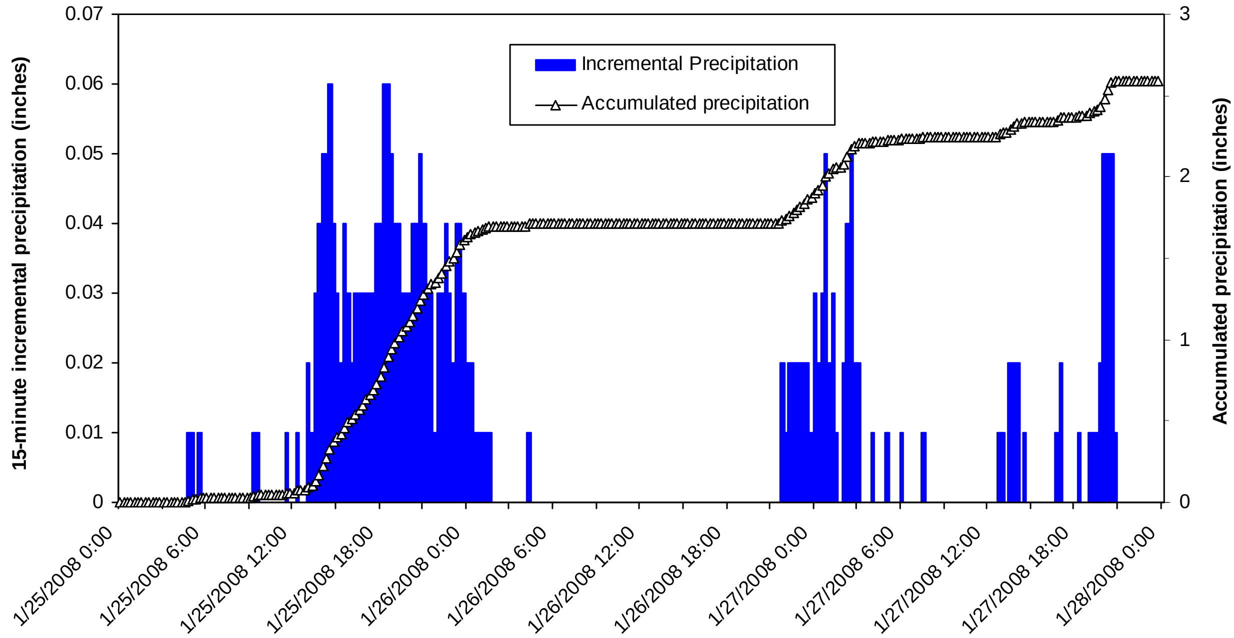

Figure 3.14. Precipitation record from SCWA rain gage at Sweeney Check for January 25, 2008 through January 27, 2008.

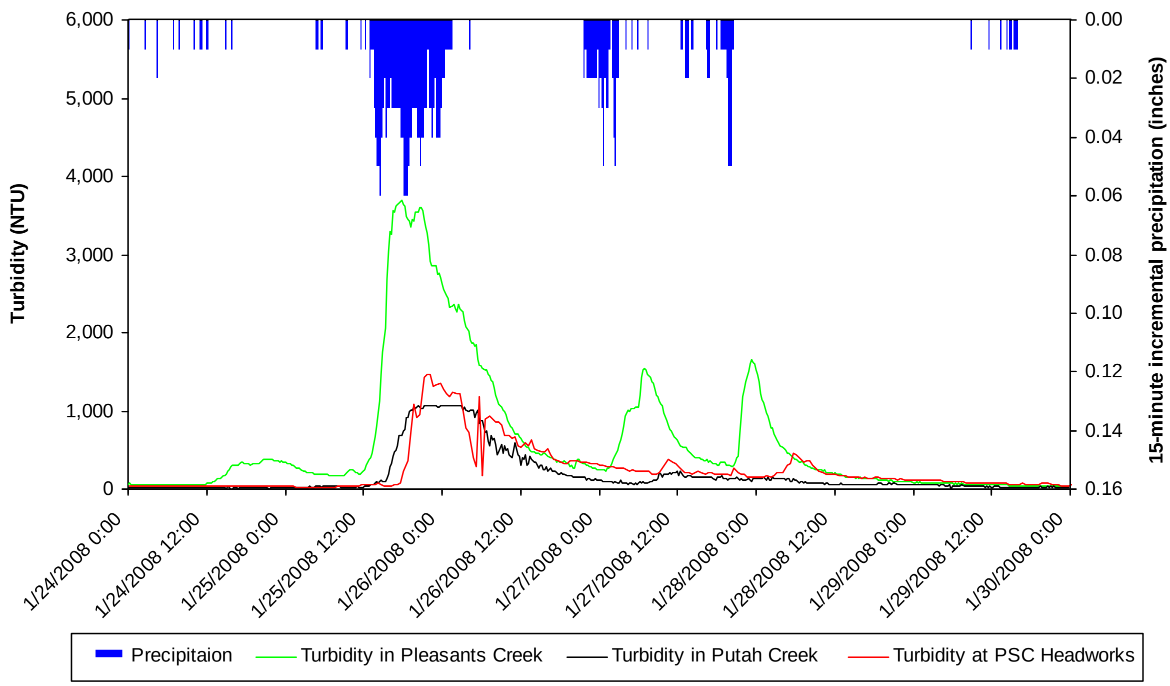

Figure 3.15. Turbidity response at Pleasants Creek, Putah Creek, and PSC Headworks to precipitation recorded by SCWA rain gage at Sweeney Check during
January 25, 2008 storm event.

Figure 3.16. Highly turbid water in Lake Solano on January 26, 2008.

Figure 3.17. Sampling suspended sediment at Putah South Canal Headworks on January 26, 2008. View upstream.

Figure 3.18. Gates at entrance to Putah South Canal on January 26, 2008. View downstream. Note muddy water entering canal.

Figure 3.19. Putah South Canal at MP 0.10 on January 26, 2008. Flow right to left. Note deposit of sediment in canal supplied by open drainage.

Figure 3.20. Suspended sediment sampling at PSC Weir at MP 0.18 on January 26, 2008. View downstream. Note muddy water in canal.

Figure 3.21. Erosion of bank of Putah South Canal at MP 0.74 caused by heavy rains. View upstream. Photo of January 26, 2008.

Figure 3.22. Deposition of debris in Putah South Canal upstream of siphon at MP 2.54 on January 26, 2008. Flow right to left.

Figure 3.23. Sediment from open drainage deposited in Putah South Canal at MP 29.54 on January 26, 2008. Flow right to left.

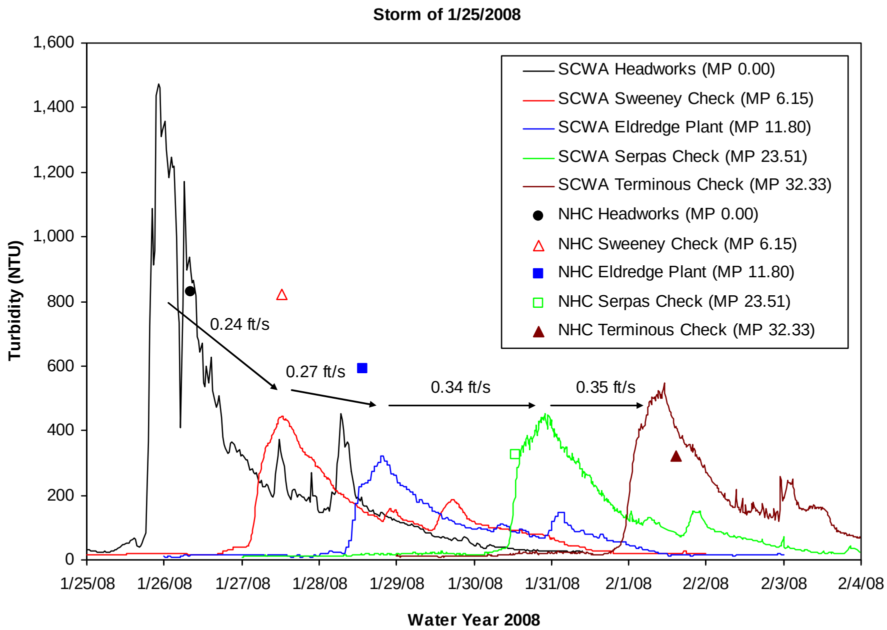

Figure 3.24. Propagation of turbidity plume along Putah South Canal during and following January 25, 2008 storm. Arrows and velocities denote travel speed of turbidity plume.

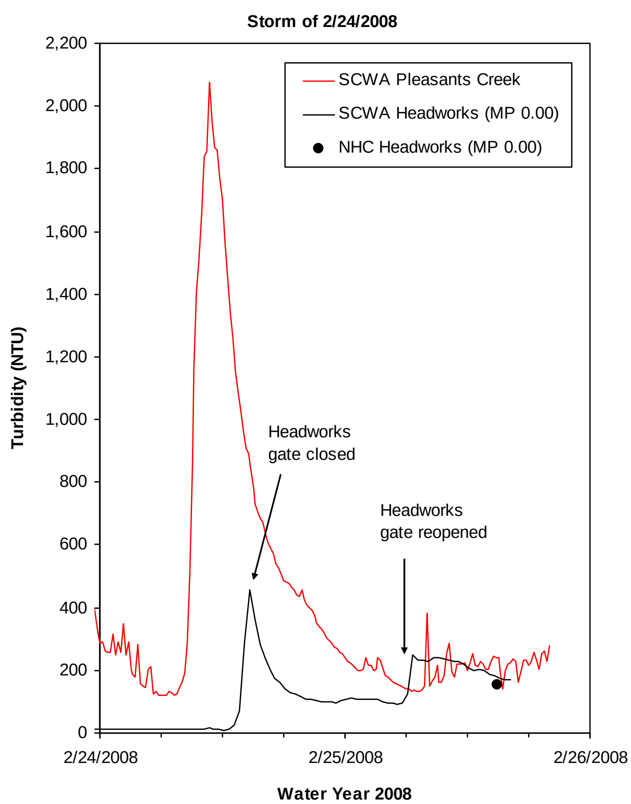

Figure 3.25. Variation of turbidity in Pleasants Creek and Putah South Canal at Headworks during and following storm of February 24, 2008.

Figure 3.26. Leading edge of turbidity plume above siphon at MP 3.74 on February 25, 2008 at 13:40 pm. View upstream. Meaured turbudity at this location is about 28 NTU.

Figure 3.27. Leading edge of turbidity plume just upstream of siphon at MP 3.74 on February 25, 2008 at 13:40 pm. Flow right to left.

Figure 3.28. Receding turbidity plume at Olive School Lane at approximately MP 0.4 on February 25, 2008 at 14:30. Flow left to right. Measured turbidity at this location is about 170 NTU.

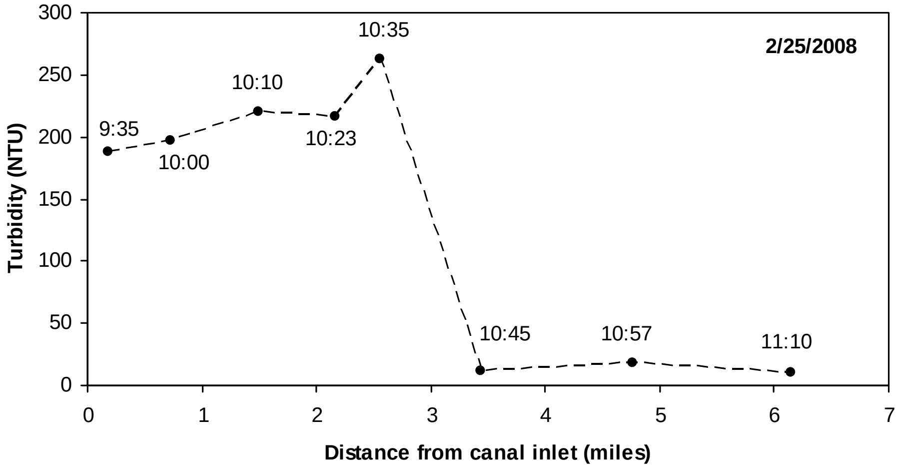

Figure 3.29. Longitudinal distribution of turbidity in second plume on February 25, 2008.

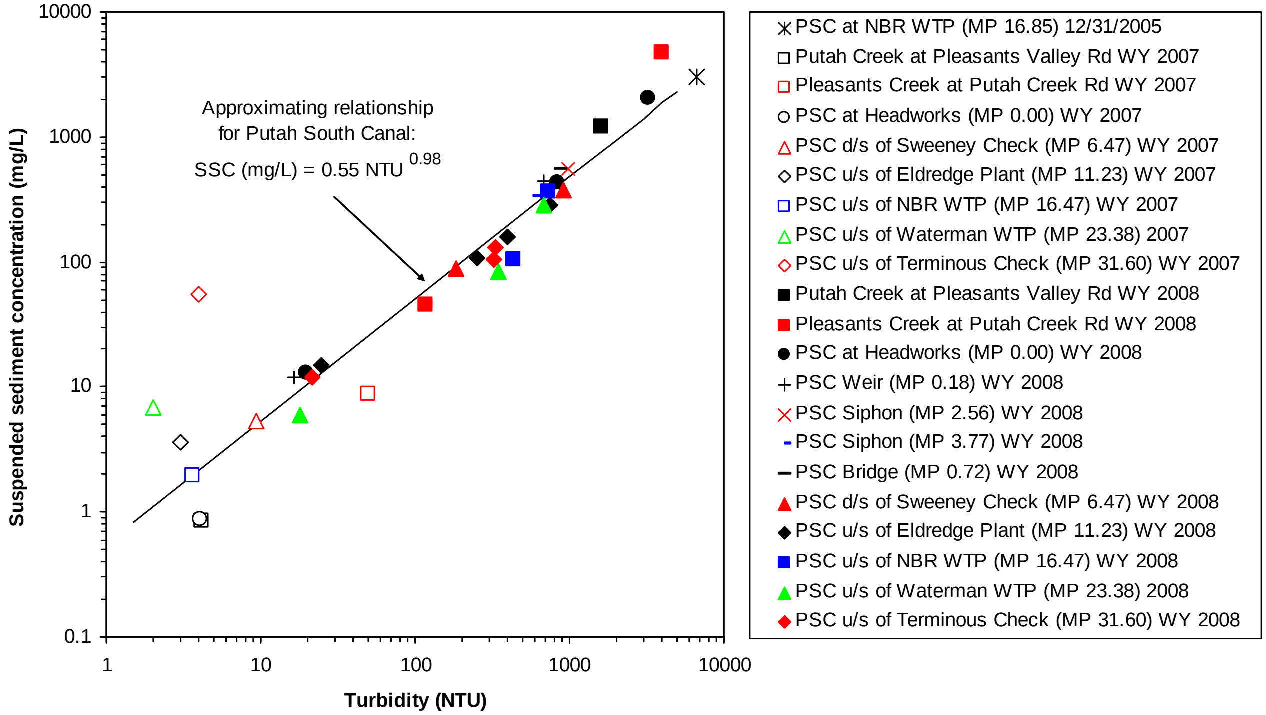

Figure 3.30. Relationship between water turbidity and suspended sediment concentration. Correlation coefficient is 0.99 and root mean square error is 118 mg/L.

4. Identification of Lateral Sources of Sediment and Preparation of Erosion Hazard Index Procedure

4.1. Objectives and Methods

Principal objectives of the project were to identify primary sources of sediment and turbidity that enter the canal and to assess the relative annual contributions from these sources. Other chapters discuss the processes and importance of sediment and turbidity that enter the canal from Lake Solano through the Headworks. This chapter focuses on identifying and ranking the importance of lateral sediment sources that enter the canal. Lateral sources include canal bank surface erosion, canal bank mass failures, discharges from direct drains, inflows from overtopping flows at stream crossings or other points along the canal, and atmospheric deposition. Sediment budget analysis procedures discussed in Chapter 7 were used to estimate components of the total annual sediment load to the canal from Lake Solano and from the sum of lateral sources and losses from canal cleanout activities and water extractions. However, quantification of each lateral source was not possible given the extreme variability of sediment loads from these sources from year-to-year, and because of the wide variability in the location, magnitude and frequency of runoff and sediment or turbidity loading relative to each other in any given year. Furthermore, intensive monitoring of potential overtopping sites, continuous flow and sediment monitoring of direct drains and field-monitored plot studies of canal bank erosion would be required to achieve detailed quantification of these sources. Hence, the overall objective was to identify primary lateral sources and rank them for consideration in developing erosion control and management strategies. This was accomplished by first conducting a detailed erosion inventory of the canal right of way. Results from the field inventory were then used to develop an erosion hazard index procedure that was applied on a reach-by-reach basis to identify locations along the canal with insignificant, low, moderate, high, and severe erosion and sediment production potential. This erosion hazard index procedure can then be used by program managers to identify reaches along the canal that warrant the application of erosion control Best Management Practices (BMPs).

During the fall of 2007, an intensive initial erosion inventory was conducted along the entire canal which allowed NHC to develop a GIS (Geographic Information System) database that identified lateral erosion sources and allowed us to produce an erosion hazard rating associated with those sources. The GIS database is a work product of this project and was provided to the SCWA. The field inventory was used to catalog various erosion-related features, but it also included the acquisition of other attribute data to allow the development of an erosion hazard index procedure. This index procedure was applied on a reach basis wherein the left and right canal banks were broken into a total of 378 reaches based on various characteristics described below. The erosion hazard ranking places all of the 378 reaches into a range of erosion hazard classes that ranks the potential for direct runoff, new sheet and rill or mass wasting erosion processes relative to all other reaches.

Following the initial 2007 field surveys, a subsequent survey was conducted in May of 2008 to document more recent erosion features that may have occurred during the 2007/2008 rainy season. This follow-up survey was originally scheduled for the spring of 2007, but as that year experienced a very dry winter with little or no runoff or overland flow, the survey was postponed until May 2008.

The present GIS database consists of spatial information linked to a digital aerial photograph of the entire canal length. Reaches and individual points can be displayed on the image, and the points and reaches are linked to ground photographs that help project managers "view conditions" that existed during the initial ground surveys. The database consists of "attribute" data for all reaches and erosion features. The database can be queried using Boolean algebra searches available in the software and the results can be displayed on the image. For example, those reaches with slope lengths greater than 22 ft that have groundcover below 30% coverage and a toe width of less than 2 ft can be highlighted on the canal image. The GIS database is an extremely useful tool that can be used to identify those reaches in need of erosion control BMPs, scheduling and tracking completed BMP applications and adding or updating the database with new information, such as the location and date of overtopping events, location of new landslides, new structures, decommissioned drain locations, etc.

The canal banks were separated into reaches based on the following physical attributes:

- Slope angle.
- Slope length.
- Percent groundcover (live plants, litter, gravel).
- Toe width.
- Toe percent groundcover.

During the initial field survey, all slides and soil slips that were readily discernable were logged. Although no specific occurrence date could be assigned to them, the vast majority are most likely to have occurred during the record storm of December 31, 2005. Since the project was initiated in November 2006, the precise locations of overtopping areas which occurred during the December 31, 2005 storm could not be exactly located and therefore were not entered into the database.

During the resurvey, all new erosion features and overtopping locations were located and coded as to the year of occurrence. The database contains the following information, in addition to the reach attribute data listed above:

- Direct drain locations and size.
- Ground photos linked to locations.
- Broad spectrum herbicide treated areas.
- Soil type by reach.
- Observations of sediment accumulation on the canal edge.
- Landslide location, dimensions and year of occurrence.

- Locations of downslope drainage from access roads.
- 2008 overtopping locations.
- Approximate watershed limits for most groups of direct drains.

All attribute and feature locations were determined with hand held Global Positioning System (GPS) units that were calibrated to California State Plane, Zone II coordinates and to approximate PSC milepost information painted on the canal. The reach attribute data, in addition to the initial landslide data, was used to develop an erosion hazard index for the entire canal. The index was developed using the parameters within the Universal Soil Loss Equation (Wischmeier and Smith 1965). Slope angle, slope length and percent groundcover are utilized in the ranking, as well as the product of toe width and groundcover. All of the attributes were broken into three or more classes with weighting points assigned by class. A final parameter utilized was the number of slides normalized by the ratio of the reach length divided by the average reach length. Each factor has a point score assigned by class and the sum of the point scores for all factors yields the erosion hazard index. This number is then also separated into five classes, from "not significant" to "severe." The point range assigned to each factor is not uniform, which allows those attributes which have a greater influence on erosion, such as percent groundcover, to exert greater weight in the overall rating procedure. The index includes the risk of both surface and mass wasting within the reach. The erosion hazard rating methodology is fully described in Appendix A-4.1.

4.2. Erosion Inventory Results

Appendix A-4.2 includes color maps of the entire canal showing the erosion hazard rating for each reach. Table 4.1 gives the total lineal distance (bank length) summed within each erosion hazard class. In general, canal reaches that have broad spectrum herbicide applied to their banks, or long slope lengths or high density of landslides are ranked with either high or severe hazard indices. Appendix A-4.3 shows the locations of all landslides recorded during the field surveys of 2007 and 2008. Each landslide has attribute data within the GIS database specifying the approximate slide dimensions.

Storm water routinely enters the canal through direct drains that discharge directly into the canal. Figure 4.1 shows the locations and characteristics of direct drains that enter the canal that were documented during the erosion inventory. These drains can be categorized as those draining land within the canal right-of-way, and those that receive additional runoff from lands outside of the canal right-of-way. During our survey of the canal, it appeared that a number of direct drains are no longer active as a result of right-of-way improvements wherein storm water that previously entered the canal is now routed to a drainage which passes under or over the canal. However, there are seven direct drains on the west side of Suisun Valley which formerly passed over the canal but have been dismantled and now drain directly into the canal (see Figures 3.11 and 3.12 in Chapter 3).

Direct drains are now confined to only two areas (see Figure 4.1): in the long through-cut section of canal extending below the Headworks and in the Suisun Valley reach. Near the Headworks, the areas drained are limited to a very short portion of the right-of-way near the Headworks, and a 3,700 ft long reach extending from the east watershed boundary that directs runoff from the access road into the McCune Creek flume, downstream to the end of the long through-cut. In Suisun Valley, there are two direct drains that drain cultivated areas on the valley floor, and seven drains along the elevated portion of the canal on the west side of the valley extending to the Rockville Check. In all cases, only those drains that enter the canal on the native surface access road (right canal bank) are important to consider. Although there are direct drains along the all-weather access road side in the long through-cut at the top end of the canal, this road has a protective blanket of gravel which greatly diminishes the exposure of underlying fine sediments to erosion, however, it may be beneficial to also consider these sources during future selection and planning of BMP locations.

Figure 4.1 shows the drain locations and approximate watershed boundaries for areas contributing direct runoff to the canal, while Table 4.2 lists pertinent characteristics of the drains. Drains #2-4 and #7-13 are treated as groups as they are contiguous and any BMPs considered should apply throughout the length of the group.

4.3. Summary of Erosion Inventory Results

Results from the field inventory of lateral sediment sources were used to develop an erosion hazard index procedure that was applied on a reach-by-reach basis to identify locations along the canal with insignificant, low, moderate, high, and severe erosion and sediment production potential. A GIS database was developed that shows the sources of lateral erosion and the erosion hazard ratings for different reaches of the canal. This database can be used to identify reaches along the canal that warrant the application of erosion control BMPs.

Table 4.1. Approximate canal bank lengths for each erosion hazard class.

Erosion hazard	Canal bank length (miles)
Not significant	13.98
Low	25.33
Moderate	11.67
High	6.55
Severe	5.17

Table 4.2. Characteristics of direct drains.

Drain #	Location	Right-of-way only?	Access road length (ft)	Off right-of-way drainage area (acres)*	Land use
1	D/s of Headworks	Yes	<100	None	N/A
2-4	D/s of Headworks	Yes	3,700	None	N/A
5	Suisun Valley	No	1,200	30	Agriculture
6	Suisun Valley	No	1,100	57	Agriculture
7-13	Suisun Valley, west side	No	5,080	153	Open space, cattle grazing

* Estimated from GIS database imagery and USGS 7.5-minute quadrangles. Locations of Drain #5 and particularly #6 may be subject to considerable error due to flat terrain.

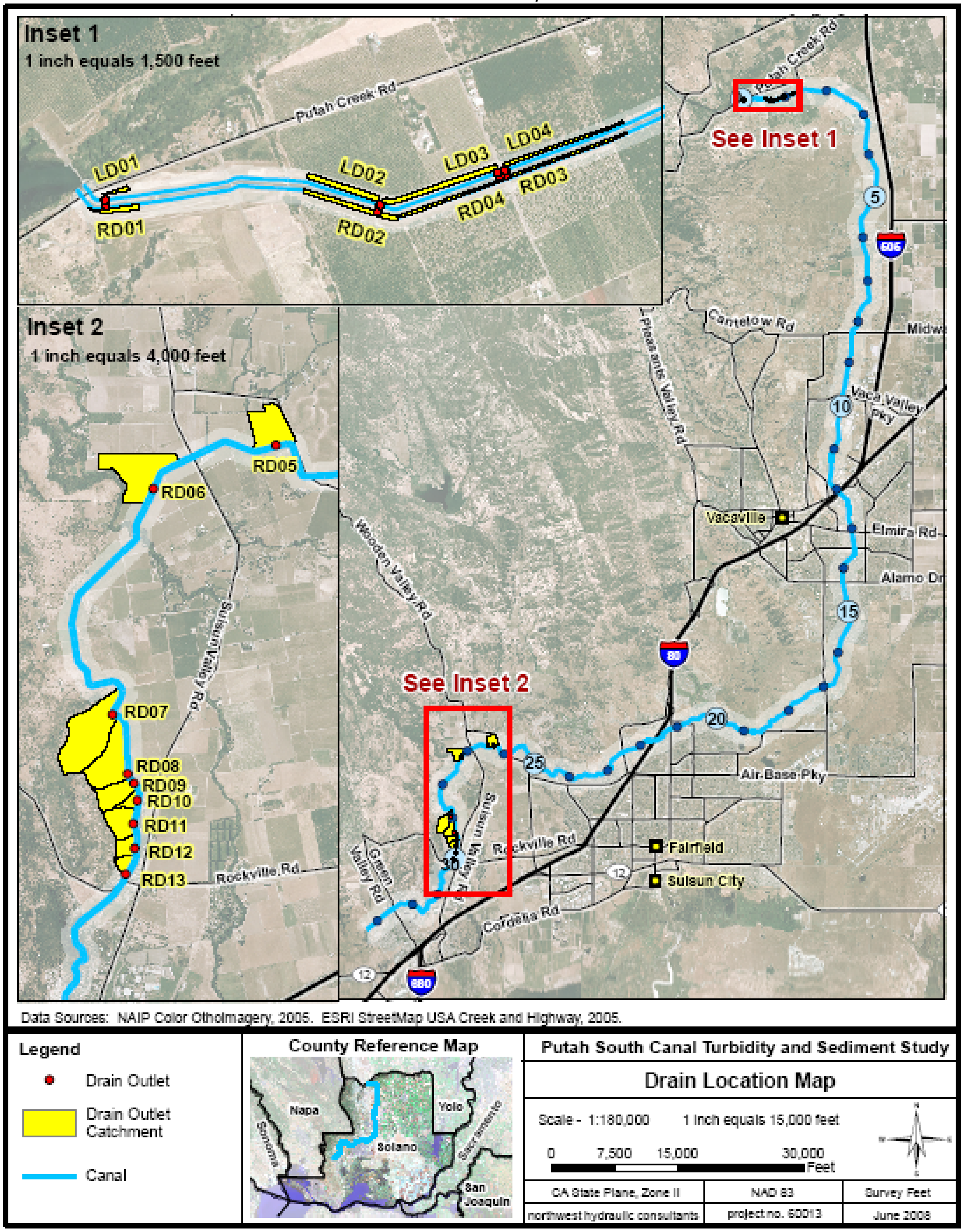

Figure 4.1. Drain location map.

5. BMP PILOT STUDIES TO EVALUATE CONTROL OF LATERAL SEDIMENT SOURCES

5.1. Purpose and Methods

5.1.1. Background

Best Management Practices (BMPs) are measures used to control nonpoint source erosion. For the Putah South Canal, BMPs are being developed and implemented to control erosion from the earthen upper banks along the canal that extend from the edge of the canal's concrete lining up to the access roads along each side of the canal. The access roads themselves slope away from the canal banks such that, except where open drains occur, runoff from the access roads does not enter the canal. Application of BMPs will control chronic sheet and rill erosion caused by overland flow on the earthen banks. Lateral sediment origins are discussed in Chapter 4.

This chapter presents the 2009 fiscal year work products including developmental aspects of several BMPs that were implemented and those planned for future implementation.

5.1.2. Chronology of 2009 Fiscal Year Work Products

At the request of SCWA a letter was issued by Hydro Science on August 22, 2008 describing BMPs that could be immediately implemented during the fall and winter of 2008-2009 (Appendix B). An initial meeting was held with SCWA and SID personnel to discuss the recommendations. Minutes of that meeting were issued by Alex Rabidoux of SCWA on September 5, 2008. Follow-up field meetings were held in October 2008 to discuss opportunities and constraints associated with the current herbicide program for the canal banks.

In December 2008, Charlotte Kimball of Kimball Neely Associates initiated grass seeding trials on nine plots located between northern Vacaville and the Suisun Valley in coordination with Hydro Science. This pilot study is further described at the end of this section.

Hydro Science sent a letter to Alex Rabidoux of SCWA and Robert MacArthur of NHC on March 2, 2009 (Appendix B) that summarized the disposition of the original "field ready" BMP recommendations. It also identified "next steps" for continuing to plan, program, and implement measures to control lateral sources. Also on March 2, 2009 Hydro Science delivered its BMP evaluation to SCWA which consisted of a spreadsheet and accompanying cover letter (Lateral Sources Evaluation Matrix). The spreadsheet listed recommended BMPs or capital improvements, assigned a priority for their implementation based on various evaluation factors, and provided cost estimates on a unit area, or, where appropriate, a lineal foot basis. The evaluation was provided as an electronic document only since it is a tool that is being provided to SCWA so they can evaluate costs and priorities, and rates for labor and equipment are subject to change. The spreadsheet evaluated all lateral sources of sediment along the canal.

During the spring of 2009, effort was devoted to formulating how earlier recommendations should be implemented. A meeting was held on March 24, 2009 between Toby Hanes of Hydro Science and SCWA personnel to discuss the Lateral Sources Evaluation Matrix. Based on that meeting, it was decided that capital improvements to control overtopping and to limit inflows from drains #5 and #6 in Suisun Valley would be evaluated for further consideration by SCWA. Hydro Science would initiate development of pilot project plans for the following alternatives using remaining available funds:

- Establish grass cover on banks formerly within herbicide "brown out" areas.
- Apply gravel mulch on operational side low banks within former "brown out" areas.
- Use polyacrylamide as an erosion control agent on operational side low banks.
- Apply gravel mulch on higher bank sites with poor soils that cannot be revegetated.
- Use polyacrylamide "floc-logs," or the equivalent to assess their viability in reducing the turbidity of storm flows entering through the direct drains.

For the lineal treatments, reaches of at least 1,000 ft and up to one mile in length would be considered for treatment. A draft pilot plan for the application of gravel mulch on banks with low revegetation potential is included in Appendix B.

A field review of the ongoing grass seeding trials was conducted on May 14, 2009 with SCWA and SID personnel, along with Toby Hanes of Hydro Science and Charlotte Kimball of Kimball Neely Associates to discuss the initial findings and to propose that SCWA or SID develop and implement a method to scarify banks prior to any other efforts to establish a grass cover through seeding. The group also reviewed the results of the interim BMP adopted the previous winter to only spray for broad-leaf weeds on the canal.

5.2. BMP Pilot Studies

5.2.1. 2009 Fiscal Year BMP Implementation

The following measures were implemented during the 2009 fiscal year. Status of these measures is found in Table 5.1.

1. Applied gravel on non-operational access road downstream of the McCune Creek overchute in the vicinity of Holmes Road. This measure, assuming proper implementation, effectively eliminates significant sediment loading from direct drains #2 through #4.

2. Applied gravel on the non-operational access road in the watersheds of direct drains #7 through #13. Implementation of this measure eliminates any significant sediment loading from the non-operational access road, although new residential development upslope of the road constitutes a potential source of sediment and other contaminants flowing into the canal within this reach.

3. Eliminated use of grass herbicide as a trial BMP during the 2008-09 rainy season. This measure resulted in the broad establishment of Italian ryegrass (*Lolium perenne*) from approximately Elmira Road downstream through Vacaville to the Union Check. In many locations the volunteer establishment of Italian rye was, to say the least, remarkable in the density of the cover, particularly on the operational side of the canal. The results of this trial indicate that vegetation establishment using Italian ryegrass is feasible and effective in establishing a grass cover on the canal banks at essentially no cost. However, former brown-out areas in Fairfield did not achieve the same results, although not all areas were surveyed. Also, no volunteer establishment occurred within the vicinity of Ulatis Road to Elmira Road. One of the issues in allowing the establishment of this aggressive annual grass is that it can commonly grow to heights of 1.5 ft or more and this height diminishes the ability to fully inspect the canal from the operational side. Further investigations of allowing volunteer establishment or seeding are planned next year.

4. The principal focus of the BMP program during the 2009 fiscal year was to conduct plot studies to assess the potential of various grass species in establishing ground cover on the canal banks. The goals and results of the study follow.

During the implementation process, several of the recommended BMPs were not adopted because of cost, priority, or internal policy. The measures not adopted are discussed below and shown in Table 5.1.

1. The non-operational access roads of direct drains #1 and #6 were not graveled. Drain #1 was not graveled because of upcoming construction at the Putah Diversion Office which may modify or change the existing drainage. Drain #6 near the Suisun Check was not graveled because the non-operational access road is used to dry out aquatic vegetation during the canal cleaning.

2. The elimination of side casting was not adopted because the U.S. Bureau of Reclamation prefers keeping a small berm on the canal side of the access road. Side casting is a result of creating and retaining this berm.

5.2.2. Grass Seeding Pilot Study

In the 2009 fiscal year SCWA initiated measures that would lead to a formal assessment of the effectiveness and practicality of revegetating portions of the Putah South Canal bank system. The initial field revegetation work consisted of a “growing season” trial in which nine pilot study sites along the canal system were identified and each was seeded with four different seed mixes in December 2008 in anticipation of the seasonal rains. The trial locations were monitored four times during the period January 2009 through early June 2009.

Site Selection

In late summer 2008, field reviews were conducted to assess soil conditions, bank lengths, and accessibility for installing trial plots. In addition, data from SID staff, the 1977 Solano County Soil Survey and overall revegetation potential of the trial plots were evaluated.

The trial plot location criteria included:

- Locations where SID/SCWA determined herbicide treatments would no longer be routinely applied;
- Soils/subsoils textures would support root systems over time, i.e. soils appeared to allow at least some root penetration;
- No broad leaf plants were to be included in the seed mix since broad leaf weed control could potentially conflict with presence of broad leaf species in the mix.
- Canal banks were sufficiently long (top to bottom) so as to warrant revegetation; and
- Accessibility during extremely wet weather.

Seven study sites were selected and of the seven, two sites included both (opposite) sides of the canal for a total of nine test plots (see Figure 5.1). The sites, along with mile point, exposure, and soil class data, are found in Table 5.2. Note that since the canal banks are essentially excavated, soil classes shown may not represent the actual trial plot soils. These soils may be partially or fully subsoils or mixtures of soil classes. In summary the soil classes provided general guidance for initial plans, whereas field observations and discussions with SCWA/SID provided “reality” checks.

Revegetation Approach

In addition to observing the existing soil conditions, slope attributes, and plant communities along the canal, grass species commonly used for revegetation purposes in the Central Valley and Bay Area interior regions were reviewed for likely success. The revegetation grasses would be subject to competition from weeds, periods of drought, wind, unknown substrates, and four locations with southern exposures. Five applications (Seed mixes A, B, C, D, E) were selected and the components in the multi-species mixes were equally blended. See Table 5.3 for seed mix components.

In early November 2008 the study areas were staked and flagged in order to identify each of the four plots within the trial area and also to identify the overall pilot zone for SID employees present on the canal system. These areas were “off limits” for herbicide applications.

The implementation process included vigorous hand raking and scarification of the soils prior to hand application of an estimated 30 pounds/acre equivalent of each of the four mixes and one single species application designated for the seven sites. Sand was added to the soil mix as an extender but no mulch or tackifier (sticking agent) was applied. Seeding occurred on December 12, 2008.

5.3. BMPs Summary Results

5.3.1. Grass Seeding Pilot Study

Following is a list of the first year monitoring objectives followed by a summary of BMP activities and results:

1. Estimate cover of each seed plot and document the primary species present and note any weedy or non-seed mix species.

2. Determine presence or absence of each species and determine most reliable seed mixes for specific site conditions.

3. Document any other observation that may help with analysis of future BMPs aimed at improving vegetative cover.

4. Summarize limitations, conclusions and recommendations learned from monitoring program.

Field monitoring of the test plots was conducted three times during the period: February 2, 2009; April 17, 2009; and June 4, 2009. Based on lack of rainfall and a site inspection on January 20, 2009 which indicated low soil moisture at the trial sites, plans for watering the trial plots were developed. On February 2, 2009 Toby Hanes and Tom Neely performed hand watering at all sites in addition to monitoring growth patterns. The extent of seeded cover (not weedy cover) expressed in percentages detected over the area of each of four trial plots was recorded. Cover areas were visually estimated and notes regarding plant condition, weed presence, and other conditions (presence of algal mat or flocculants) were made during monitoring visits.

Table 5.4 shows the monitoring results. Photographs showing conditions observed on the third monitoring event conducted on June 4, 2009 are found in Figure 5.2. Four sites performed poorly: Vaca Valley Parkway, Elmira Road, Cement Hill, and to some extent Suisun Valley North. These sites were characterized by minimal cover of the seeded species (or bare), weed presence, particularly at the toe of the bank, and remaining bank area bare or nearly bare.

Vaca Valley Parkway appeared to start off well but declined over the trial period. Elmira showed a small burst of cover early in the year but the vegetative cover did not increase during late winter and spring. Cement Hill declined from an initial 20-25% vegetative cover to essentially bare slopes (with exception of weedy species), and Mix C was the only visible component at Suisun Valley North, and of the mix, California barley was the primary species present. This species was not flowering at the time of the last monitoring period and therefore may not sustain itself. This species may require more moisture than it received initially this past growing season to continue development, including flowering.

The remaining five plots, Youngsdale, Dover South and Dover North, Mankas Drain, and Suisun Valley South were satisfactory. Wimmera rye (a cultivated variety of Italian Rye, *Lolium sp.*) was the most abundant in all these plots, followed by Mix C which is composed of Purple and Nodding Needlegrass, one-sided bluegrass, and California barley. The Wimmera rye was flowering at all sites, as were the majority of the needlegrass and bluegrass. California barley was not flowering at any of the sites but its stature had increased between April and June.

Broadleaf weeds were obvious and included species common to Solano County, including filaree (*Erodium botrys*), fluvellin (*Kickxia spuria*), lambsquarters (*Chenopodium alba*.), mare's tail (*Conyza canadensis*), mustards (*Brassica nigra, B. campestris*), common groundsel (S*enecio vulgaris*), sow thistle (*Sonchus oleraceus*), and several weedy grasses. Vaca Valley Parkway site expresses its own cover with filaree and annual grasses such as Medusa head (*Taeniatherum medusa*), ripgut brome (*Bromus rigidus*), and cheat grass (*B. tectorum*). These weedy rangeland species are prevalent in soils with clay substrates and limited topsoil.

Generally rye grass requires more soil moisture than needlegrass species. In 2009-2010 tracking the presence and sustainability of the grass species remaining in the current pilot study plots may provide insight into longer term vegetation management; and California barley, though stunted this year, may prove to be a potential future component. In the present trial, its overall cover increased during the trial and it may be worthwhile to trial this species again in fall 2009. A more typical rainfall pattern may induce production of plants capable of reproduction and future sustainability.

Overall, the abnormally dry conditions, especially during the critical month of February 2009, does not allow for firm conclusions. Wimera rye shows the most promise in becoming widely established and controlling erosion. However, based on the May 14, 2009 field review, it is not the most desirable species because of its slightly excessive height. Wimmera rye may also prove problematic since the genus Lolium shows resistance to glyphosate herbicide and future management actions may be restricted.

The reviewers agreed that California barley would be preferable, if it can be shown to become established and provide a sufficiently dense cover to control erosion. Some of the other trial species may also prove viable when seeded under more normal climatic conditions. The fact that many of the plots performed poorly, including Wimera rye which aggressively established itself throughout Vacaville without seeding (see following section), particularly the Elmira and Cement Hill plots suggests that other soil factors are influencing the results, including the possibility of herbicide residuals.

In the 2008-2009 pilot study, the Wimmera rye achieved the greatest cover in the most number of plots. Other trial species that may perform under a more typical rainy season regime are California barley, the purple and nodding needlegrasses, and Idaho fescue. Although the one sided bluegrass was apparent in several plots, it did not appear to be a suitable erosion control species due to its weak root systems. Bentgrass did not survive the drought conditions. Future trials, if any, should include all of the species discussed above with the omission of one sided bluegrass and bentgrass despite the fact that Wimmera rye dominated the current trial.

Broadleaf weed control remains an issue. The current pilot study indicated that broadleaf weeds compete and interfere with the establishment of the grass species. SCWA may wish to explore use of pre-emergent broadleaf applications, or other treatments, in areas where bank revegetation is a goal.

The soil/subsoil conditions and slope of the canal banks are sufficiently steep and impenetrable to warrant scarification prior to any future reseeding. The purpose of scarification is to provide surface roughness which in turn provides a more stable seed bed, including some soil coverage of the grass seeds. In addition seeding with a hydroseeder/mulcher should be considered, particularly if costs can be controlled by performing this task in house. Hydro seeding/mulching add even more stability to the seedbed and adds a mulch which further protects the seedbed and helps to hold moisture in the seedbed. This approach was discussed during the May 14, 2009 field review and will require technical input and design from SCWA staff.

5.3.2. Gravel, Brown Out, and Italian Rye Grass

Based on the cost estimates established during the BMP evaluation (Lateral Sources Evaluation Matrix), revegetating former brown-out areas with grass is the most cost effective means of controlling chronic sheet erosion on the canal banks. The estimated cost of treatment is approximately $3,000 per acre, assuming full cover is established. This compares to estimated costs of approximately $17,000 per acre for grass establishment with the aid of temporary netting, from $30,000 to $44,000 per acre for application of gravel mulch, and an estimate of $63,000 per acre using permanent geotextiles. However, as the results of the plot studies indicate, assurance that a grass cover of sufficient density can be reliably established has yet to be demonstrated at all sites and for low-stature species which are favored since they do not obstruct visibility of the canal.

In many locations erosion from the canal banks has reduced or eliminated the as-built 3 ft wide vertical toe at the canal edge. From an erosion control perspective, this toe can act to store sediment eroded from the adjacent banks. However, in general, where there is a grass cover between the canal bank and the canal edge, regardless of the amount of previous sediment deposition, there is little sediment delivery into the canal. As a result, a higher priority has been given to eliminating sheet erosion from canal banks in the “brown out” areas through establishment of grass, application of gravel mulch, or sealing the surface through use of a polyacrylamide, than restoring the 3 ft wide vertical toe.

The remarkably successful establishment of a dense cover of volunteer Italian rye (Figure 5.3) indicates that successful treatment of miles of the canal can be accomplished simply by not applying broad-spectrum herbicides typically used to kill all grass on the canal banks. However, there are some trade-offs associated with allowing the establishment of Italian ryegrass. It is becoming resistant to certain herbicides and allowing its establishment along the Putah South

Canal in the former brown-out areas could hamper efforts to control it elsewhere. It should be noted, however, that it has been a dominant species elsewhere throughout the canal in locations outside of the brown-out areas. It also appears to be slightly too tall as a desirable grass from the perspective that it can reduce full visibility of the canal from inspections performed from the operational side of the canal, although it may be possible under some circumstances to limit its height by using very dilute concentrations of herbicide. Additionally, the height concern is generally limited to a 3-4 month period beginning in February when the grass is green and mature. In late spring the current year's growth dies and it begins to lie down and form a thatch.

Even if other species are utilized to revegetate the canal banks to avoid the trade-offs discussed above, they may eventually be supplanted by Italian rye. Also, the results of the first grass seeding trials indicate that there may be a number of locations where grass establishment may be difficult or infeasible. Trials conducted in the vicinities of the Vacaville and Cement Hill water treatment plants, in addition to areas in Suisun Valley had poor results, even accounting for the difficult conditions for grass establishment last winter. Further investigations are needed to determine if grass establishment is universally feasible. It may be possible that, in certain soil types, long use of broad-spectrum herbicides has lead to residuals in some locations.

For 2009, the greatest <u>immediate</u> progress in BMP implementation could be attained by allowing Italian rye to become established as a volunteer. It is recommended that SCWA either adopt this strategy or work toward identifying under what specific circumstances it could be allowed. Further trials and investigations may be needed to establish a long term policy for Italian rye, particularly if further grass seeding trials indicate that it can be supplanted by more desirable species.

The following recommendations and considerations are provided in moving forward with the application of BMPs on the canal banks.

1. Continue monitoring of the existing grass seeding plots and initiate new trials with specific emphasis on determining if California barley can become established, be self-sustaining, and have sufficient density to control erosion.

2. Contingent upon the results of #1 above, SCWA should consider adopting a policy on allowing volunteer Italian rye, which has been found to be a highly effective erosion control species, to establish itself, and the use of Wimera rye (the same species as Italian rye) in other locations where volunteer establishment may not occur.

3. SCWA should develop a scarification implement to use for any additional grass seeding on the canal banks within the former brown-out areas.

4. Additional grass seeding trials or broader efforts should utilize a hydromulcher, as this will simulate the revegetation technique which will be used to revegetate larger areas.

5. Some problem soils exist which may limit the use of erosion control through grass establishment on the canal banks. Some specific efforts at testing these soils to determine

why they apparently resist revegetation efforts should be made. These problems could be related to salinity, defloculation, or possibly residual herbicide toxicity. Once the causes are known, then efforts should be made to determine if these soils can be remediated or if other BMPs need to be applied.

Table 5.1. Status of lateral source sediment control measures.

BMP	Imple-mented in fall 2008	Planned for 2009	Low priority, high cost	SCWA to conduct further planning	Deferred possible capital improve-ment	Recommen-dation not adopted
Dicot only herbicide use	●					
Gravel non-op road in vicinity of drains #1-4 (Holmes Road)	●					
Gravel non-op road, drains #7-13	●					
Gravel non-op road in vicinity of drains #5 and #6 in Suisun Valley		●				
Initiate grass seeding trials	●					
Eliminate side casting						●
Reestablish minimally-acceptable access road outslope						●
Apply gravel mulch to banks with low revegetation potential		Pilot project				
Apply polyacrylamide to banks with low revegetation potential				●		
Apply gravel mulch to low banks, operational side		Pilot project				
Apply polyacrylamide to low banks, operational side		Pilot project				
Use floc-logs on direct drains #5-13		Pilot project				
Volunteer establishment of Italian ryegrass				●		

Table 5.1. (continued)

BMP	Imple-mented in fall 2008	Planned for 2009	Low priority, high cost	SCWA to conduct further planning	Deferred possible capital improve-ment	Recommen-dation not adopted
Reduce overtopping frequency					●	
Reduce / eliminate off-ROW inputs, drains 5 and 6				●		
Additional grass seeding trials		●				
Grass establishment, desirable species		Pilot project				
Toe recovery			●			
Grass revegetation with nettings / geotextiles			●			

Table 5.2. Trial grass seeding plot locations.

Site Name	MP (est.)	Exposure	Soil class	Description
Vaca Valley Parkway	10.4	Eastern	CvDz	Corning soils, mixed clays/gravel alluvium
Elmira	13.1	Eastern, very shady in afternoon	BrA	Brentwood series, found with Yolo soils, alluvial
Youngsdale	15	Eastern	Dbc	Dibble/Los Osos loam over weathered sandstone
Cement Hill	20	Southwest	CeA	Clear Lake clay, poorly drained
Dover – N Dover – S	20.5	Northern & Southern	AcE	Altamont clay, mixtures of Diablo clay and clay-loam
Mankas Drain	25.4	Southern	Ss	Alluvial loam
Suisun Valley – N Suisun Valley – S	27	Northern & Southern	Br	Brentwood alluvium

Table 5.3. Seed mixes A-E - grass components.

Seed mix	Grass	Grass	Grass	Grass
A	Bent grass	Idaho fescue	Purple Needlegrass	Red Fescue
B	3 Week fescue	Rat tail fescue	Nodding Needlegrass	
C	Purple Needlegrass	One sided bluegrass	CA barley	
D	Wimmera Rye grass			
E	Bent grass			

Table 5.4. Percent cover of seeded grasses in 5 seed mixes at pilot study sites.

Plot monitoring dates	February 2, 2009					April 17, 2009					June 4,2009				
Site / Seed Mix	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**	**A**	**B**	**C**	**D**	**E**
V Valley Pkwy	45	45	40	50	N/A	10	5	10	20	N/A	5	5	5	10	N/A
Elmira	0	5	10	10	N/A	1	3	2	3	N/A	1	2	0	3	N/A
Youngsdale	10	20	20	30	N/A	15	20	25	30	N/A	3	10	20	40	N/A
Cement Hill	10	25	5	20	N/A	0	0	0	1	N/A	0	0	0	10	N/A
Dover South	30	20	30	50	N/A	50	10	20	20	N/A	20	15	30	65	N/A
Dover North	50	10	25	75	N/A	20	25	25	100	N/A	45	25	35	98	N/A
Mankas Drain	70	N/A	35	50	0	60	N/A	50	85	0	45	N/A	25	80	0
Suisun Valley S	15	N/A	30	40	5	25	N/A	45	70	1	10	N/A	45	35	10
Suisun Valley N	0	N/A	10	0	0	1	N/A	25	5	1	0	N/A	20	5	0

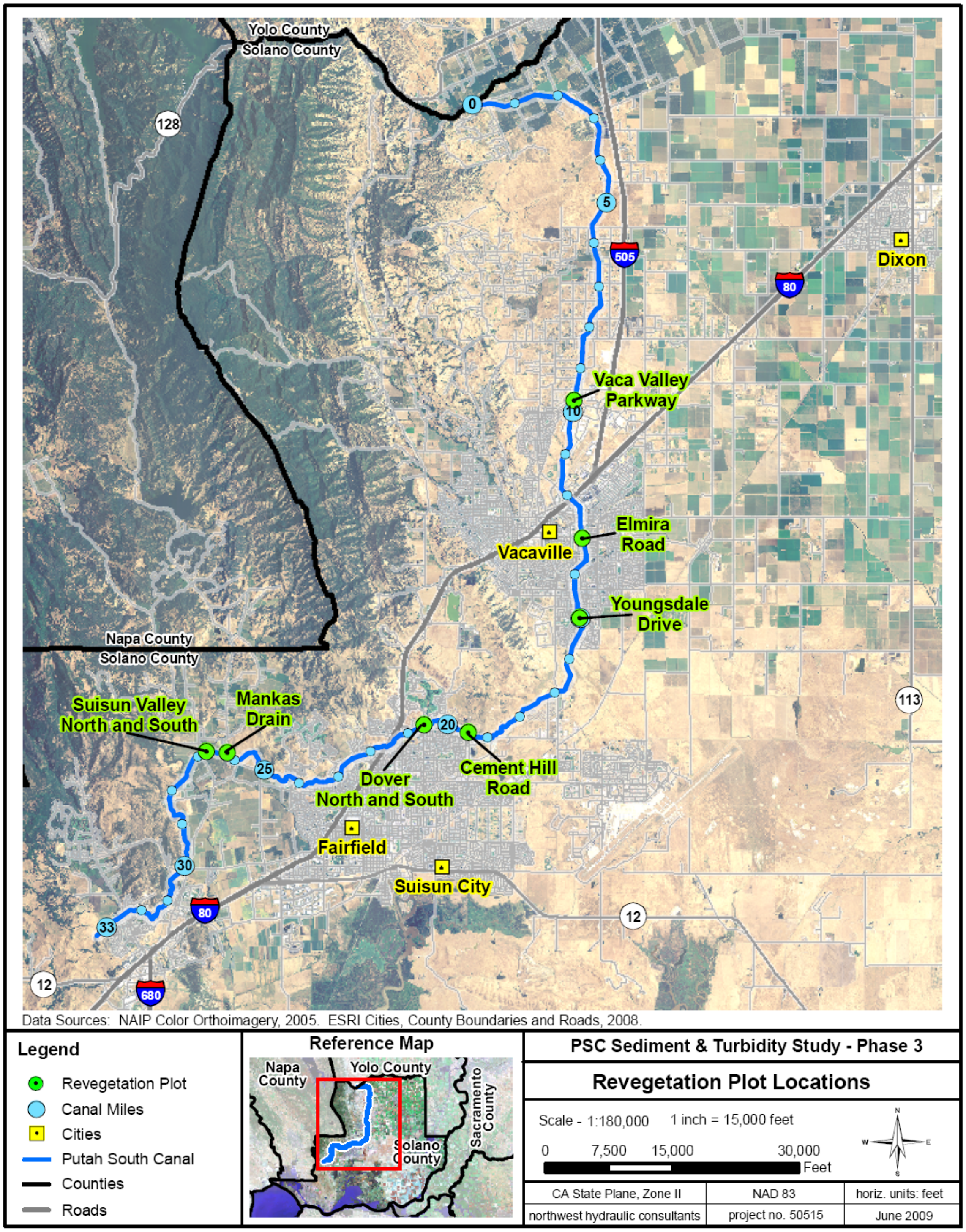

Figure 5.1. Revegetation test plot locations.

Vaca Valley Parkway to North
Plots similar to adjacent areas

Elmira to East
Mix D- Wimmera Rye Plot – bare

Youngsdale to North
Closest Plot – Mix D -Wimmera Rye

Dover to North
Mix B - Nodding needlegrass & broadleaf weeds

Dover to South
Seed Mix C - Note California barley in foreground and weed presence

Cement Hill
Seed Mix D – Wimmera Rye – 4 grass plants

Figure 5.2. Photos showing pilot study grass seeding trial locations.
Date of photos – June 4, 2009.

Cement Hill Adjacent area to East
(Not in study area)

Mankas Junction Mix D -Wimmera Rye
Note weed presence at toe

Suisun Valley, South Side
Broadleaf weeds dominate plots

Suisun Valley, North Side
Mix E - Bentgrass at flag, otherwise missing

Figure 5.2. (continued).

Figure 5.3. Volunteer Italian ryegrass growing on canal bank. View downstream from Alamo Drive, Vacaville, Date of Photo June 29, 2009.

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6. ADCP MEASUREMENTS

6.1. Purpose and Methods

The purpose of this task was to measure general flow characteristics, such as depth-average flow velocity and typical lateral and vertical flow distributions found in the Putah South Canal (PSC). Flow characteristics occurring in Lake Solano for flows that approach the PSC Headworks and flow characteristics that occur in the forebay of the Headworks were also measured. Vertical and horizontal velocity profiles where measured at several typical canal locations and in Lake Solano just upstream from the Headworks and in the forebay of the Headworks. Results help identify flow conditions that may contribute to dead zones and gyres that can influence local sediment deposition and encourage the growth of aquatic vegetation occurring in the main canal. All measurements were made using an RD Instruments WorkHorse Rio Grande (1,200 kHz) model Acoustic Doppler Current Profiler (ADCP) mounted on a boat. Flow monitoring sites included: (1) portions of the PSC upstream and near the Weyand Intake structure located at MP 5.6, (2) a section of the canal near MP 23.5 in the vicinity of the Waterman WTP Intake, (3) in Lake Solano at the Headworks, and (4) in the Headworks forebay.

In simplified terms, during measurements, the ADCP generates a series of pings (energy pulses) which are directed down through the water column. Based on the travel time and phase shift of returning energy that has been reflected off of particles in the water column, water velocity (both the magnitude and direction) is determined. Energy reflected off of the canal or lake bottom is used to determine the approximate depth of water, and the direction and distance the ADCP has traveled. The water column is divided into a series of bins (segments) with a consistent vertical dimension (bin depth). All readings within a bin are averaged to produce a representative velocity (magnitude and direction) for that bin. Bin discharges are calculated using uniform flow principles and the total measured discharge is the summation of the flow in the bins.

Figures 6.1 and 6.2 show the ADCP mounted on a Madison inflatable double pontoon Trout Unlimited drift boat. Instrument commands and data communication with the ADCP occurs through a wireless (radio-telemetered) connection between the ADCP unit mounted on the boat and a portable laptop computer located on the shore. Sixteen equally spaced transect locations at 50-ft spacing were laid out normal to the canal alignment starting at MP 5.6, at the Weyand Intake structure and progressed approximately 750 ft upstream from the Weyand Intake. ADCP measurements taken near the Weyand Intake structure were made on September 24, 2007. The upstream portion of the study reach is a straight channel where flow is expected to be relatively straight and parallel to the canal alignment (Figure 6.3). These measurements were compared to ADCP measurements made around the gentle left-hand bend portion of the study reach to show that there is a higher concentration of flow along the outside portion of bends which explains why sediment and aquatic vegetation tend to colonize inner portions of canal bends. Additional canal measurements were obtained in the vicinity of the Waterman WTP (near MP 23.5) on September 28, 2007.

Figure 6.4 shows the approximate locations of the nine velocity measurement transects used in Lake Solano and the Headworks on May 20, 2008. Figures 6.5 and 6.6 show the WorkHorse Rio Grande ADCP, battery pack, and radio-telemetered instrument package mounted in an Oceanscience RiverBoat and being deployed at Lake Solano.

6.2. 2007-2008 ADCP Measurement Results

6.2.1. Measurements at Weyand Intake

A series of ADCP measurements were conducted in the Putah South Canal near the Weyand Intake on September 24, 2007. Figure 6.7 shows flow velocity fields measured at two canal transects looking downstream. The top transect is located at Station 7+50 in the straight section of the canal 750 ft upstream from the Weyand Intake and one at Station 2+00 in a gentle bend section 200 ft upstream from the Weyand Intake structure. Measurements made at these two Stations were conducted about 6 hrs apart, so the flow in the canal had changed slightly (increased by about 50 cfs) to meet downstream water demands. The lateral distribution of streamwise velocity measured across the canal at these two stations is shown by different colors. The highest velocities are shown in red and orange, while the lowest velocities are depicted by the light to dark blue colors. The black borders on either side represent the concrete sides of the canal. As shown in the straight canal section at Station 7+50 (the top portion of Figure 6.7), the highest velocities are located in the central and deepest portion of the canal and decrease as you move away from the center of the canal toward the sides of the canal. With a discharge of approximately 195 cfs, the velocity was about 0.8 ft/s in the center of the high flow zone at Station 7+50 and decreased to 0.1 ft/s or less near the sides and bottom of the canal.

Figure 6.8 shows how well the measured vertical velocity profiles match a theoretical “log law velocity distribution” in the straight and parallel reach. The horizontal red lines located below the velocity profiles shown in Figure 6.8 show depth to the canal bottom or depth to the canal sides.

The lower portion of Figure 6.7 shows how flow becomes less organized and shifts toward the outer canal bank as flow moves around a bend. As shown by the dark blue areas located along the inner bank (left bank looking downstream), flow along the inner toe of the canal has lower velocities than the flow measured along the outer toe in the bend. This lateral shift of flow toward the outer bank becomes more pronounced with higher discharges. The concentrated high flows located in the central portion of the canal in the upper figure at Station 7+50 become less organized and skewed toward the outer bank as shown in the lower portion of Figure 6.7 due to a helical, or cork-screw-type current pattern that develops as flow moves around a bend (Chow 1959). This lateral adjustment of flow and displacement of the central core of high flow toward the outer bank of the canal reduces the bottom shear stress along the inboard toe through a bend, allowing sediment to deposit and aquatic vegetation to colonize inner portions of bends. These flow characteristics are common in open channel flow and are observed in most bends found in the PSC.

6.2.2. Measurements near Waterman Water Treatment Plant

Additional ADCP measurements were conducted in the canal near the Waterman WTP Intake on September 28, 2007. Velocity measurements were made in a short reach of the canal located approximately 200 ft upstream from the Waterman WTP Intake. There was a significant amount of aquatic vegetation (macrophytes and algae) growing in the reach. Figure 6.9 presents a view of the reach looking upstream from the Serpas Check.

Figure 6.10 shows the ADCP being deployed in the straight section of canal approximately 300 ft upstream from the Waterman WTP. A first set of flow and velocity measurements were collected across the canal section with all of the vegetation in place. Then, prior to the next set of measurements, our field team dragged a steel tow chain along the bottom of a 200-ft section of the canal to remove some vegetation growing in the canal. The field team was only able to dislodge a portion of the higher aquatic plants and weeds; some clumps of vegetation remained in place. A second set of flow and velocity measurements was made at the previous transect location with a portion of the vegetation removed. Figure 6.11 shows both sets of measurements made at the same transect; the upper figure with vegetation in place and the lower figure with a portion of the vegetation removed. This comparison shows how the growth of thick colonies of macrophytes in the canal can dramatically affect flow distribution and efficiency in the canal. If the field team had been able to dislodge more attached vegetation from the canal sides and bottom, the measured differences would have been even more dramatic. Nevertheless, these results show how thick colonies of vegetation significantly reduce channel conveyance and alter the location of relatively free-flowing zones of water toward the upper and outer edges of the canal. Note that there is a significant portion in the center and bottom of the canal where there is little or no flow velocity due to thick mats of vegetation and deposits of sediment and organic materials that accumulate beneath the vegetation. Our field team spoke with operators at the Waterman WTP and they said that they have to manually remove aquatic vegetation along the right canal bank in the vicinity of the plant's intake quite frequently. Figure 6.11 shows the effects of previous vegetation removal along the right bank line where pockets of flow are located near the surface along the right bank.

Results from the ADCP measurements show how bends in the canal affect lateral flow distributions and may encourage the deposition of sediment and the growth of aquatic vegetation in areas with less shear stress, such as along the inside of canal bends or just upstream of canal control structures. This is the situation at the Waterman WTP which is located just upstream from the Serpas Check, where water depth increases and bottom velocities decrease because flow moving through the canal is metered over the top of the control structure (rather than under the control structure) in order to maintain a constant head condition in the canal. Note that the highest velocity readings in the canal were all less than 0.8 ft/s with significant portions of the flow area along the canal bottom and sides being zero or near zero velocity. Sediment, decomposed plant and organic materials can rapidly deposit in these low energy zones which then provides an optimal location for aquatic vegetation to grow. It is also likely that the application of algaecides is dramatically affected by lateral changes in channel hydraulic conditions (in bends and near control structures), as well as the growth of thick vegetation which decrease full channel mixing and chemical distribution in the water column.

6.2.3. Measurements in Lake Solano and Headworks

On May 20, 2008 additional flow and current (velocity) measurements were made in Lake Solano in the approach area to the Headworks and in the forebay of the Headworks. Figure 6.4 shows the approximate locations of the nine measurement transects near the Headworks. Six transects were located in Lake Solano to measure currents that approach the Headworks and three transects were measured inside the Headworks forebay. Figures 6.5 and 6.6 show the ADCP, battery pack, and radio-telemetered instrument package and how it was deployed in a Oceanscience RiverBoat at Lake Solano near the Headworks. For each transect, a 1/8 inch steel cable tag-line was pulled tight across the lake at the elevation of the top of the work pads and road around the diversion dam (approximately 10 ft above lake level). The RiverBoat was attached to the tag-line with a pulley block with tether lines connected to either side so the boat could be pulled slowly across each section, or held in place during stationary readings. Figure 6.12 shows a typical full section display of the measured flow field (velocity contour profile), water depth, and bed topography crossing Section #1 (see Figure 6.4). This section is displayed looking downstream and provides a 2-dimensional view of the vertical and lateral variations in flow velocity crossing the vertical plane cut by the upstream most section, Section #1. The total length of Section #1 is approximately 308 ft and extends from the upstream corner on the southern face of the Headworks across Lake Solano to the north face of the concrete turning island which is part of the left abutment for the diversion dam. In Figure 6.12, the velocity magnitude is represented by different colors, with purple and lavender being the lowest (near zero) and red being the maximum value within a specified range. A velocity legend is located at the top of the Figure 6.12. There are narrow regions near the surface and bottom of the water column where reliable velocity measurements are not available. These regions are “blanked out” due to high levels of noise generated by the pinging of the instrument and reflections off the bed as well as the effects of flow around the head of the ADCP which make readings unreliable to report.

Quality control and assurance procedures undertaken for the measurements at the site included repeatability of transect discharges (loop test), tests for bed movement and comparison of measured discharge passing a section with those reported by operators for the release flow through the Headworks into the Putah South Canal. During the validation runs, a total flow of approximately 620 cfs was measured passing Section #1 while operators for the Solano Project told us that they were pulling approximately 630 cfs through the Headworks at that time. The difference between these values is well within the error limits of the instrument and the methods used to establish the Headworks release rating curve. Therefore, it is considered that the measurements obtained were reliable with the instrument settings and procedures used.

Figure 6.13 shows how flows begin to accelerate as they approach the entrance to the Headworks. This figure shows the measured flow field crossing Section #4. Note that there are many locations within the flow field where bin velocities are between 1 and 2 ft/s. Also note from the bottom profiles shown in Figures 6.12 and 6.13, that there is an appreciable sediment and debris mound located about 40 ft upstream and lakeward from the entrance to the Headworks and upstream about 25 to 35 ft from the diversion dam. Figure 1.12 in Chapter 1 of this report shows a photograph of this mound of deposited sediment and debris that was exposed during inspections of the dam and Headworks during the late 1990's.

In addition to measuring the flow field across an entire transect, individual stationary readings were made at locations along each transect spaced approximately 30 ft apart. Figure 6.14 shows a typical stationary velocity profile measured at a stationary point located approximately in the middle part of Transect #1. Figure 6.15 shows the six transects located in Lake Solano and the measurement locations where individual "stationary" measurements were taken. Appendix C-6.1 provides a summary of the flow field and individual stationary measurements collected on May 20, 2008. The red line in Figure 6.14 (and velocity profiles in Appendix C-6.1) indicates the approximate location of the lake bottom at that transect point. This figure shows a reasonably smooth velocity profile with near bottom velocity readings of approximately 0.38 ft/s up to 0.75 ft/s approximately 1.5 ft beneath the water surface at that location.

Measured velocities increase as the transects and flow measurements get closer to the face of the dam and the Headworks because flows approaching the Headworks accelerate as they enter the narrow opening into the forebay behind the trash rack. Figure 6.16 shows a plan view of the depth-averaged velocity vectors (velocity field) along each of the six lake transects and along the three transects located inside the forebay behind the trash racks. The orientation of the colored arrows indicates the direction of the depth-averaged flow and the lengths of the arrows indicate the depth-averaged magnitude of velocity in ft/s. The scale bar in Figure 6.16 indicates a depth-averaged (not maximum) velocity of magnitude 1 ft/s.

Figure 6.17 shows contours of depth-averaged velocity near the entrance to the Headworks and inside the forebay. This figure shows that mild approach velocities exist in the main body of Lake Solano. Once approaching flows get to within 50 to 100 ft from the inlet to the Headworks they begin to accelerate as they enter the forebay with depth-averaged velocities of approximately 1-1.5 ft/s. Note, because of the skewed angle of approach to the Headworks, unevenly distributed (laterally and vertically) accumulations of vegetation and debris on the trash racks, and wing walls, the entrance velocities are not uniform across the entrance to the Headworks. Also note that there is a large eddy located in the north-east corner of the forebay. Therefore, only about 1/2 to 3/5 of the entrance cross-section is being effectively used to convey inlet flows to the canal.

A final set of flow measurements was made along Sections #5 and #6 adjacent to the inlet to the Headworks and adjacent to the diversion dam with the gate in Bay #12 partially open by the operator to about 6 inches (~125 cfs) for a period of only 4 minutes to measure how a partial gate opening may affect approach velocities. Opening the tainter gate 6 inches in Bay #12 slightly accelerated the bottom velocities approaching the south-east corner of the diversion dam because the release was being made near the bottom of the structure, 15 ft below the surface. This short duration experiment showed that if the Headworks was closed and the gates in Bays #11 and #12 in the diversion dam could be periodically opened a small amount for 15 minutes to an hour on a more regular basis, it may generate sufficient sweeping flows parallel to the Headworks near the bottom to help clean accumulations of sediment away from the entrance to the Headworks. These preliminary results indicate that it may be worth while to plan and implement additional test releases from the diversion dam at different times of the year to assess the effectiveness of cleaning bottom materials from the entrance to the Headworks. Periodic releases with greater magnitude flow pulses and durations longer than 4 minutes may reduce sediment accumulations.

It is also very important to realize that flow conditions during the summer low river flow period is significantly different from conditions observed during the winter when high flows occur on Putah Creek. Flows entering Lake Solano during significant winter storms can be thousands of cfs and can be extremely turbid and carry high loads of suspended sediment into the lake and Headworks (in excess of 4,000 NTUs) if it is open. NHC staff members have observed surface flow velocities on the order of 5-10 ft/s approaching the Headworks and diversion dam when the dam is releasing flood flows (refer to Figure 3.3 in Chapter 3). Large trees, floating debris, and high concentrations (and loads) of suspended sediment move into and through the lake during large storm events. During periods of high flow, there is more than enough turbulence and flow velocity to transport gravel, sand, silt, and clay materials into and through the lake. Pleasants Creek is well known to be a large producer of sediment. Figure 1.11 in Chapter 1 shows a huge sediment delta that formed at the mouth of Pleasants Creek. Understanding that high intensity storm events generate runoff with high suspended sediment concentrations, NHC prepared a draft set of interim facilities operation procedures for the Headworks to minimize suspended sediment loading into the PSC during significant storm events. The interim procedure tested during an event in February 24, 2008 and proved to be quite effective. Since then, the SCWA and Solano Project operators refined NHC's draft procedures into a new "Interim Protocol for Reducing Suspended Sediment into the PSC." A copy of this new interim protocol is provided in Appendix C-6.2.

It may be beneficial to plan and test re-operation scenarios at the diversion dam during the recession period after large storm events to keep the entrance to the Headworks and forebay clean of sediment deposits. We recommend that such tests be planned and tested next winter during periods of high flow.

6.3. Summary of ADCP measurements

Hydraulic flow characteristics were measured using the ADCP at selected locations in the Putah South Canal and in Lake Solano. Flow monitoring sites included (1) a straight reach of the canal and a canal bend in the vicinity of the Weyand Intake (MP 5.6), (2) a straight reach of the canal upstream of the Waterman WTP Intake (MP 23.5), (3) Lake Solano in the vicinity of the diversion dam and the Headworks, and (4) inside the Headworks forebay. The flow patterns measured in the non-vegetated reaches of the PSC at the Weyand Intake were common to open channel flows. The highest velocity was located in the central, deepest portion of the canal in the straight reaches and was shifted toward the outer bank in the canal bend. During the measurements, water discharge ranged from 195 to 245 cfs, with maximum measured velocities of approximately 0.8-1 ft/s. Vertical velocity profiles followed a typical “log law” distribution.

The flow measurement in a heavily vegetated reach of the PSC at the Waterman WTP revealed a dramatic effect of aquatic vegetation on flow distribution in the canal. The thick vegetation growing on the bottom of the trapezoidal canal significantly slowed flow in the central portion of the canal and resulted in a highly non-uniform velocity distribution. Velocities in the lower 1/2 to 1/3 of the water column in the vegetated portion of the canal were near zero. The highest velocities were observed in free-flowing zones at the water surface along the canal edges. Partial removal of the vegetation increased stream velocities in the central portion of the canal and resulted in more uniform vertical and lateral velocity distributions. Maximum velocities measured at the Waterman WTP were approximately 0.6-0.8 ft/s.

The ADCP measurements in Lake Solano revealed converging and accelerating flows at the entrance to the Headworks. During the measurements, outflow from the lake into the PSC was 620 to 630 cfs. Measured depth-average velocities ranged from 0.25 to 0.75 ft/s in the lake near the diversion dam to 0.75-1.25 ft/s at the trash screens. The highest velocities (over 3 ft/s) were observed in the narrowest section of the Headworks forebay near the sluice gates. A large eddy was detected in the north-east corner of the forebay, which indicated that only 1/2 to 3/5 of the entrance cross section was effectively conveying flows into the canal on the day of the measurements. Briefly opening the right-most gate in the diversion dam slightly accelerated near-bottom velocities approaching the dam. Based on this observation, it was concluded that periodic flow releases from the diversion dam could help to clean bottom materials from the entrance to the Headworks. Further testing is recommended.

Figure 6.1. Inflatable pontoon boat with WorkHorse Rio Grande ADCP mounted beneath it. Photo of September 24, 2007.

Figure 6.2. Inflatable pontoon boat with WorkHorse Rio Grande ADCP, battery pack, and radio-telemetered instrument package. Photo of September 24, 2007.

Figure 6.3. Boat-mounted ADCP being used to measure current profiles in Putah South Canal upstream from Weyand Intake structure. Photo of September 24, 2007.

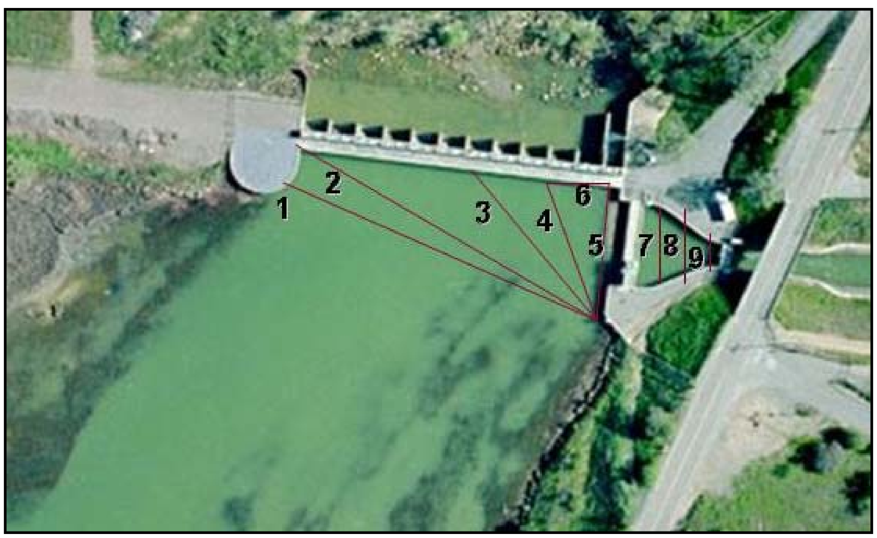


Figure 6.4. Approximate location of six ASCP velocity measurement transects in Lake Solano and three transects in forebay of Putah South Canal.

Figure 6.5. WorkHorse Rio Grande ADCP, battery pack, and radio-telemetered instrument package mounted in Oceanscience RiverBoat at Lake Solano. Photo of May 20, 2008.

Figure 6.6. WorkHorse Rio Grande ADCP, battery pack, and radio-telemetered instrument package being deployed in Oceanscience RiverBoat at Lake Solano near Headworks.
Photo of May 20, 2008.

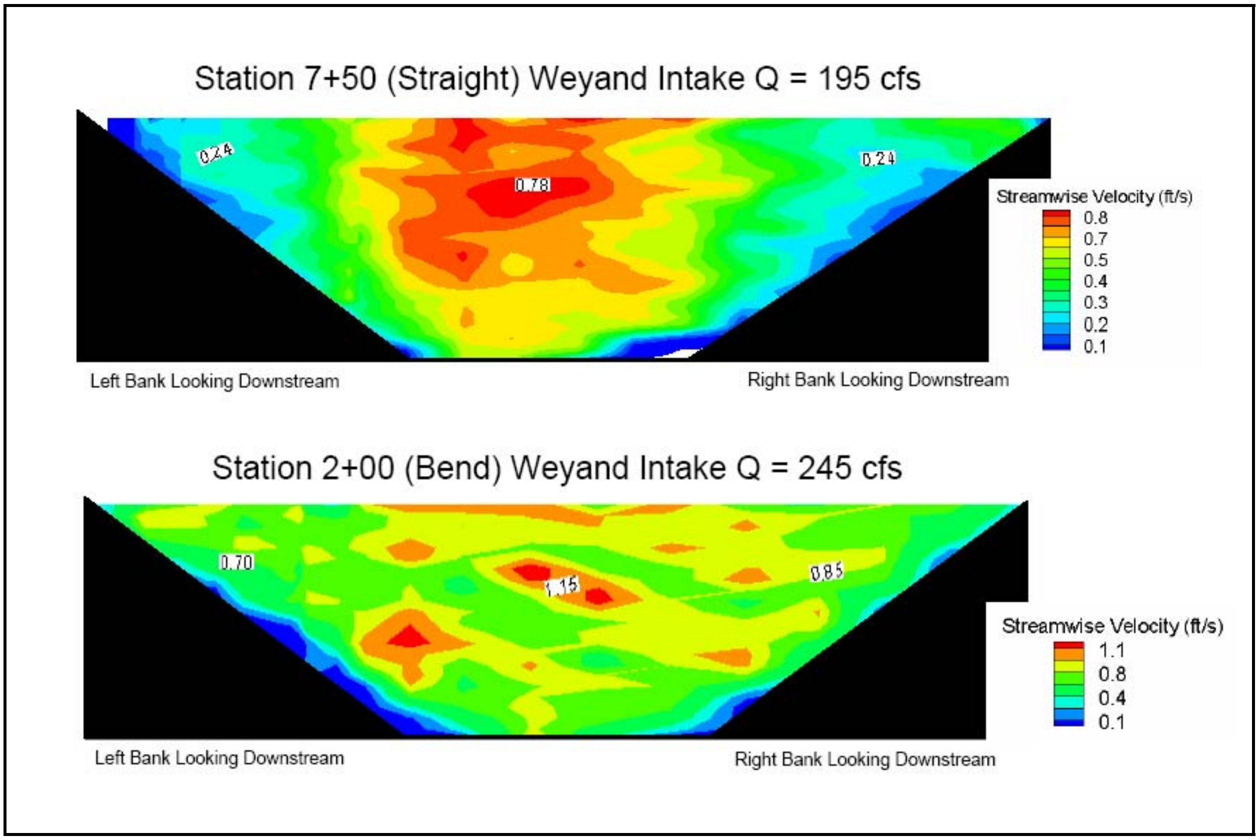


Figure 6.7 ADCP velocity field measurements at Station 7+50 in straight reach of Putah South Canal and at Station 2+00 in canal bend reach upstream from Weyand Intake.

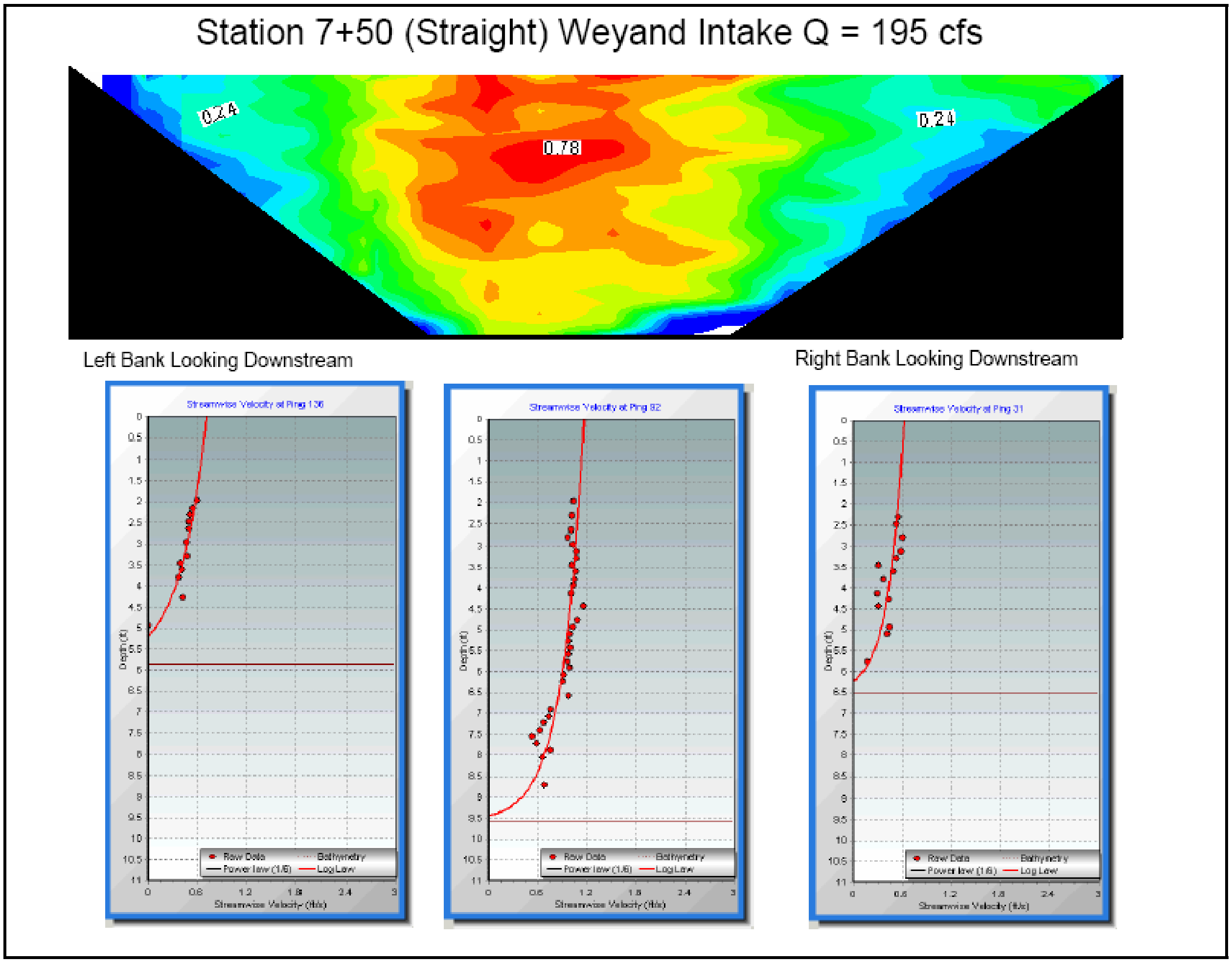


Figure 6.8. Measured vertical velocity profiles are well represented by a typical "log law" distribution in straight reaches of Putah South Canal.

Figure 6.9. Putah South Canal near Waterman WTP at MP 23.50 during ADCP measurements. View upstream. Photo of September 28, 2007.

Figure 6.10. ADCP measurements upstream from Waterman WTP. Photo of September 28, 2007.

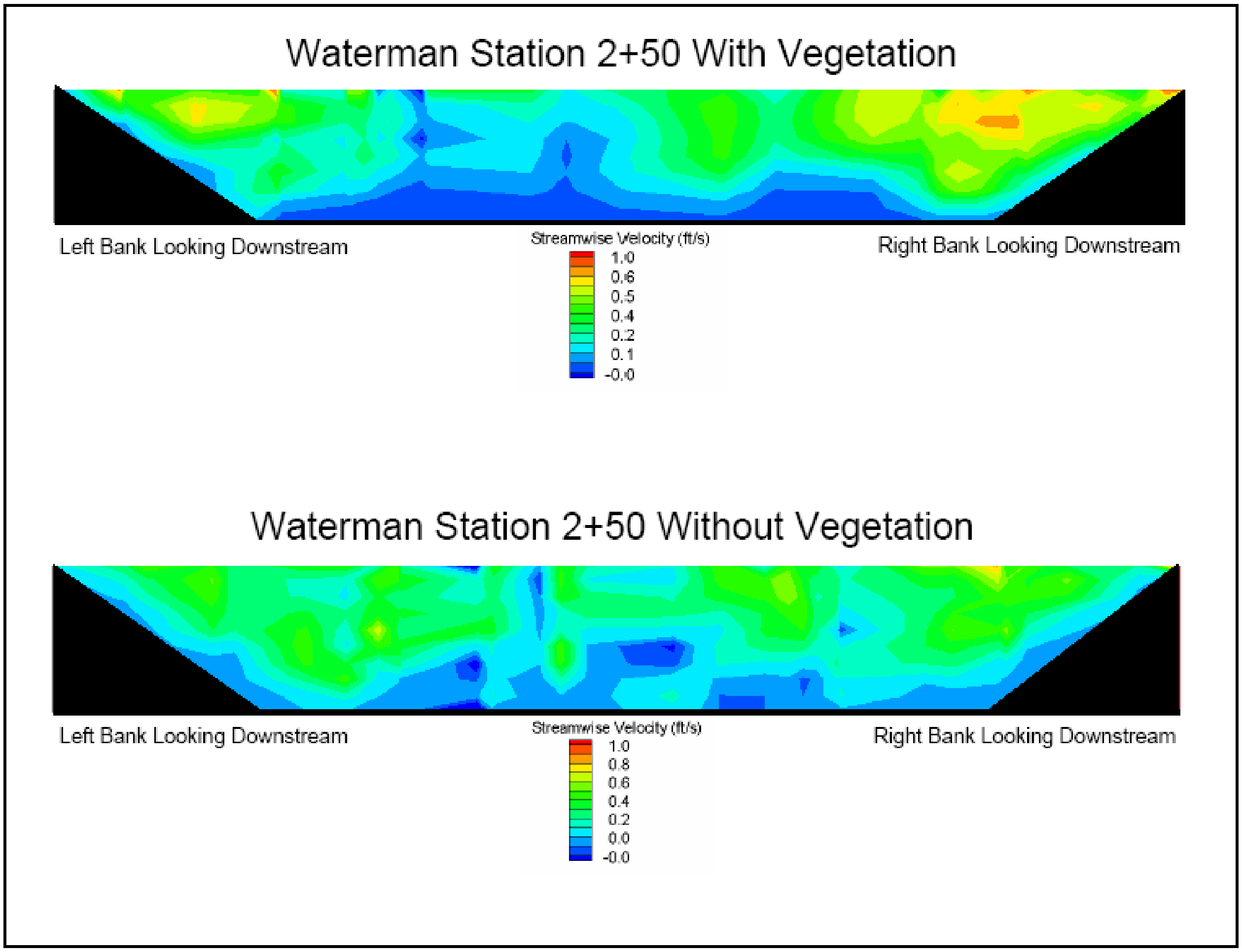


Figure 6.11. Measured velocity distributions in Putah South Canal near Waterman WTP Intake showing how flow distribution and channel conveyance can be significantly affected by presence of aquatic vegetation.

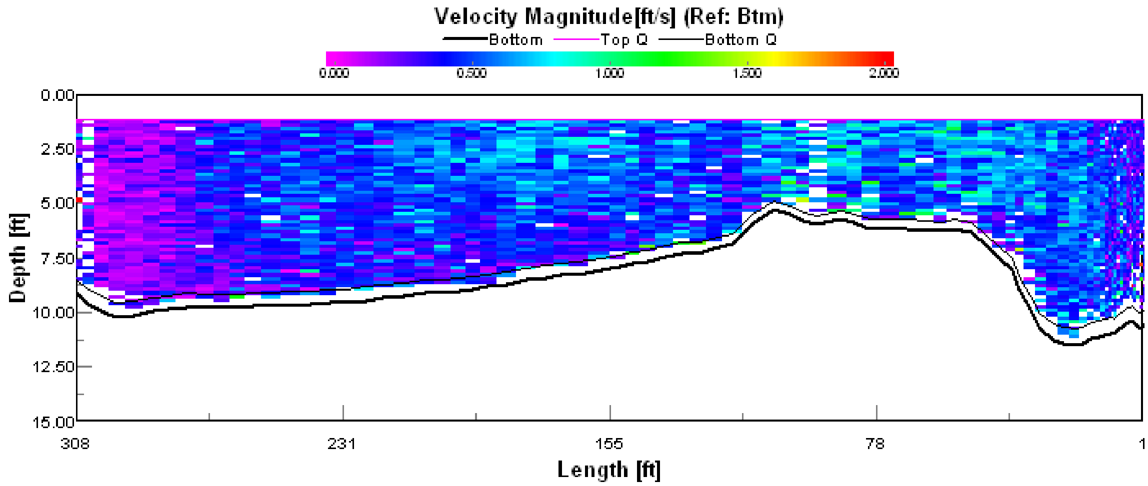


Figure 6.12. Measured flow field (velocity magnitudes in ft/s) crossing Section #1 in Lake Solano. View downstream.

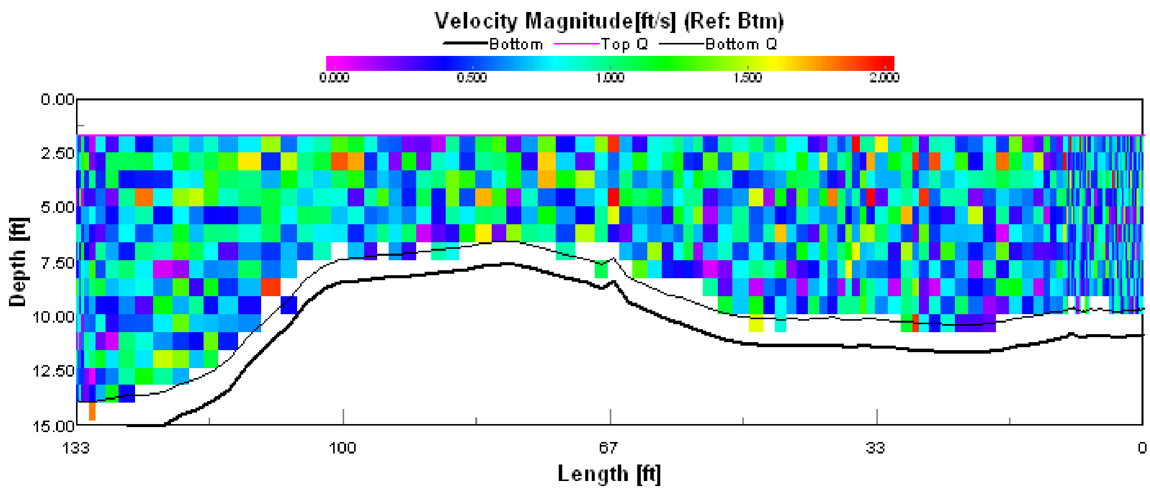


Figure 6.13. Measured flow field (velocity magnitudes in ft/s) crossing Section #4 in Lake Solano. View downstream. Vertical size of bins in this plot was increased (compared to Figure 6.12) due to greater water depth.

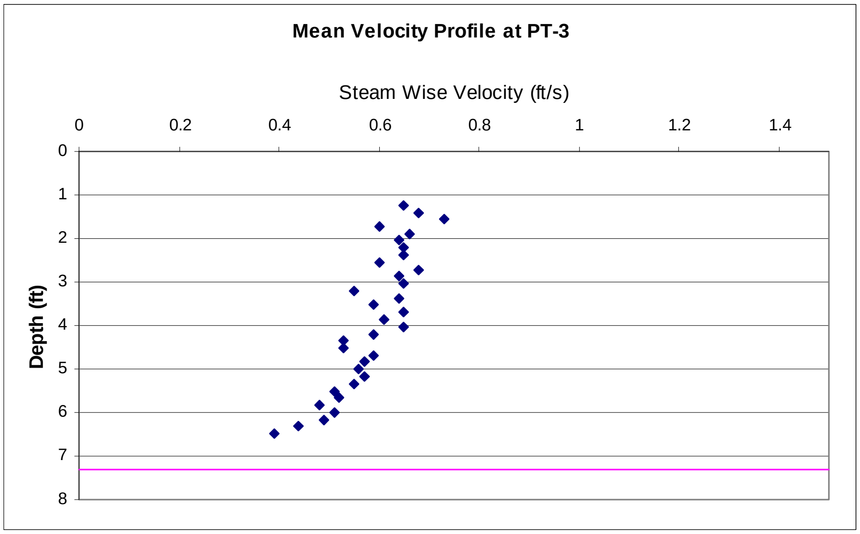


Figure 6.14. Stationary velocity profile measurements from surface to bottom approximately in middle part of Transect #1 in Lake Solano.

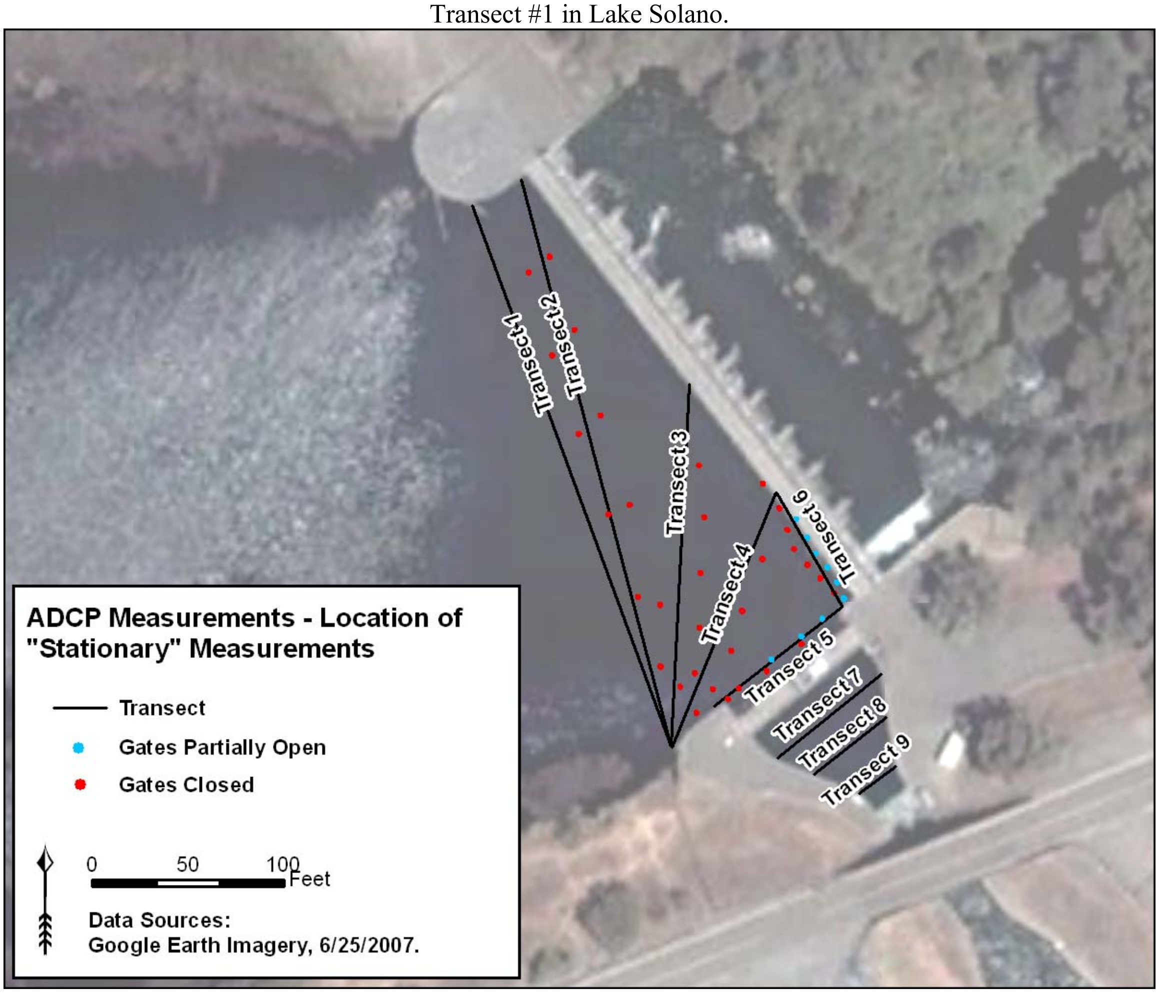


Figure 6.15. Location of “stationary” measurements along six transects in Lake Solano.

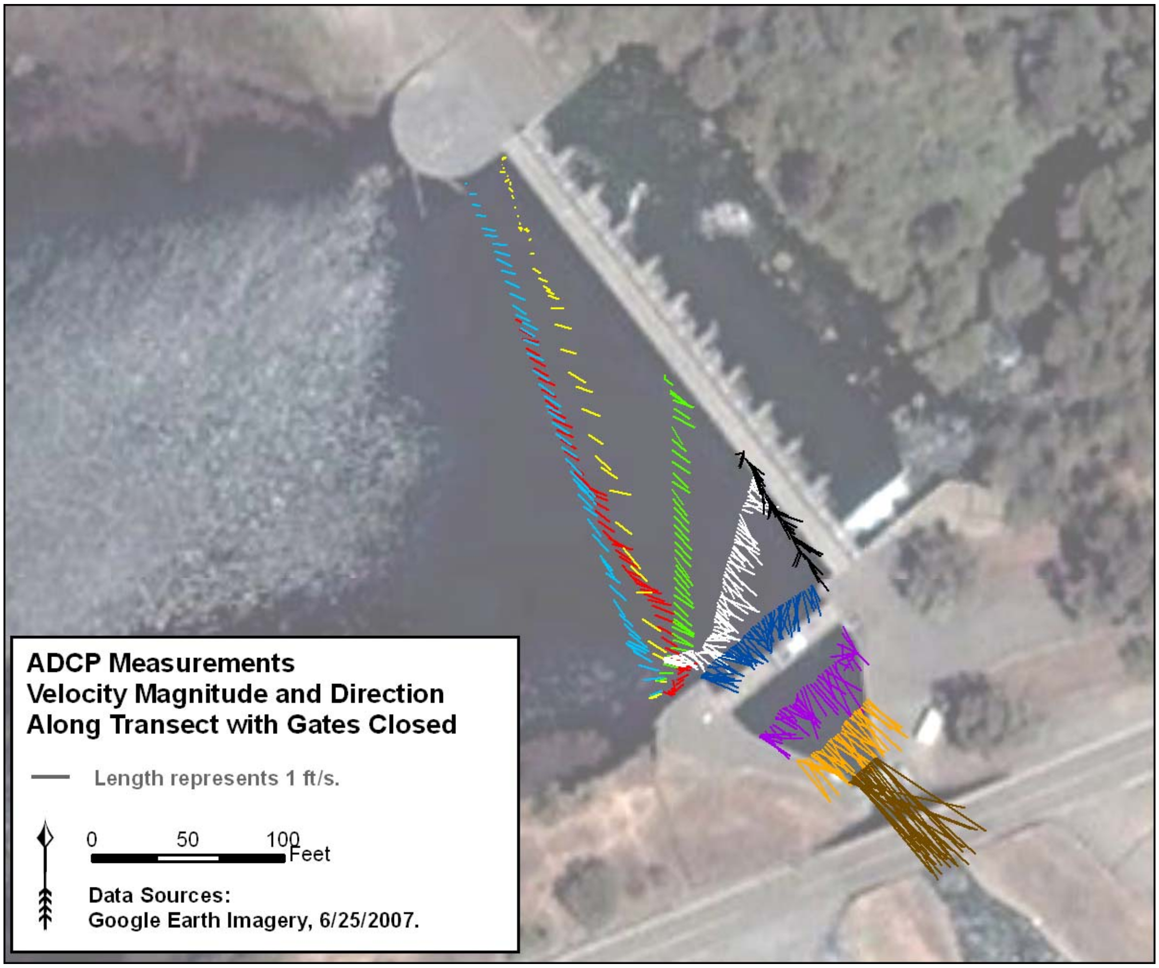


Figure 6.16. Plan view of depth-average velocity vectors along six transects in Lake Solano and three transects inside forebay.

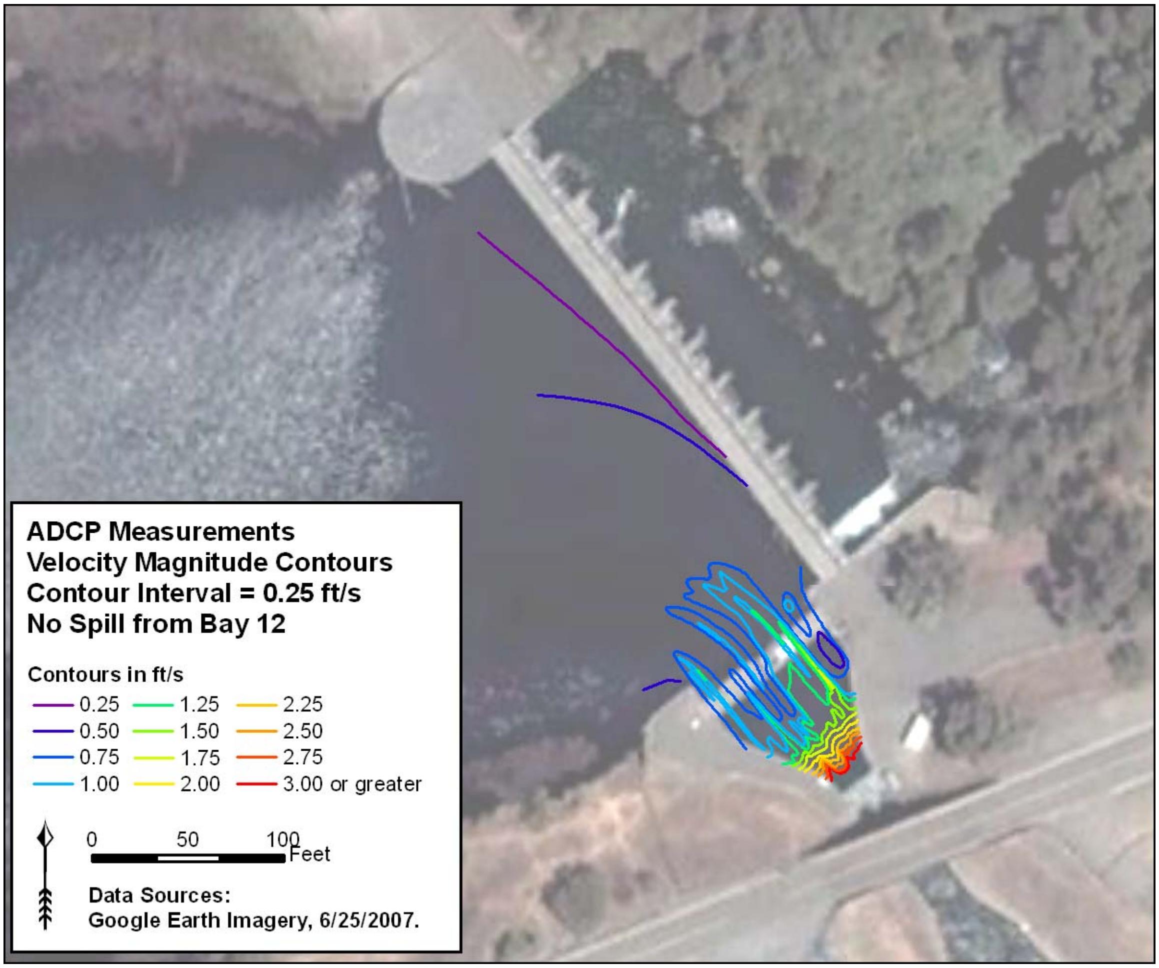


Figure 6.17. Contours of depth-average velocity near entrance to Headworks and inside forebay.

7. ASSESSMENT OF ANNUAL SEDIMENT BUDGETS

7.1. Objectives and Methods

For the purpose of this study, all sources of sediment entering the Putah South Canal (PSC) were combined into two major groups:

(1) Lake Solano

This source includes fluvial sediment delivered to the lake by its tributaries. Putah Creek is the major tributary of Lake Solano, however, it conveys relatively clean waters from Lake Berryessa and therefore does not supply significant amounts of sediment to the lake. The most important sediment contributors to Lake Solano include Pleasants Creek and Proctor Draw. Canyon Creek, Thompson Creek, and Bray Creek periodically produce high sediment loads into Putah Creek downstream from Lake Berryessa during large storm events.

(2) Lateral sources

This group includes sediment delivered to the PSC from local runoff, open lateral drainages (drains), bank failures, road cast, and episodic inflows associated with stream crossings, overchutes, or flood flows from adjacent drainages that overtop canal embankments and access roads and flow into the canal. Atmospheric deposition is also included in this group even though it is difficult to measure and may be relatively small compared to other lateral sources of sediment.

The main objectives of the assessments were to estimate all the major components of the PSC annual sediment budget and to determine the relative contribution of each of the two major sources of sediment identified above (Lake Solano or lateral sources). Results from the sediment budget assessment were later used to develop recommendations for reducing sediment delivery to the PSC and more effective ways to manage sediment in the canal.

A schematic of the PSC annual sediment budget is presented in Figure 7.1. All major components of the PSC sediment budget are described by the following equation:

Sediment inflow Sediment outflow and deposition

$$Vs\ Lake\ Solano + Vs\ lateral = Vs\ outtakes + Vs\ Terminal\ Reservoir + Vs\ deposition \qquad (7.1)$$

where *Vs Lake Solano* = total amount of sediment delivered to the PSC at the Headworks from Lake Solano (tons/yr), *Vs lateral* = total amount of sediment derived to the PSC from lateral sources (tons/yr), *Vs outtakes* = total amount of sediment leaving the canal with water outtakes (tons/yr), *Vs Terminal Reservoir* = total amount of sediment conveyed from the canal to

Terminal Reservoir (tons/yr), and *Vs deposition* = total amount of sediment deposited in the canal (tons/yr). In equation 7.1, *Vs Lake Solano, Vs outtakes, Vs Terminal Reservoir*, and *Vs deposition* can be measured directly or estimated (this is explained in more detail later in this report). The only unknown parameter is *Vs lateral*, which can be calculated from equation 7.1.

Annual sediment budgets of the PSC were estimated for WYs 2006, 2007, and 2008. Data used to estimate the PSC annual sediment budget were daily water releases into the PSC from Lake Solano, daily water outtakes along the canal, daily water outflow into Terminal Reservoir, continuous time series of measured water turbidity at various monitoring locations along the canal, initial volume of sediment in the canal, and total volume of annual accumulated sediment deposits in the canal prior to annual cleanout. Daily water releases into the PSC from Lake Solano were determined using flow records available from the U.S. Geological Survey (USGS) gage 11454210 (Putah South Canal near Winters) and USBR monthly reports (USGS 2008, USBR 2008). Daily water outtakes and outflows into Terminal Reservoir were determined from daily water orders provided by the Solano Project operators. It was assumed that additional water inflow with precipitation and water losses on evaporation and infiltration were insignificant compared to water volume in the canal. Continuous turbidity records were available from the SWCA turbidity stations located at the Headworks (MP 0.0), Sweeney Check (MP 6.15), Eldredge Pumping Plant (MP 11.80), Serpas Check (MP 23.51), and Terminous Check (MP 32.33). Additionally, 4-hr and daily turbidity data were available for the North Bay Regional Water Treatment Plant (NBR WTP) (MP 16.85) and Waterman WTP (MP 23.50). According to the winter monitoring data (see Chapter 3 of this report), turbidity was relatively uniformly distributed across the canal. Therefore, it was assumed that the point turbidity data recorded at the SCWA turbidity stations could be used as section-average values.

The amount of sediment entering the PSC at the Headworks from Lake Solano (*Vs Lake Solano*) was determined using turbidity time series provided by the SCWA. Measured turbidity values were converted into suspended sediment concentrations using the relationship established from the winter monitoring of the canal (see Chapter 3 of this report). This relationship is reproduced in Figure 7.2 and is approximated by the following equation:

$$\text{SSC (mg/L)} = 0.55\ \text{NTU}^{0.98} \qquad (7.2)$$

where SSC = suspended sediment concentration (in mg/L) and NTU = turbidity (in NTU). Time series of suspended sediment concentrations (SSCs) calculated for the Headworks from equation 7.2 were then used in conjunction with daily flow data to determine daily and annual sediment loads entering the PSC from Lake Solano. Given that sediment deposits in the canal are mainly composed of easily suspendible silt and clay materials (see results from canal cleanout monitoring in Chapter 2 of this report), the amount of sediment transported in the canal as bedload (i.e. moving by rolling, sliding, and saltating along the bottom) is likely to be negligible.

The amount of sediment leaving the canal through water outtakes (*Vs outtakes*) was determined for reaches located between the turbidity monitoring stations. Continuous turbidity data measured at the stations bordering the reaches were used to calculate time series of reach-average turbidity. Reach-average turbidity values were converted into reach-average SSCs using equation 7.2, which were then used in conjunction with daily outtakes in the reaches to calculate daily and annual sediment loads leaving the PSC with water outtakes.

The amount of sediment conveyed from the PSC to Terminal Reservoir (*Vs Terminal Reservoir*) was determined using turbidity data measured at the Terminous Check, equation 7.2, and daily flow data available for this location.

The annual amount of sediment deposited in the PSC (*Vs deposition*) was determined as the difference between the final amount of sediment accumulated in the canal prior to the fall cleanout and initial amount of sediment left in the canal after the previous-year cleanout. For WY 2006, the initial amount of sediment in the canal was unknown and was estimated using results from the 2006, 2007, and 2008 post-cleanout monitoring. For WY 2007, the initial amount of sediment in the PSC was the amount of residual sediment measured in the canal after the fall 2006 cleanout. For WY 2008, the initial amount of sediment in the canal was the amount remaining after the fall 2007 cleanout. The final amount of sediment accumulated in the canal was measured at the end of WYs 2006, 2007, and 2008 during cleanout monitoring (see Chapter 2 of this report).

Sediment deposition in the canal was measured in volumetric units and was converted into weight units using a bulk sediment density. However, there is uncertainty as to what density should be used for the conversion. Bulk density of sediment deposits is known to vary over a range of several-fold depending on a number of factors including the sediment's mechanical composition, environment in which deposits are formed, flow (flow velocity) strength, water level variations, exposure to air, time during which deposits are formed, degree of sediment compaction, and degree of deposits disturbance during sampling (ASCE 1975). According to the cleanout monitoring results, PSC sediment deposits are mostly composed of silt and clay, with occasional accumulations of sand and gravel (see Figure 2.26 in Chapter 2). The typical bulk density for this type of material is about 74 lb/ft^3 (ASCE 1975). However, bed material samples collected in the fall of 2006 and analyzed in the laboratory had an average bulk density of 27 lb/ft^3. These low measured densities for deposits could be related to the fluid-like character of most of the bed material samples (very high water content), presence of significant amounts of organic matter in the sediment, and uncertainty in determining physical properties (such as volume, weight, density) of these easily suspendable sludge-type deposits. Therefore, items that can affect the precision with which the "floc-like, soupy sludge" sediment materials can be measured in the canal include: highly non-uniform deposits, significant variability in physical characteristics and mechanical composition of the sediment and along the canal, limited number of sediment samples analyzed (10 for the entire 33-mile long canal), presence of a significant amount of organic matter in the sediments, and uncertainty in determining bulk density of slurry-type sediment deposits. Therefore, HHC used both of these densities (74 and 27 lb/ft^3) to convert volumetric deposition data into weight units. Such an approach gave two different weight values (in tons) for sediment deposition, which can be viewed as a range of uncertainty in sediment deposition for the PSC.

The amount of lateral sediment inflow (*Vs lateral*) was calculated from equation 7.1. Since this equation contains sediment deposition amount (which was determined as a range of possible values), lateral sediment inflow was also calculated as a value range.

The following section presents a discussion of the sediment budget assessment results obtained for WYs 2006, 2007, and 2008.

7.2. WY 2006 Sediment Budget

During the winter of WY 2006, record high rainfall and runoff occurred throughout Solano County that led to high turbidity flows and significant sediment loading into the PSC. Daily flow hydrographs in Putah Creek upstream of Lake Solano (USGS gage 11454000 Putah Creek near Winters) and at the inlet of the PSC (USGS gage 11454210 Putah South Canal near Winters) are shown in Figure 7.3. Ten major storm events with peak turbidity exceeding 70 NTU at the Headworks occurred in WY 2006. Propagation of turbidity plumes from Lake Solano along the canal during these events detected at the SCWA turbidity stations and selected WTPs is shown in Figure 7.4. Peak turbidity and propagation speed of the plumes are summarized in Table 7.1. Peak turbidity for these events ranged from 20 NTU in the lower sections of the canal to more than 1,000 NTU in the middle and upper reaches and in some instances exceeded the calibration limit and measurement range of the turbidity probes. Peak turbidity generally reduced with the distance from the canal inlet (Figure 7.5), which results as fine sediments gradually settle out of the water column and deposit along the canal. Observed propagation speed of the turbidity plumes along the canal was 0.2 to 0.5 ft/s. During the 12/31/2005 storm event, many areas along the PSC were flooded, which increased the amount of sediment derived into the canal. Sources of this sediment were from overbank flow, local drainages, and bank failures along the canal. SCWA turbidity data are in general agreement with available turbidity data from the WTPs, although there are some discrepancies in peak turbidity for the extremely high storm events observed on December 31, 2005 (see Table 7.1).

At the beginning of the irrigation season in May 2006, periodic turbidity spikes in the PSC (typically within 200-500 NTU) were recorded at the SCWA's turbidity probe installed at the Headworks (Figure 7.6). The cause of these turbidity spikes is uncertain. Possible causes could be re-entrainment of sediment deposited in Lake Solano during winter months in front of the canal forebay; entrainment of aquatic vegetation, sediment and debris deposited on the trash screens by the increased canal inflows and disturbed by screen cleaning operations at the Headworks; and malfunction of the turbidity probe. These turbidity spikes were recorded only at the Headworks and were not observed at the Sweeney Check.

Measured turbidity data were used in accordance with the method described above to calculate sediment inflow to the PSC from Lake Solano, sediment outflow from the canal with water outtakes, and sediment outflow into Terminal Reservoir. According to the calculations, approximately 900 tons of sediment entered the PSC at the Headworks from Lake Solano (*Vs Lake Solano*), 700 tons of sediment exited the canal with water outtakes (*Vs outtakes*), and 100 tons were transported out of the canal to Terminal Reservoir (*Vs Terminal Reservoir*) during WY 2006.

Calculated monthly sediment inflows from Lake Solano into the PSC at the Headworks during WY 2006 are shown in Figure 7.7. Significant increases in turbidity were observed during winter storm events of WY 2006, when flows in the canal were relatively small (around 30-60 cfs). During the summer dry period, turbidity was low (on the order of 4-5 NTU), but flows in the canal were the highest (around 500-700 cfs). As a result, total sediment inflow into the canal from Lake Solano during winter months appeared to be slightly less than sediment inflow during the irrigation and summer months. Figure 7.7 shows that approximately 45% of the estimated total 900 tons of sediment that entered the canal through the headworks during WY 2006 occurred during the winter low flow (high rainfall) period from November through April and approximately 55% entered the canal during the summer irrigation months of May through October. These results, however, should be treated with caution as summer turbidity readings may be influenced by aquatic vegetation. Additional research is needed to confirm the presently derived seasonal distribution of sediment loading from Lake Solano into the PSC.

It should be noted that the estimated annual sediment inflow of 900 tons at the Headworks does not include turbidity spikes observed at the beginning of the irrigation seasons. With these turbidity spikes, the total annual sediment inflow would be almost 100 tons higher. However, due to the uncertain cause of these turbidity spikes, they were excluded from sediment load calculations (as requested by the SCWA).

The total volume of sediment deposits in the canal measured in the fall of 2006 (during cleanout monitoring, see Chapter 2 of this report) was approximately 13,000 yd^3. Initial volume of sediment in the canal (residual sediment remaining after the fall 2005 cleanout) was unknown. According to the 2006, 2007, and 2008 post-cleanout observations, residual volumes of sediment remaining in the canal after these cleanouts were approximately 3,000 yd^3, 500 yd^3, and 2,000 yd^3, respectively. Year 2005 was moderately wet, with rainfall and runoff conditions similar to those observed in 2007 and 2008. Therefore, the initial volume of sediment in the canal in WY 2006 was assumed to be on the order of 1,000 yd^3. This produces an amount of sediment deposition in the canal during WY 2006 of approximately 12,000 yd^3, or 12,000 tons with a density of deposits of 74 lb/ft^3, or 4,500 tons with a density of 27 lb/ft^3 (*Vs deposition*).

Substituting the calculated values into equation 7.1, one arrives at the following equation:

$$\underset{Vs\ Lake\ Solano}{900\ \text{tons}} + \underset{Vs\ lateral}{X} = \underset{Vs\ outtakes}{700\ \text{tons}} + \underset{Vs\ Terminal\ Reservoir}{100\ \text{tons}} + \underset{Vs\ deposition}{12{,}000\ \text{or}\ 4{,}500\ \text{tons}} \quad (7.3)$$

Using this equation one can estimate the annual amount of sediment delivered to the PSC from lateral sources (*Vs lateral*); they are approximately 4,400-11,900 tons (the result depends on the bulk sediment density value used to convert the measured volumetric deposition into weight units).

All the components of sediment budget estimated for WY 2006 are summarized in Table 7.2 and graphically presented in Figure 7.8. In the table and figure, estimated sediment budget components are presented in weight units (tons) and as percentages (%) of total sediment inflow or total sediment outflow. As discussed above in Section 7.1, sediment deposition in the canal was measured in volumetric units and converted to weight units using two different sediment densities – a typical silt and clay bulk density of 74 lb/ft^3 and an average measured density of 27 lb/ft^3; therefore a range of weight values is given for the deposition in Table 7.2. Calculated sediment inflows from lateral sources and percentages depend on the weight of sediment deposits and therefore are also given as value ranges in the table.

Thus, between 5,300 and 12,800 tons of sediment was supplied into the canal from all sources during WY 2006. Of this amount, approximately 900 tons (7-17%) were derived from Lake Solano and between 4,400 and 11,900 tons (83-93%) were derived from all lateral sources including overbank flows, local drainages, and bank failures (most of which occurred during the extreme rains and flooding that occurred in December and January of WY 2006). Of the sediment supplied into the canal, approximately 700 tons (5-13%) exited the canal with water outtakes, 100 tons (1-2%) were conveyed into Terminal Reservoir, and between 4,500-12,000 tons (85-94%) deposited in the canal. Given the existing uncertainties in turbidity data and approximate nature of sediment deposit measurements, the presented sediment budget values should be regarded as approximate order of magnitude estimates.

Lateral sediment source loading appears to have been the dominant source of sediment that entered the PSC during WY 2006. However, it is important to remember that this was an unusually high rainfall and runoff year that included significant lateral inflows, including overbank flows into the canal, canal panel failures, bank sloughing that occurred along the canal, and substantial local drainage that entered the canal downstream from the Headworks.

7.3. WY 2007 Sediment Budget

WY 2007 was a relatively dry year with only a few mild winter storms. Daily flow hydrographs in Putah Creek upstream of Lake Solano and in the inlet of the PSC during WY 2007 are shown in Figure 7.3. Water turbidity in the PSC during the winter period was generally within 5-10 NTU. A few turbidity spikes exceeding 50 NTU were recorded at the Headworks in February 2007, but they were not recorded at the downstream turbidity stations and therefore were likely caused by turbidity probe malfunction. No detectable propagation of turbidity plumes along the PSC was recorded at the SCWA turbidity stations during WY 2007.

Turbidity records collected by the SCWA and WTPs were used to calculate sediment inflow to and outflow from the canal. Calculated monthly sediment inflows from Lake Solano into the PSC at the Headworks during WY 2007 are shown in Figure 7.7. Annual sediment inflow from Lake Solano to the PSC at the Headworks during WY 2007 was calculated to be 540 tons (*Vs Lake Solano*), of which approximately 20% was derived during winter months (with low canal flows) from November through March and 80% during summer period (with high canal flows) from April through October. Sediment outflow with water outtakes was estimated at 420 tons (*Vs outtakes*), and sediment outflow to Terminal Reservoir at 20 tons (*Vs Terminal Reservoir*).

The initial volume of (residual) sediment in the canal (measured after the fall 2006 cleanout) was approximately 3,000 yd^3. The final volume of sediment deposits (measured during the fall 2007 cleanout) was approximately 4,000 yd^3. Therefore, the net amount of sediment deposited in the canal during WY 2007 was approximately 1,000 yd^3, or 1,000 tons at a density of deposits of 74 lb/ft^3 and 500 tons at a density of 27 lb/ft^3 (*Vs deposition*).

After substitution of the calculated parameters in equation 7.1, the following equation is obtained:

Vs Lake Solano		*Vs lateral*		*Vs outtakes*		*Vs Terminal Reservoir*		*Vs deposition*	
540 tons	+	X	=	420 tons	+	20 tons	+	1,000 or 500 tons	(7.4)

Using equation 7.4, the annual amount of sediment derived from lateral sources (*Vs lateral*) was calculated to be about 400 to 900 tons.

The calculated components of the WY 2007 sediment budget are summarized in Table 7.2 and graphically shown in Figure 7.9. Thus, a total of between 940 to 1,440 tons of sediment was supplied into the canal during WY 2007, of which about 540 tons (38-57%) were derived from Lake Solano and 400 to 900 tons (43-62%) were derived from lateral sources. Of the sediment supplied into the canal, estimated 420 tons (29-45%) left the canal with water outtakes, 20 tons (1-2%) were conveyed into Terminal Reservoir, and an other 500 to 1,000 tons (53-69%) was deposited in the canal. According to the calculations, the amounts of sediment supplied into the PSC from Lake Solano and lateral sources during relatively dry WY 2007 were comparable.

7.4. WY 2008 Sediment Budget

WY 2008 was moderately wet, with a few very intense winter storms in the study area. Daily flow hydrographs in Putah Creek upstream of Lake Solano and in the inlet of the PSC during WY 2008 are shown in Figure 7.3. It is seen from this figure that although runoff in Putah Creek may vary significantly from year to year (especially during winter rainy period), seasonal flows in the PSC remain relatively constant. Five major storm events with peak turbidity exceeding 200 NTU at the Headworks occurred in WY 2008. Propagation of turbidity plumes from Lake Solano along the canal during these events is shown in Figure 7.4. Peak turbidity and propagation speed of the plumes are summarized in Table 7.1. The most severe storm occurred on January 4, 2008 and was concentrated in the upper part of the PSC. During this event peak turbidity at the Headworks exceeded 3,000 NTU. Flood flows exceeded channel capacity of McCune and Sweeney Creeks, which resulted in sediment-laden waters spilling into the Sweeney and Gibson Checks of the canal from the McCune Creek overchute and from inundated adjacent overbank areas of Sweeney Creek. Monitoring during this event is described in more detail in Chapter 3 of this report. Peak turbidity of the monitored storm-induced turbidity plumes propagating down the canal generally reduced with the distance from the PSC inlet due to the settling of suspended fine sediment (Figure 7.5). All the turbidity plumes passed through the entire length of the canal and were detected at the most downstream SCWA turbidimeter installed at the Terminous Check.

Continuous time series of turbidity in the PSC measured by the SCWA and WTPs were used to calculate sediment inflow to and outflow from the canal. Calculated monthly sediment inflows from Lake Solano into the PSC at the Headworks during WY 2008 are shown in Figure 7.7. The highest monthly sediment inflow of approximately 190 tons was observed in January 2008 when the most intense storm events occurred in the study area. Annual sediment inflow from Lake Solano to the PSC at the Headworks during WY 2008 was calculated at about 900 tons (*Vs Lake Solano*). Of this amount, approximately 40% was derived from the lake during winter months (with low canal flows) from November through March and 60% during summer period (with high canal flows) from April through October. Sediment outflow with water outtakes was estimated at 800 tons (*Vs outtakes*), and sediment outflow to Terminal Reservoir was approximately 100 tons (*Vs Terminal Reservoir*).

The initial volume of sediment remaining in the canal after the fall 2007 cleanout was measured at about 500 yd^3. Final volume of sediment accumulated in the canal by the end of WY 2008, measured during the fall 2008 cleanout was approximately 6,500 yd^3. Therefore, the net volume of sediment deposited in the PSC during WY 2008 was on the order of 6,000 yd^3. This amount is equivalent to 6,000 tons with a density of sediment deposits of 74 lb/ft^3 or 2,000 tons with a density of 27 lb/ft^3 (*Vs deposition*).

After substitution of the calculated values into equation 7.1, the following equation is obtained:

Vs Lake Solano *Vs lateral* *Vs outtakes* *Vs Terminal Reservoir* *Vs deposition*
900 tons + X = 800 tons + 100 tons + 6,000 or 2,000 tons (7.5)

Using equation 7.5, the annual amount of sediment delivered to the PSC from lateral sources (*Vs lateral*) was calculated to be between 2,000 and 6,000 tons.

The calculated WY 2008 sediment budget components are summarized in Table 7.2 and graphically shown in Figure 7.10. According to the calculations, a total of between 2,900 to 6,900 tons of sediment was introduced into the PSC during WY 2008. Of this total amount, about 900 tons (13-31%) entered the canal from Lake Solano and between 2,000 and 6,000 tons (69-87%) were derived from lateral sources along the PSC. Of the sediment supplied into the canal, about 800 tons (12-28%) were extracted with water outtakes, 100 tons (1-3%) were conveyed into Terminal Reservoir, and between 2,000 and 6,000 tons (69-87%) deposited in the canal. Despite the sensitivity of the sediment budget to the bulk density, it is apparent that lateral sediment sources were the dominant source of sediment in the PSC during WY 2008.

7.5. Summary of Sediment Budget Assessment Results

Annual sediment budgets for WYs 2006, 2007, and 2008 were developed for the PSC using available flow and turbidity data, results of suspended sediment sampling, and measured pre- and post-cleanout volumes of sediment deposits in the canal. According to the calculations, during WY 2006 (extremely wet year, with heavy winter storms and widespread overbank flooding) a total of between 5,300 and 12,800 tons of sediment was supplied into the canal, of which about 900 tons (7-17%) were derived from Lake Solano and between 4,400 and 11,900 tons (83-93%) were derived from lateral sources. Of the sediment supplied into the canal during WY 2006, approximately 700 tons (5-13%) exited the canal with water outtakes, 100 tons (1-2%) were conveyed into Terminal Reservoir, and between 4,500 and 12,000 tons (85-94%) were deposited in the canal.

During WY 2007 (dry year), altogether between 940 and 1,440 tons of sediment was supplied into the canal, of which about 540 tons (38-57%) came from Lake Solano and 400 to 900 tons (43-62%) were derived from lateral sources. Of the sediment supplied into the canal in WY 2007, an estimated 420 tons (29-45%) exited the canal with water outtakes, 20 tons (1-2%) were conveyed into Terminal Reservoir, and around 500 to 1,000 tons (53-69%) were deposited in the canal.

During WY 2008 (moderately wet year, but with a few very strong storm events and localized overbank flow), a total of between 2,900 and 6,900 tons of sediment was introduced into the PSC. Of this total amount, about 900 tons (13-31%) entered the canal from Lake Solano and between 2,000 and 6,000 tons (69-87%) were derived from lateral sources. Of the sediment supplied into the PSC in WY 2008, about 800 tons (12-28%) were extracted with water outtakes, 100 tons (1-3%) were conveyed into Terminal Reservoir, and between 2,000 and 6,000 tons (69-87%) were deposited in the canal.

Due to the lack of precision with which the floc-like sediment deposits can be measured in the canal, natural variability of sediment transport processes, the episodic character of sediment inputs into the canal, limited number of sampling locations, and significant length of the canal, the estimated sediment amounts should be regarded as approximate, order of magnitude estimates. Even though the measurements are not precise, the estimated annual budget information provides valuable project management information.

The results obtained indicated that of the two major sources of sediment considered in this study (Lake Solano and lateral sources, which include local runoff, overbank flows, open drainages, canal panel failures, and bank sloughing), lateral sources were most significant during WYs 2006 and 2008. During WY 2007, sediment supply from Lake Solano and lateral sources was comparable. It should be remembered, however, that all the three water years may be atypical for the study area. WY 2006 was extremely wet, with record high rainfall and runoff throughout Solano County. In comparison, WY 2007 was very dry and no significant rainfall events occurred in the study area. WY 2008 was moderately wet but with one very substantial storm event that caused extensive flooding into the canal. Nevertheless, the results obtained for WY

2008 are believed to be more representative of average rainfall and runoff conditions in the study area.

According to the three years of data and estimates developed for the annual amount of sediment entering the PSC from Lake Solano, approximately half or less of the annual sediment load is derived during winter storm events (when the flow in the canal is low and sediment concentrations are high) and the remaining amount is derived during summer irrigation periods (when the flow in the canal is high and concentrations are low). This seasonal distribution of sediment loading from Lake Solano into the PSC needs additional research to verify if summer turbidity readings are influenced by aquatic vegetation growth in the lake and in the canal.

In summary, the study clearly demonstrated the significance of the both major sources (Lake Solano and lateral sources) to sediment supply into the PSC. Overall, sediment supply entering the canal closely related to and dependent on local rainfall and runoff conditions. The more it rains in winter and the greater the rainfall intensity, the more sediment is supplied into the canal and the greater the contribution from lateral sediment sources. Sediment delivery from lateral sources dramatically increases if overbank flooding occurs along the PSC alignment. During extremely wet years, total annual sediment delivery into the canal significantly increases and can be around 5,000 to 13,000 tons. During such wet years, the relative contribution of Lake Solano sediment into the canal is approximately 10-20% of the total annual load and the contribution from lateral sources is about 80-90%. During dry years, annual sediment supply into the canal may reduce to less than 1,000 tons/yr, with roughly equal supply coming from Lake Solano and lateral sources. During average years, annual sediment inflow into the PSC is likely to be on the order of 2,000 to 7,000 tons, with about 20-40% of sediment coming from Lake Solano and 60-80% from lateral sources.

Table 7.1. Propagation characteristics of turbidity plumes from Lake Solano along Putah South Canal during selected winter storm events of WYs 2006 and 2008.

Canal site	PSC milepost	Date & Time	Peak turbidity (NTU)	Travel distance (miles)	Travel time (hrs)	Travel speed (ft/s)
Storm of 12/19/2005						
SCWA Headworks	0.00	12/19/2005 20:40	153	6.15	33.4	0.27
SCWA Sweeney Check	6.15	12/21/2005 6:02	50	5.65	23.3	0.36
SCWA Eldredge Plant	11.80	12/22/2005 5:14	49	5.05	21.8	0.34
NBR WTP	16.85	12/23/2005 3:00	33	6.65	28.0	0.35
Cement Hill WTP	19.61	12/23/2005	35			
Waterman WTP	23.50	12/24/2005 7:00	32			
SCWA Serpas Check	23.51	12/24/2005 4:35	30			
Storm of 12/23/2005						
SCWA Headworks	0	12/23/2005 9:10	368	6.15	25.9	0.35
SCWA Sweeney Check	6.15	12/24/2005 11:02	120	5.65	21.7	0.38
SCWA Eldredge Plant	11.80	12/25/2005 8:44	94	5.05	18.3	0.40
NBR WTP	16.85	12/26/2005 3:00	80	6.65	24.0	0.41
Cement Hill WTP	19.61	12/26/2005	87			
Waterman WTP	23.50	12/27/2005 3:00	86			
SCWA Serpas Check	23.51	12/27/2005 3:05	78			
Storm of 12/26/2005						
SCWA Headworks	0.00	12/26/2005 22:40	74	6.15	26.9	0.34
SCWA Sweeney Check	6.15	12/28/2005 1:32	37	5.65	24.2	0.34
SCWA Eldredge Plant	11.80	12/29/2005 1:44	28	5.05	17.3	0.43
NBR WTP	16.85	12/29/2005 19:00	20			
Storm of 12/28/2005						
SCWA Headworks	0.00	12/28/2005 16:10	679	6.15	27.4	0.33
SCWA Sweeney Check	6.15	12/29/2005 19:32	316	5.65	23.7	0.35
SCWA Eldredge Plant	11.80	12/30/2005 19:14	210			
Storm of 12/31/2005						
SCWA Headworks	0.00	12/31/2005 14:10	>1,200*	6.15	39.9	0.23
SCWA Sweeney Check	6.15	1/2/2006 6:02	>500*	5.65	30.7	0.27
SCWA Eldredge Plant	11.80	1/3/2006 12:44	>500*	5.05	22.3	0.33
NBR WTP	16.85	12/31/2005 11:00	6,610**	6.65	36.0	0.27
		1/4/2006 11:00	670		24.0	0.41
Cement Hill WTP	19.61	1/1/2006	2,950			
		1/4/2006	396			
Waterman WTP	23.50	1/1/2006 23:00	2,598			
		1/5/2006 11:00	580			
SCWA Serpas Check	23.51	1/5/2006 13:05	193			

* Turbidity exceeded calibrated range of turbidity probe.
** Overbank flow occurred during this storm event at approximately milepost 14.0 and resulted in massive failure of canal panels.

Table 7.1. (continued)

Canal site	PSC milepost	Date & Time	Peak turbidity (NTU)	Travel distance (miles)	Travel time (hrs)	Travel speed (ft/s)
Storm of 2/27/2006						
SCWA Headworks	0.00	2/27/2006 22:10	>1,200*	6.15	23.9	0.38
SCWA Sweeney Check	6.15	2/28/2006 22:02	222	5.65	24.2	0.34
SCWA Eldredge Plant	11.80	3/1/2006 22:14	306	5.05	16.8	0.44
NBR WTP	16.85	3/2/2006 15:00	297	6.65	32.0	0.30
Cement Hill WTP	19.61	3/2/2006	268			
Waterman WTP	23.50	3/3/2006 23:00	293			
SCWA Serpas Check	23.51	3/3/2006 21:35	105			
Storm of 3/6/2006						
SCWA Headworks	0.00	3/6/2006 0:10	400	6.15	26.9	0.34
SCWA Sweeney Check	6.15	3/7/2006 3:02	128	5.65	22.7	0.37
SCWA Eldredge Plant	11.80	3/8/2006 1:44	71	5.05	25.3	0.29
NBR WTP	16.85	3/9/2006 3:00	60	6.65	24.0	0.41
Cement Hill WTP	19.61	3/9/2006	49			
Waterman WTP	23.50	3/10/2006 3:00	51			
SCWA Serpas Check	23.51	3/10/2006 4:35	47			
Storm of 3/25/2006						
SCWA Headworks	0.00	3/25/2006 6:40	255	6.15	32.4	0.28
SCWA Sweeney Check	6.15	3/26/2006 15:02	39	5.65	16.2	0.51
SCWA Eldredge Plant	11.80	3/27/2006 7:14	52	11.70	39.8	0.43
Cement Hill WTP	19.61	3/28/2006	35			
Waterman WTP	23.50	3/28/2006 23:00	36			
SCWA Serpas Check	23.51	3/28/2006 22:05	32			
Storm of 4/3/2006						
SCWA Headworks	0.00	4/3/2006 5:10	192	6.15	27.4	0.33
SCWA Sweeney Check	6.15	4/4/2006 8:32	65	5.65	25.2	0.33
SCWA Eldredge Plant	11.80	4/5/2006 9:44	31	5.05	21.3	0.35
NBR WTP	16.85	4/6/2006 7:00	33	6.65	28.1	0.35
SCWA Serpas Check	23.51	4/7/2006 12:05	20			
Storm of 4/11/2006						
SCWA Headworks	0.00	4/11/2005 19:10	428	6.15	31.4	0.29
SCWA Sweeney Check	6.15	4/13/2006 2:32	99	5.65	24.7	0.34
SCWA Eldredge Plant	11.80	4/14/2006 3:14	53	5.05	23.8	0.31
NBR WTP	16.85	4/15/2006 3:00	45	6.65	28.1	0.35
SCWA Serpas Check	23.51	4/16/2006 7:05	28			

***** **Turbidity exceeded calibrated range of turbidity probe.**

Table 7.1. (continued)

Canal site	PSC milepost	Date & Time	Peak turbidity (NTU)	Travel distance (miles)	Travel time (hrs)	Travel speed (ft/s)
Storm of 1/4/2008						
NHC Headworks	0.00	01/04/2008 15:30	3,220	6.15	33.5	0.27
SCWA Sweeney Check	6.15	01/06/2008 1:00	>500*	5.65	30.2	0.27
SCWA Eldredge Plant	11.80	01/07/2008 7:15	475	11.71	57.2	0.30
SCWA Serpas Check	23.51	01/09/2008 16:30	794	8.82	29.8	0.43
SCWA Terminous Check	32.33	01/10/2008 22:15	741			
Storm of 1/25/2008						
SCWA Headworks	0.00	1/25/2008 22:10	1,470	6.15	38.3	0.24
SCWA Sweeney Check	6.15	1/27/2008 12:30	444	5.65	30.8	0.27
SCWA Eldredge Plant	11.80	1/28/2008 19:15	323	11.71	51.0	0.34
SCWA Serpas Check	23.51	1/30/2008 22:15	452	8.82	36.8	0.35
SCWA Terminous Check	32.33	2/1/2008 11:00	548			
Storm of 2/1/2008						
SCWA Headworks	0.00	2/1/2008 11:40	253	6.15	15.8	0.57
SCWA Sweeney Check	6.15	2/2/2008 3:30	139	5.65	23.8	0.35
SCWA Eldredge Plant	11.80	2/3/2008 3:15	106	11.71	45.8	0.37
SCWA Serpas Check	23.51	2/5/2008 1:00	>50*	8.82	38.5	0.34
SCWA Terminous Check	32.33	2/6/2008 15:30	109			
Storm of 2/3/2008						
SCWA Headworks	0.00	2/3/2008 12:40	410	6.15	22.6	0.40
SCWA Sweeney Check	6.15	2/4/2008 11:15	106	5.65	23.0	0.36
SCWA Eldredge Plant	11.80	2/5/2008 10:15	78	11.71	44.8	0.38
SCWA Serpas Check	23.51	2/7/2008 7:00	>50*	8.82	32.2	0.40
SCWA Terminous Check	32.33	2/8/2008 15:15	98			
Storm of 2/24/2008						
SCWA Headworks	0.00	2/25/2008 6:40	248**	6.15	23.3	0.39
SCWA Sweeney Check	6.15	2/26/2008 6:00	123	5.65	24.2	0.34
SCWA Eldredge Plant	11.80	2/27/2008 6:15	106	11.71	36.8	0.47
SCWA Serpas Check	23.51	2/28/2008 19:00	>50*	8.82	26.2	0.49
SCWA Terminous Check	32.33	2/29/2008 21:15	116			

* **Turbidity exceeded calibrated range of turbidity probe.**
** Peak turbidity after Headworks gate was reopened.

Table 7.2. Sediment budget components for Putah South Canal.

Source	WY 2006 (wet year)	WY 2007 (dry year)	WY 2008 (moderately wet year)
Sediment inflow			
Lake Solano	900 tons (7-17%)	540 tons (38-57%)	900 tons (13-31%)
Lateral sources	4,400-11,900 tons (83-93%)	400-900 tons (43-62%)	2,000-6,000 tons (69-87%)
Sediment outflow & deposition			
Water outtakes	700 tons (5-13%)	420 tons (29-45%)	800 tons (12-28%)
Terminal Reservoir	100 tons (1-2%)	20 tons (1-2%)	100 tons (1-3%)
In-canal deposition	4,500-12,000 tons (85-94%)	500-1,000 tons (53-69%)	2,000-6,000 tons (69-87%)

Note: Estimated sediment budget components are presented in weight units (tons) and as percentages (%) of total sediment inflow or total sediment outflow. Sediment inflow from Lake Solano, sediment outflow with water outtakes, and sediment outflow to Terminal Reservoir were determined directly in weight units and therefore are given as single values. Sediment deposition in the canal was measured in volumetric units and converted to weight units using two different sediment densities – a typical silt and clay bulk density of 74 lb/ft^3 and an average measured density of 27 lb/ft^3 obtained from samples of PSC bottom deposits. Therefore, a range of weight values is given for deposition. Calculated sediment inflows from lateral sources and percentages depend on the weight of sediment deposits and therefore are also given as value ranges.

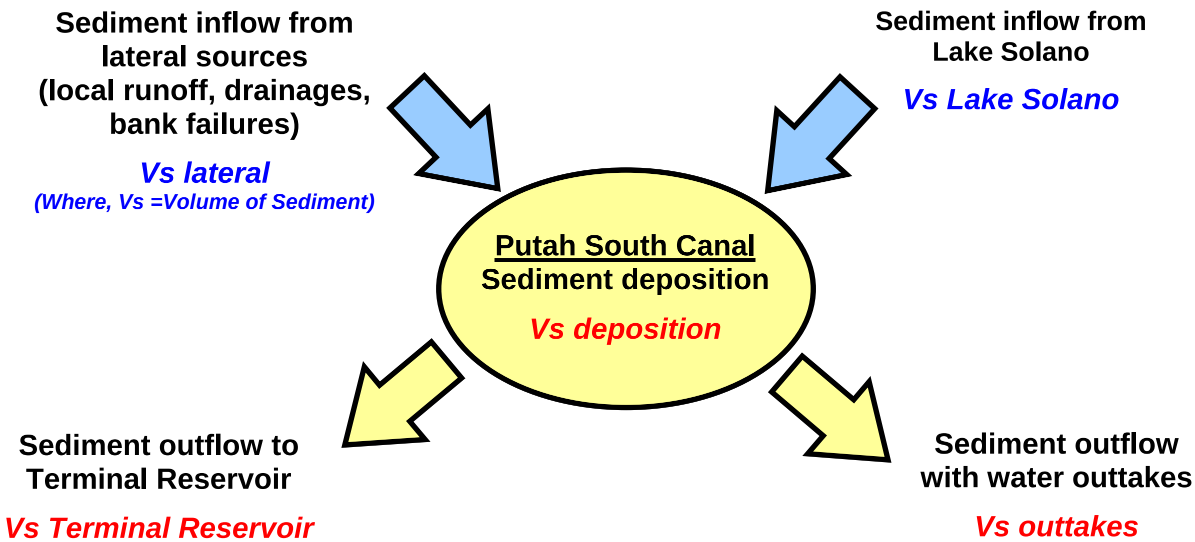


Figure 7.1. Putah South Canal sediment budget schematic.

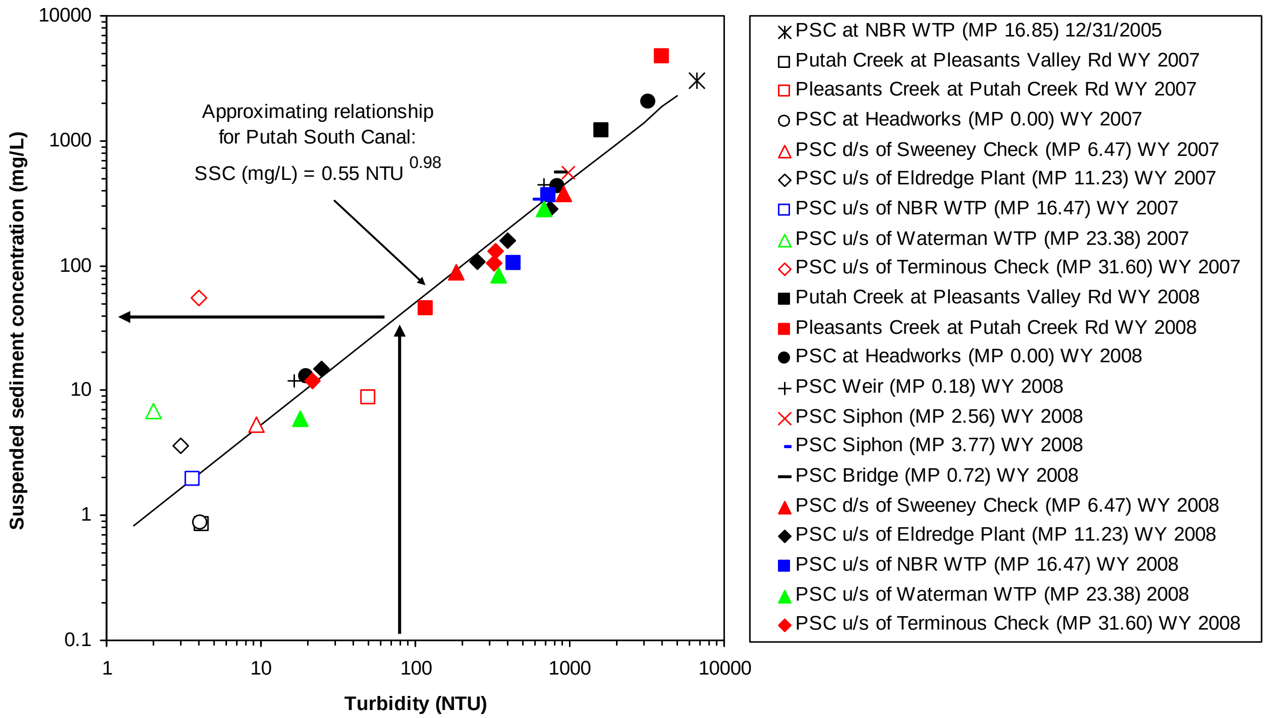
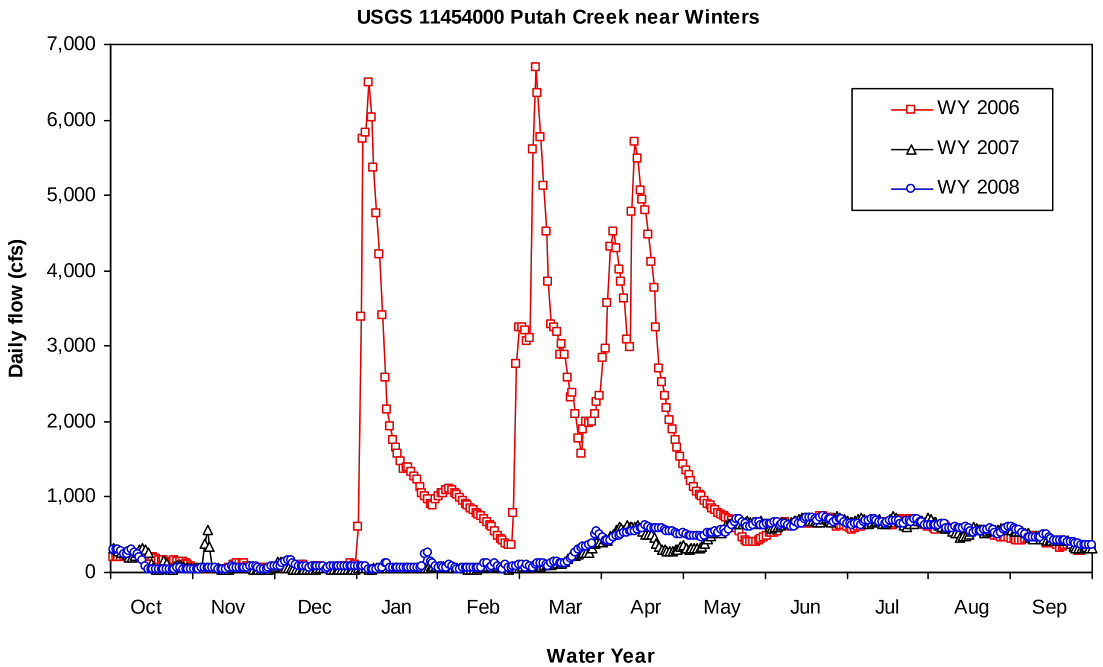


Figure 7.2. Relationship between water turbidity and suspended sediment concentration.



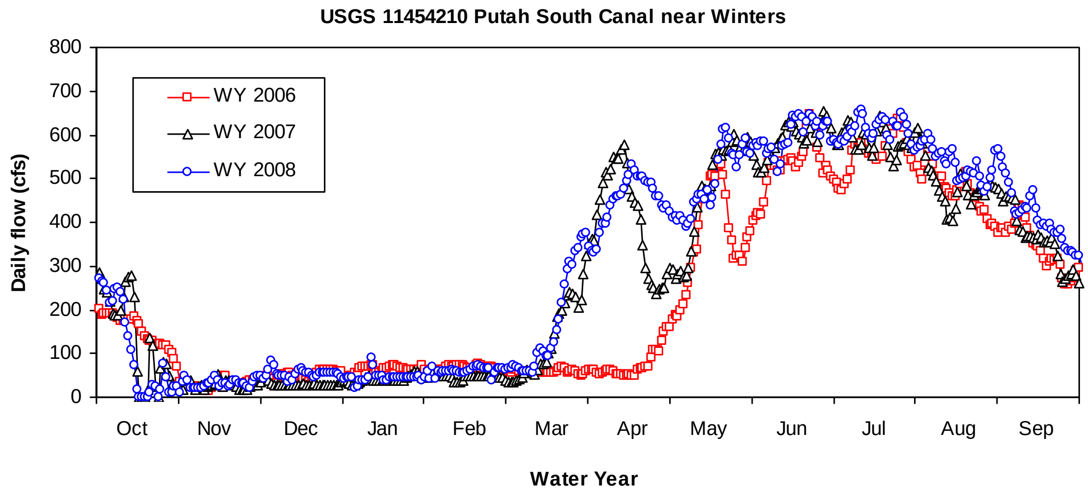
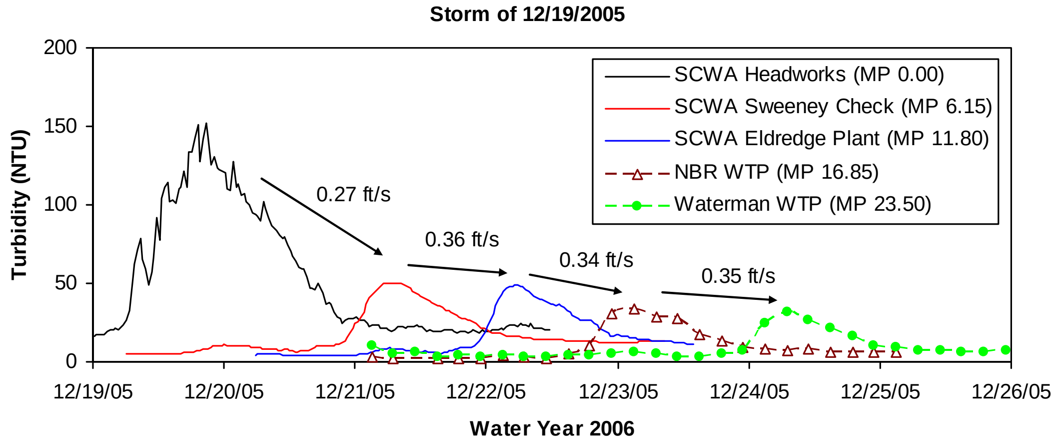


Figure 7.3. Daily flow hydrographs for Putah Creek and Putah South Canal.



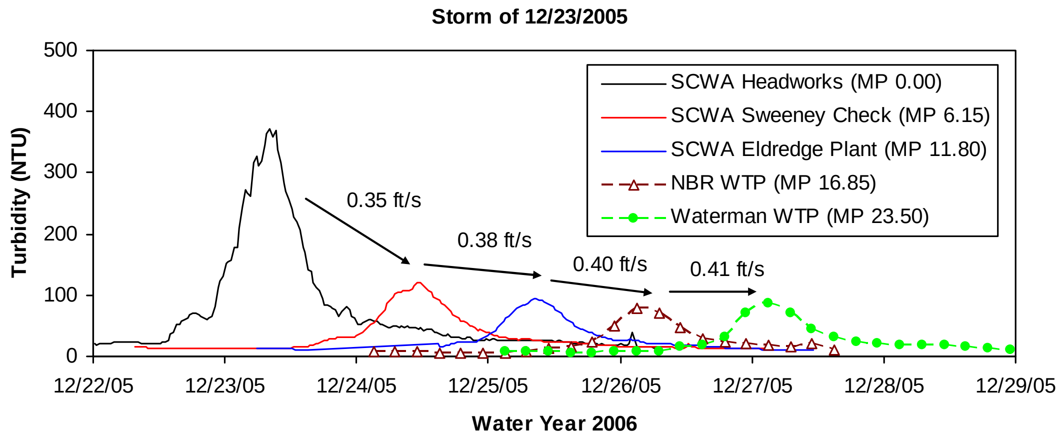


Figure 7.4. Propagation of turbidity plumes from Lake Solano along Putah South Canal during selected winter storm events of WYs 2006 and 2008. Arrows and velocities denote propagation speed of turbidity plumes.

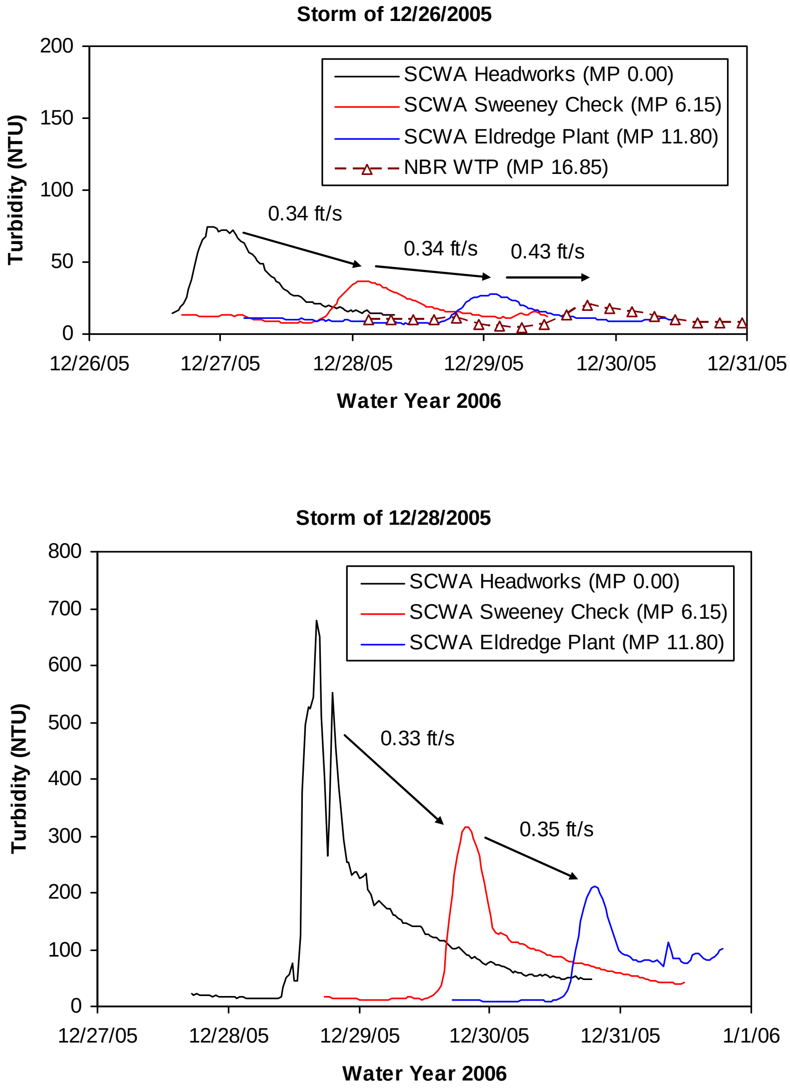


Figure 7.4. (continued).

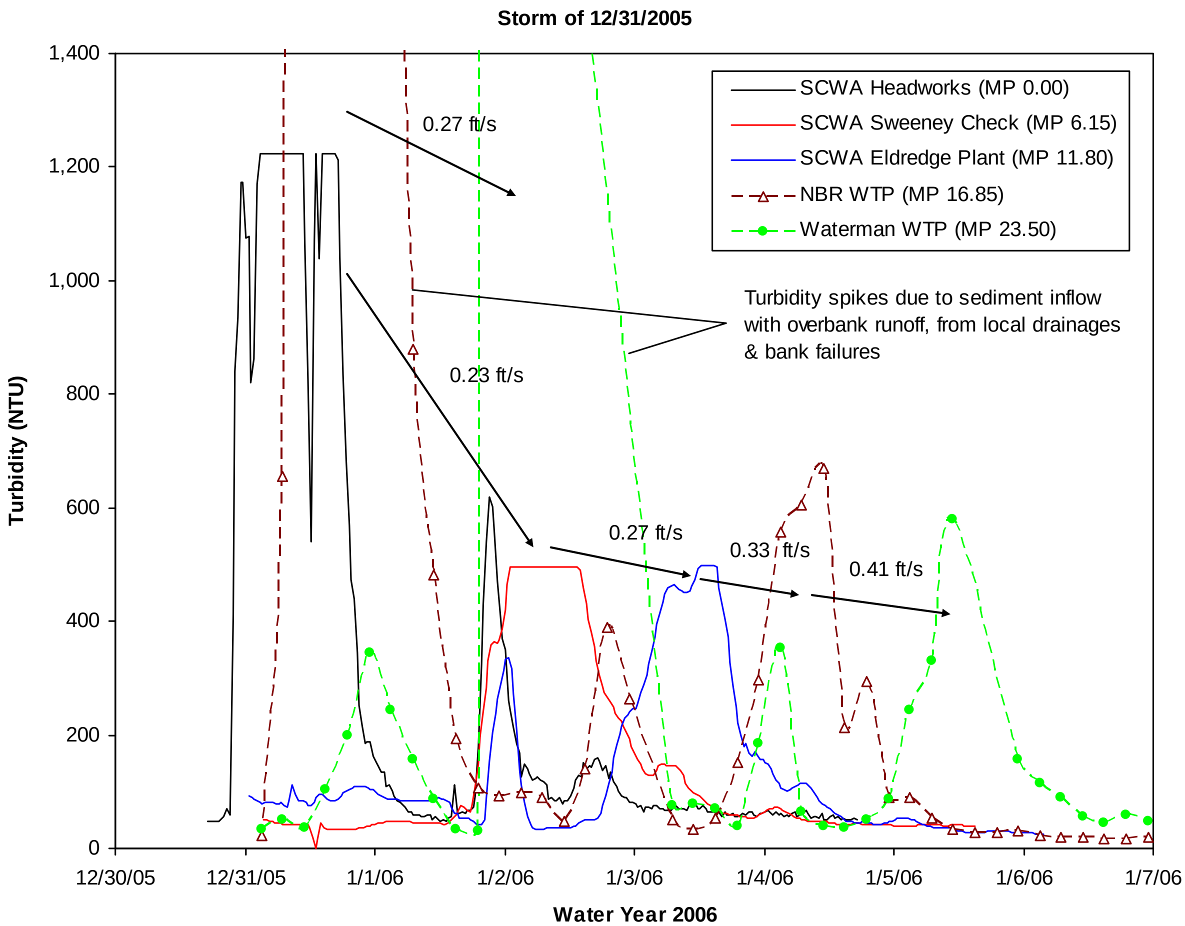
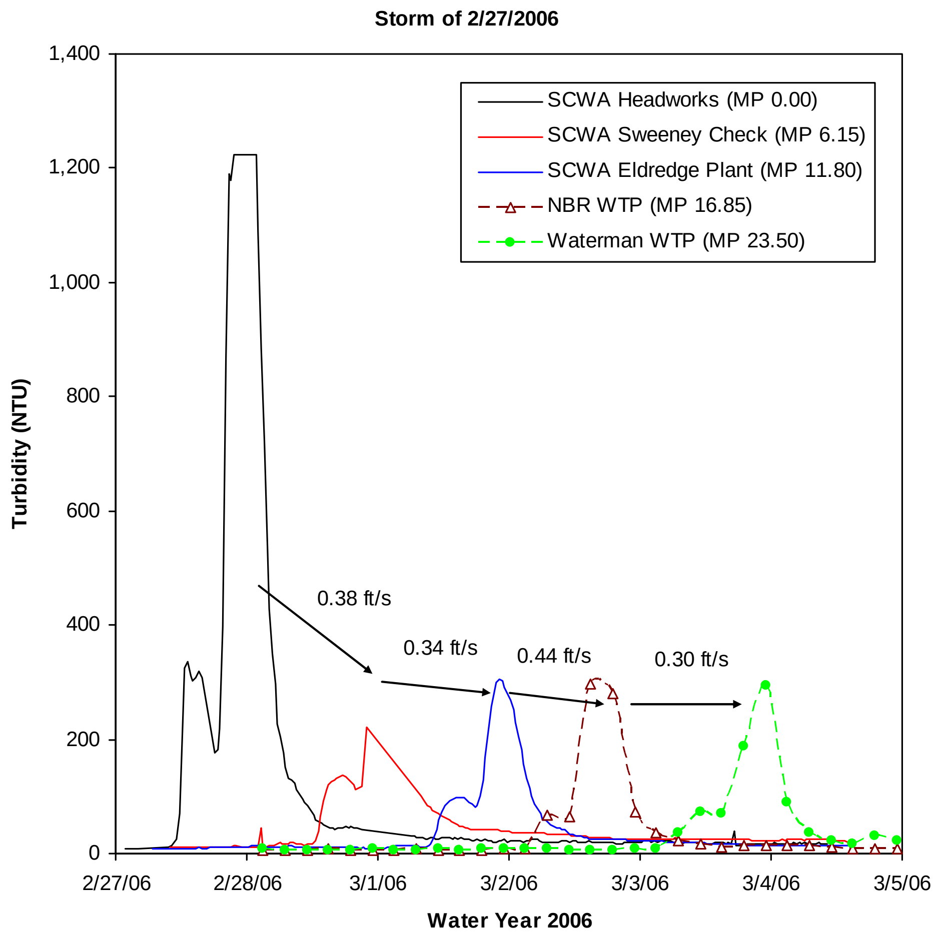


Figure 7.4. (continued).



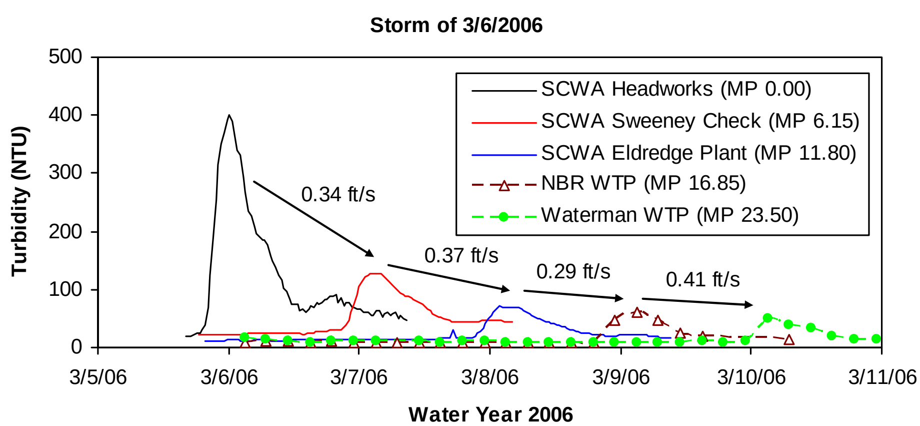
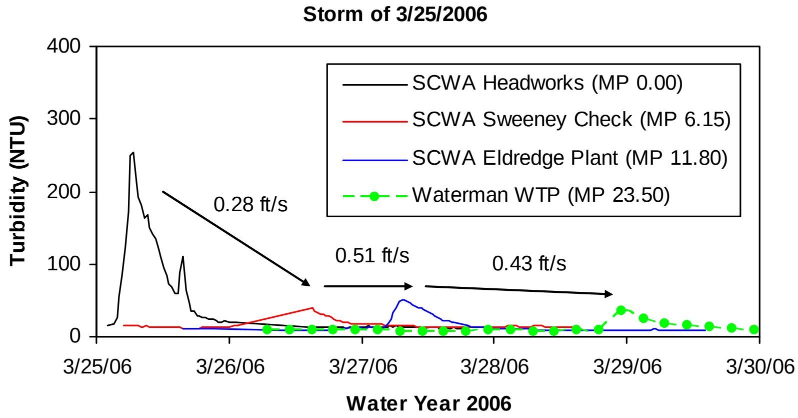
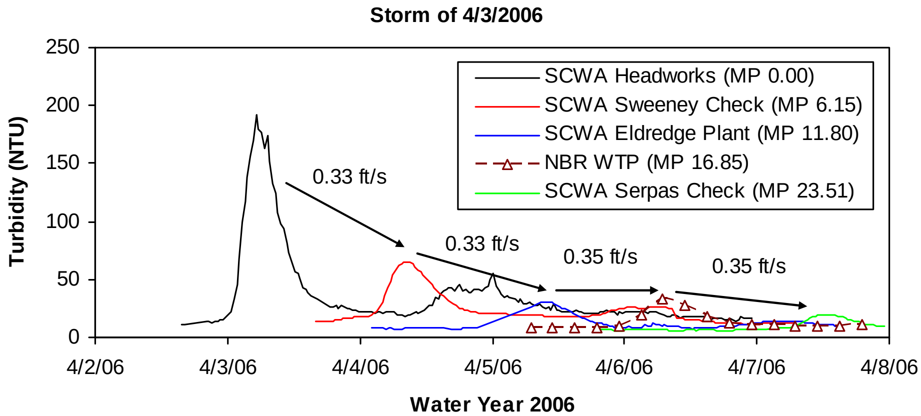


Figure 7.4. (continued).





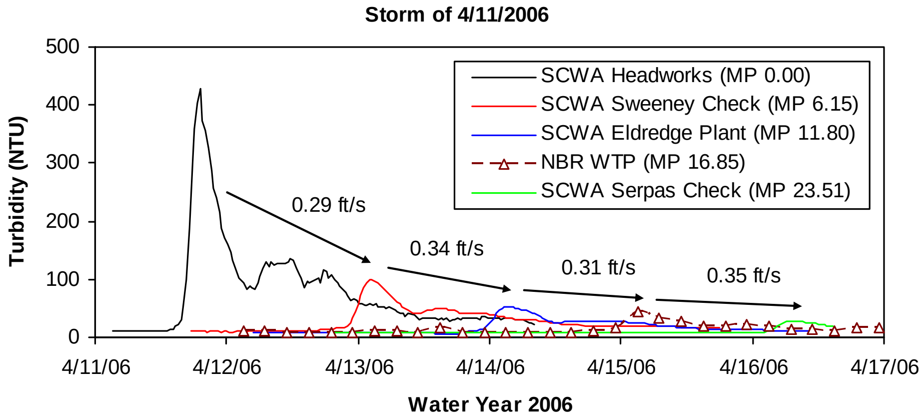


Figure 7.4. (continued).

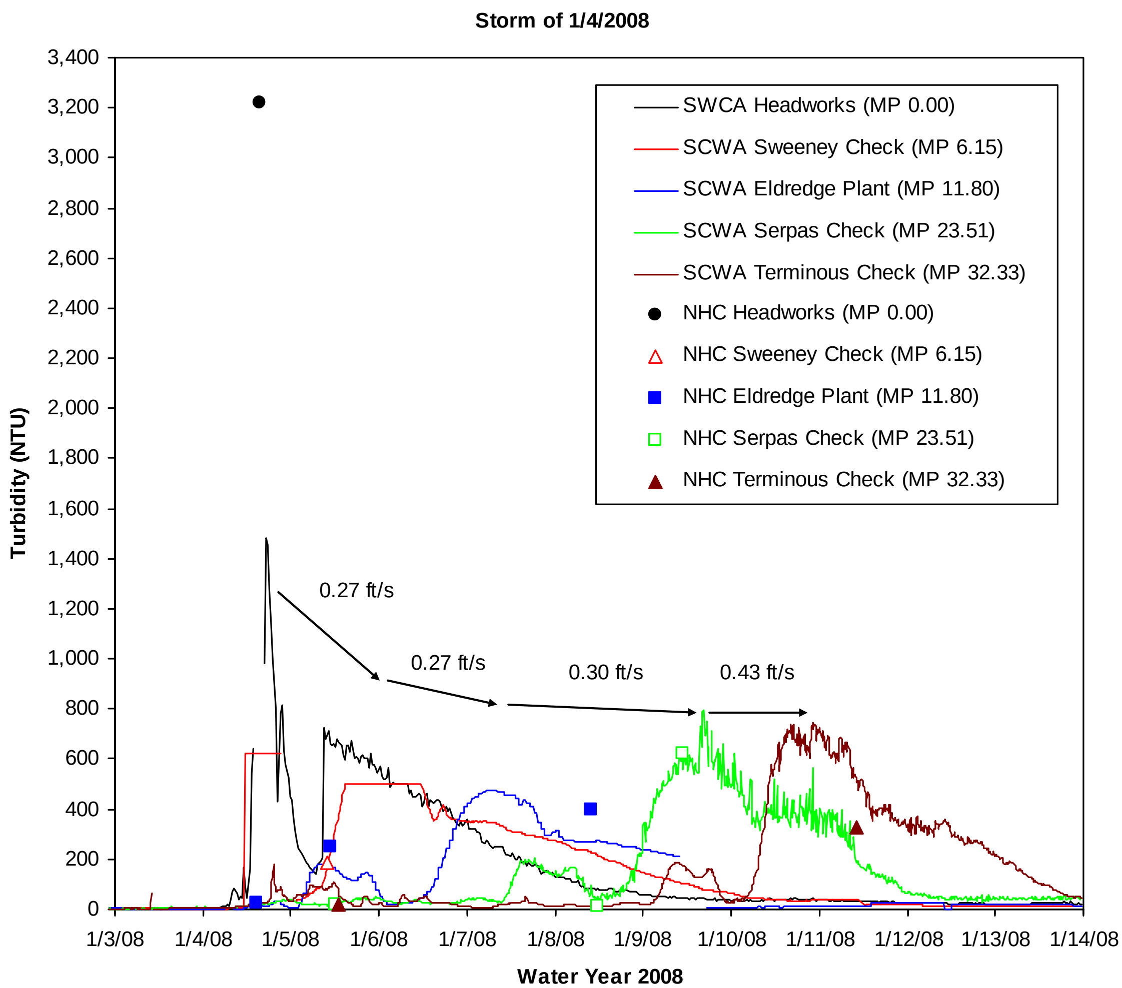
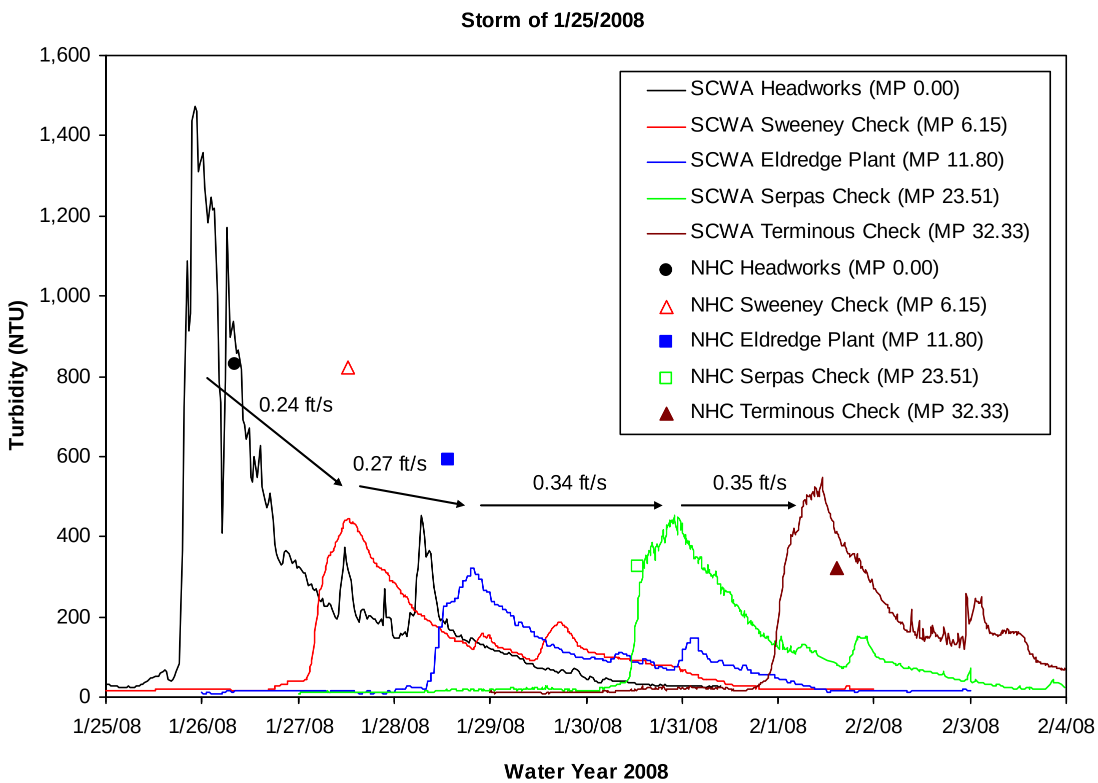


Figure 7.4. (continued).



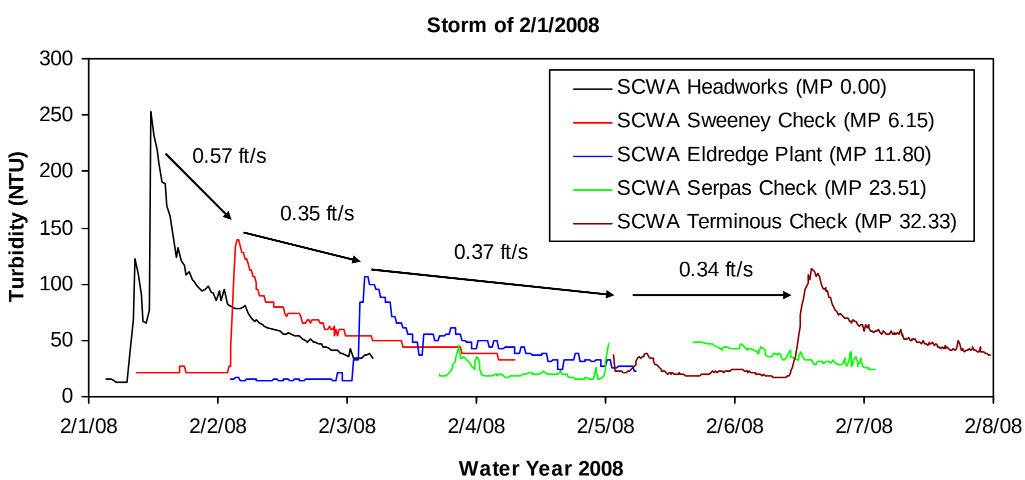
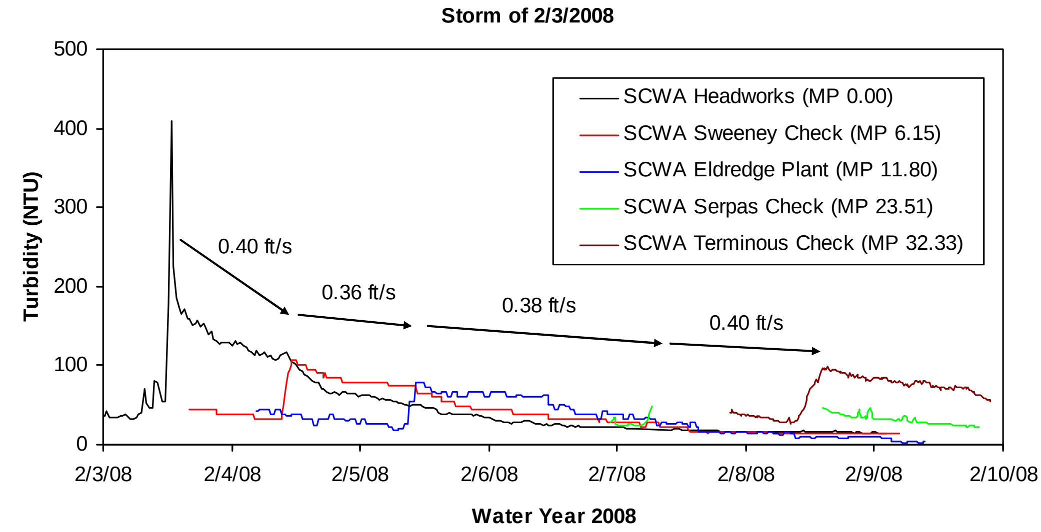


Figure 7.4. (continued).



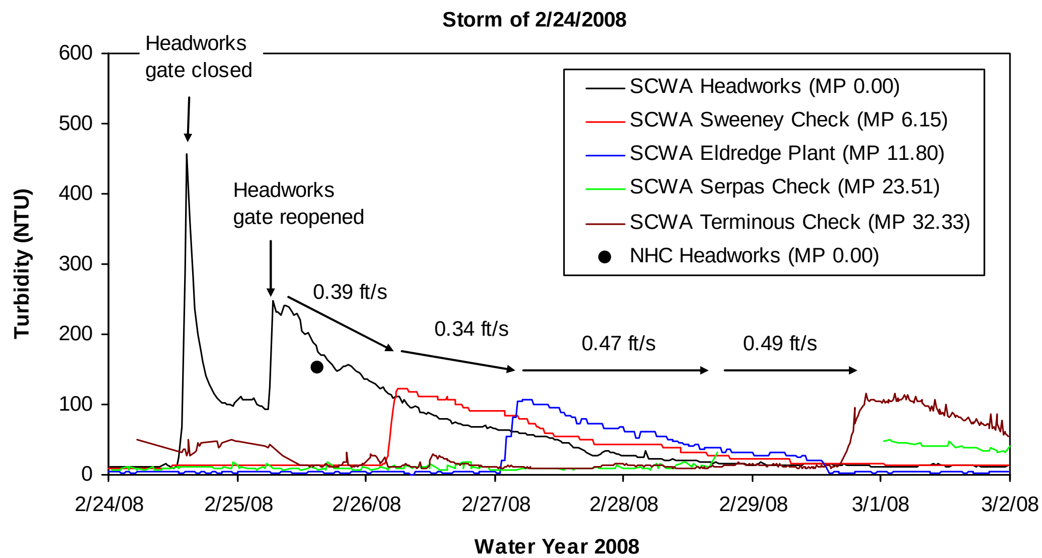
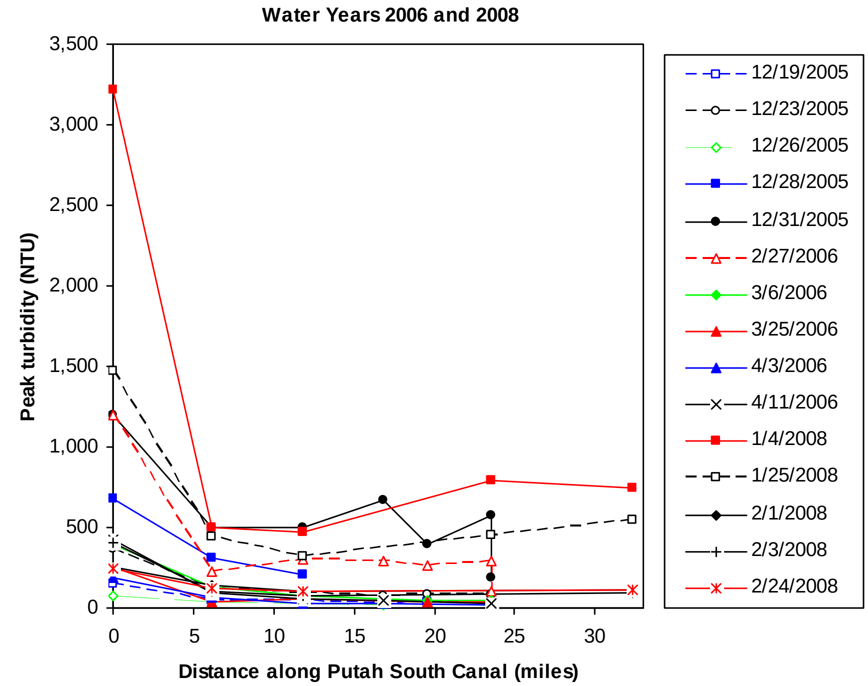


Figure 7.4. (continued).



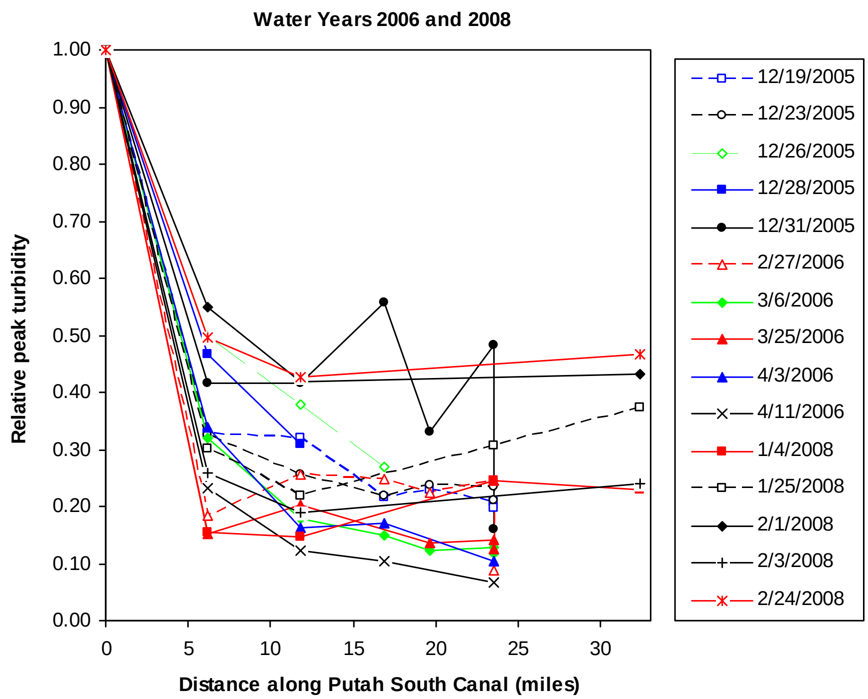


Figure 7.5. Variation of absolute (top) and relative (bottom) peak turbidity along Putah South Canal during winter storm events of WYs 2006 and 2008. Relative peak turbidity is normalized by inflow peak turbidity at Headworks.

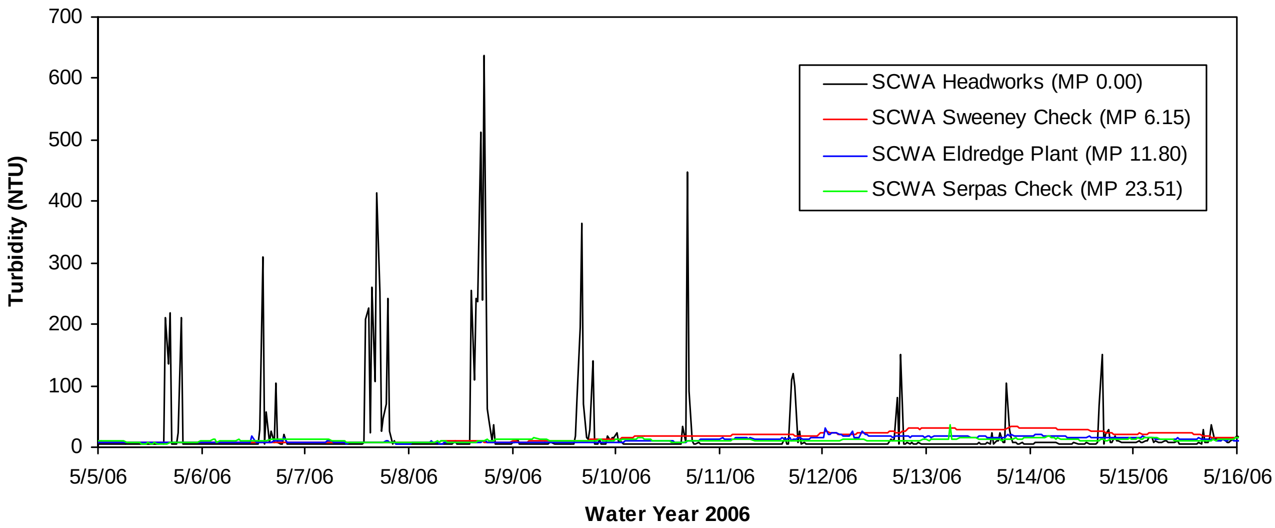


Figure 7.6. Periodic turbidity pulses at inlet to Putah South Canal in late spring of WY 2006 (SCWA turbidity data).

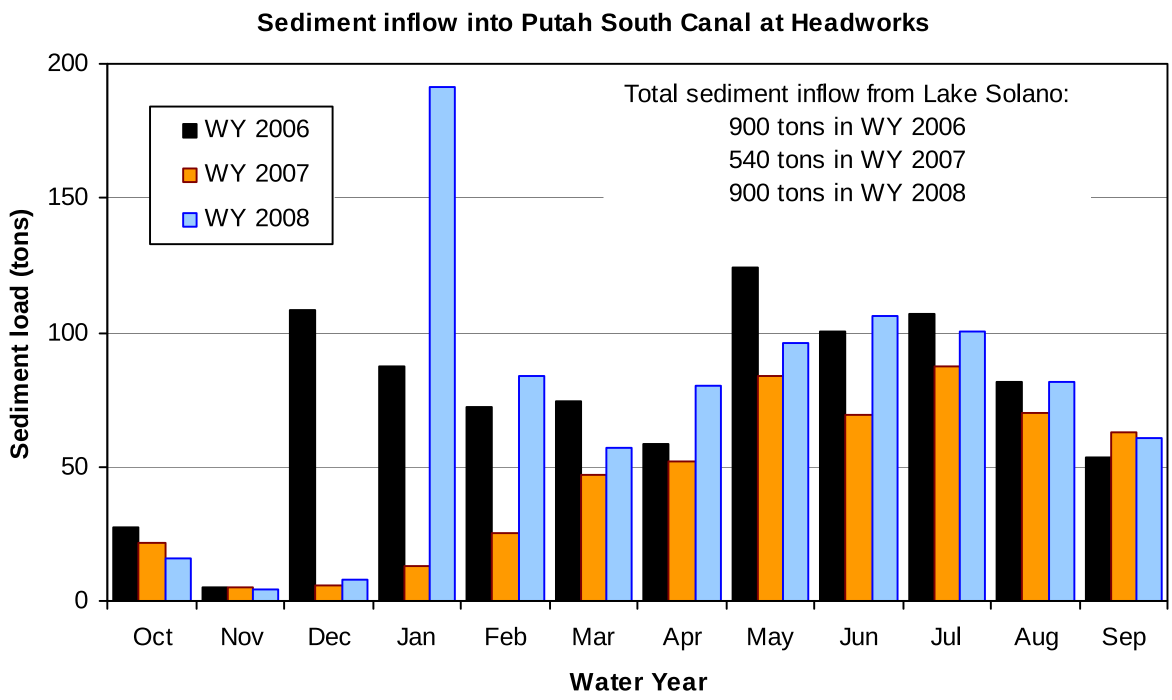


Figure 7.7. Calculated monthly sediment inflow from Lake Solano into Putah South Canal at Headworks during WYs 2006, 2007, and 2008.

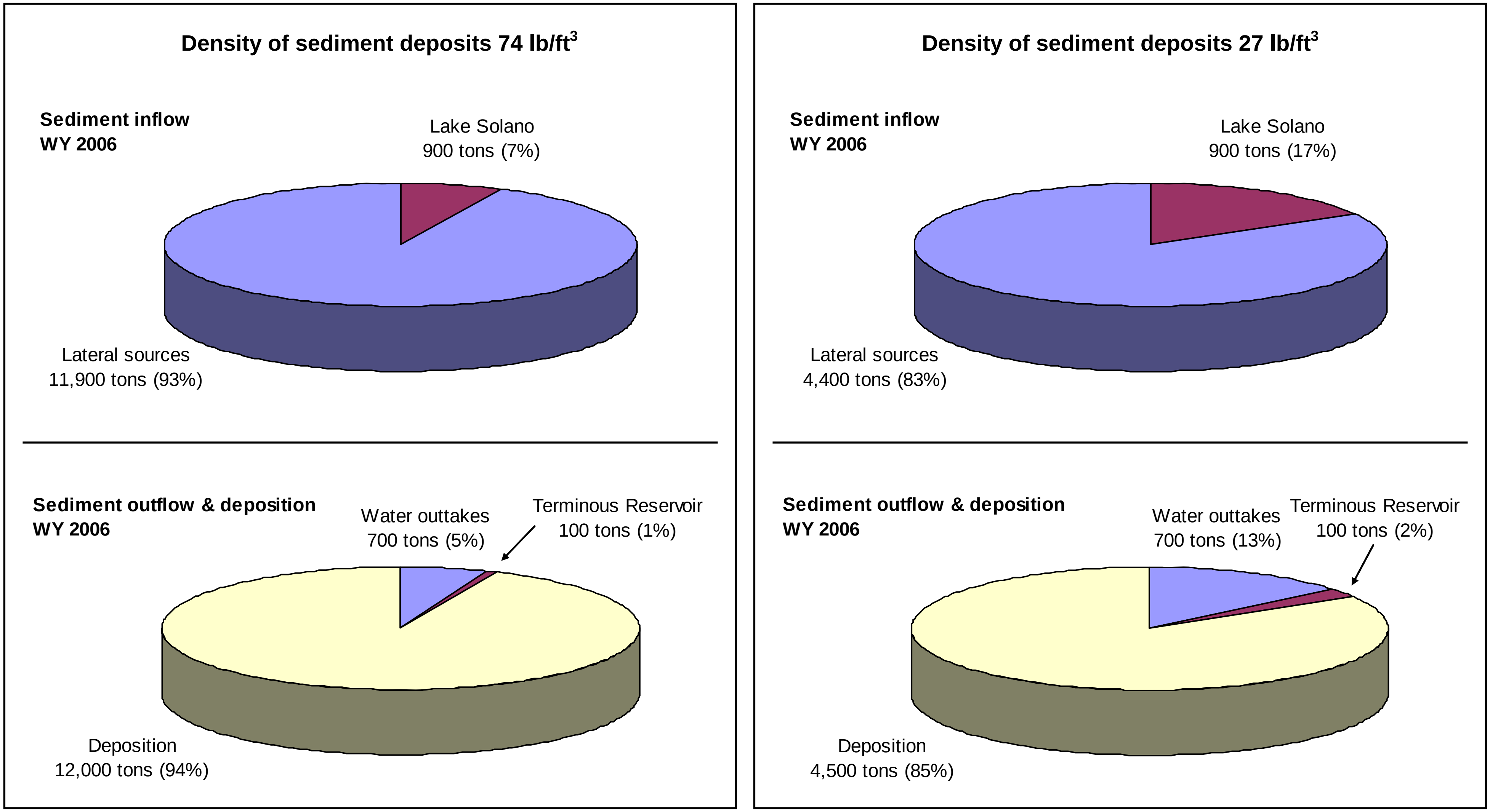


Figure 7.8. Components of Putah South Canal sediment budget for WY 2006 (wet year) for different densities used to convert volumetric deposition into weight units.

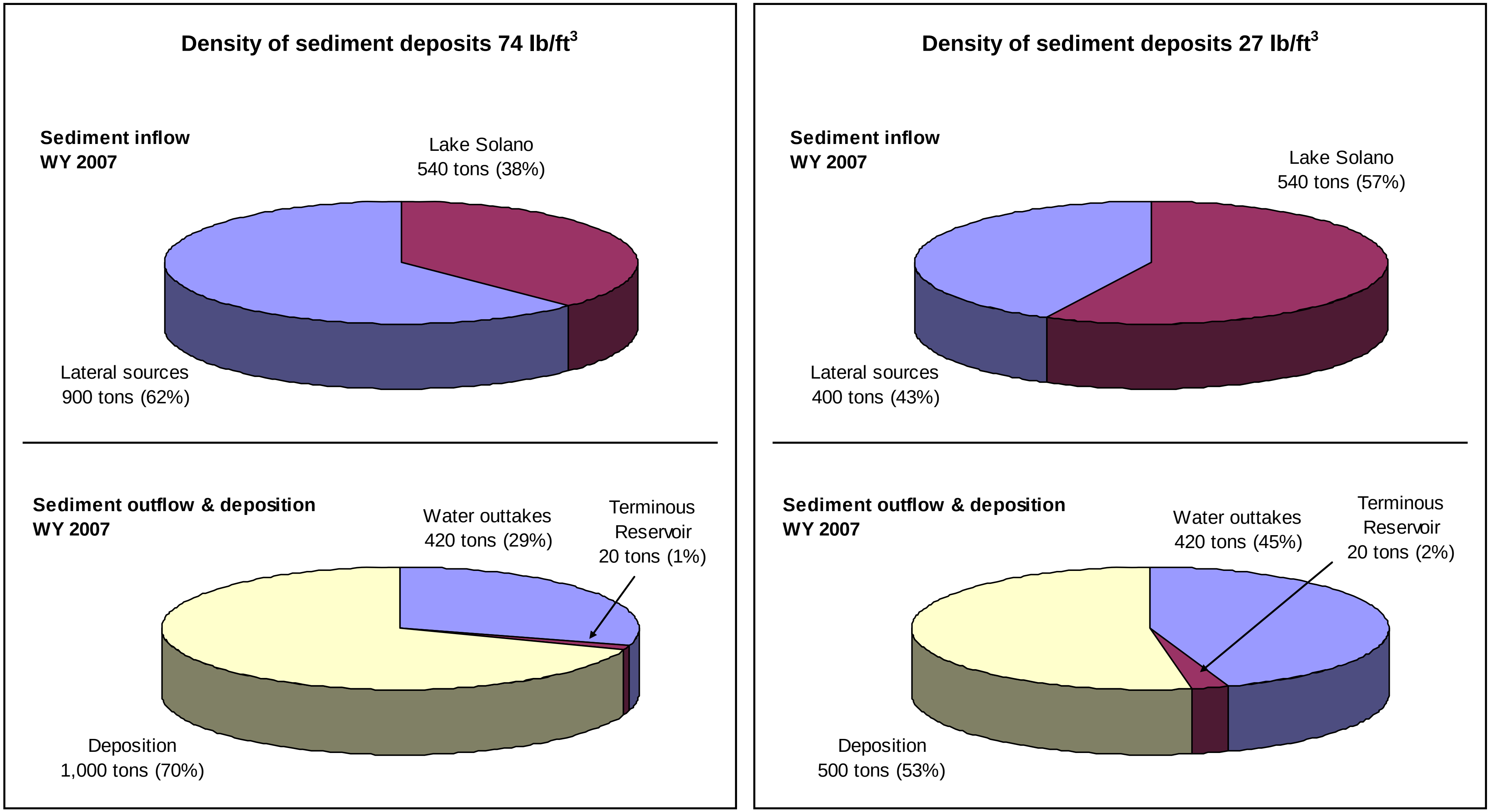


Figure 7.9. Components of Putah South Canal sediment budget for WY 2007 (dry year) for different densities used to convert volumetric deposition into weight units.

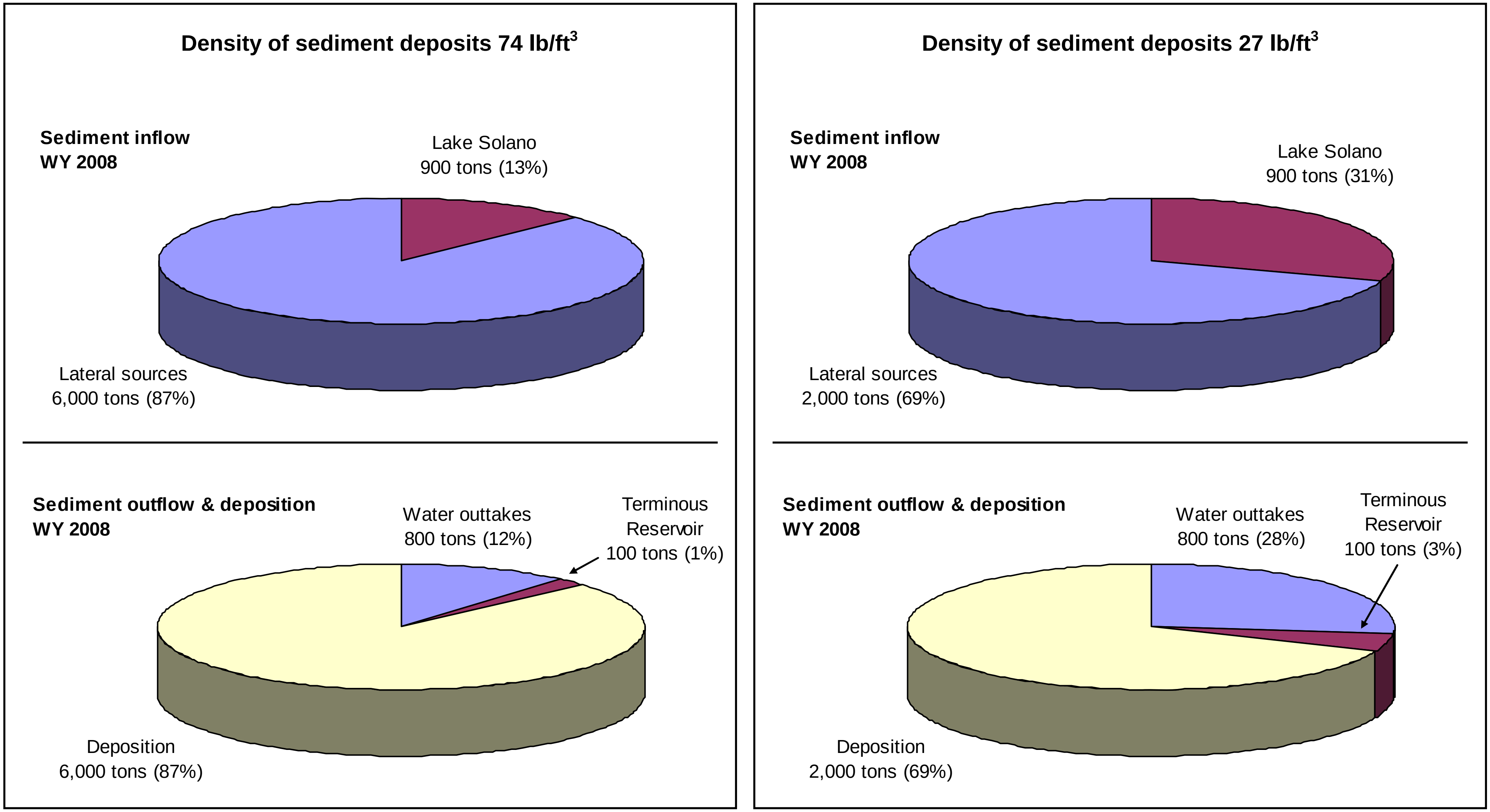


Figure 7.10. Components of Putah South Canal sediment budget for WY 2008 (moderate year) for different densities used to convert volumetric deposition into weight units.

8. IDENTIFICATION AND ANALYSIS OF SEDIMENT AND TURBIDITY SOURCES

During the course of these studies, NHC examined information and data related to rainfall, runoff, and turbidity, and found that each of the three water years studied (WYs 2006, 2007, and 2008) was somewhat unique from a hydrologic perspective and none of the three years may be representative of typical annual hydrologic conditions. By typical conditions we mean "the rainfall and runoff conditions that typically occur during most years and therefore contribute to chronic sediment inputs and annual loading of sediment deposited in the canal". WY 2006 was an extreme year because of a few severe rainfall events and especially the December 31, 2005 storm. This storm resulted in significant flooding over the entire study area (Figures 8.1-8.3). WY 2007 was a dry year, but is more likely to depict more mild hydrologic conditions that may occur 1 to 2 years out of 10. WY 2008 was perhaps more representative of average annual conditions for the most part, but it too experienced the occurrence of an extremely intense localized storm event on January 4, 2008. This intense event produced over 8 inches of rain in the Allendale area extending north to the Headworks. According to the SCWA, this storm event produced rainfall intensities in some drainage basins on the order of a 1,000-year recurrence interval or more. The January 4, 2008 rainfall event produced high flows from the Sweeney Creek watershed that resulted in overflows that left the creek channel and entered the canal at three locations (see Figures 3.8 and 3.9 in Chapter 3). Similar conditions occurred in the McCune Creek watershed near the Headworks resulting in significant overtopping flows that exceeded the capacity of the McCune Creek overchute that flows over the canal at MP 0.47 (see Figures 3.6 and 3.7 in Chapter 3).

Two primary sources of sediment and turbidity in the PSC are identified in Chapter 7: (1) one from inflows that enter the PSC from Lake Solano and (2) the second from the sum of all lateral sources, including canal bank surface erosion, canal bank mass failures, inputs from direct drains, and inflows from overtopping flows at stream crossings or other points, and atmospheric deposition. Annual sediment budget estimates developed by NHC for WYs 2006, 2007, and 2008 show the large variability in annual sediment inputs resulting from different annual hydrologic conditions. Depending on the bulk density of sediment deposits used to convert volumetric data into weight units (see discussion in Chapter 7), NHC estimated between 5,300 and 12,800 tons of total sediment loading from all sources in WY 2006, 940 to 1,440 tons in WY 2007, and 2,900 to 6,900 tons in WY 2008. Unfortunately, with only three complete water years of data available, there is insufficient long-term information to accurately describe the likely range and nature of the sediment yields generated from each sediment source along the canal during different hydrologic conditions. Based on the three annual sediment budget analyses completed, lateral sources contributed 83-93%, 43-62%, and 69-87% of the sediment load during WYs 2006, 2007, and 2008, respectively.

The results on sediment source contributions obtained in this study should be used with caution. It appears that lateral sources of sediment were the major sources of sediment entering the canal during two of the past three years, but this may not be true for all years and hydrologic conditions. During those two years, there were lateral inflows of turbid water associated with two rare events (on December 31, 2005 and January 4, 2008) which introduced large volumes of sediment into the canal from lateral sources, principally overflows from local creeks (McCune, Sweeney, Alamo, and Ledgewood/Suisun) and from slides and soil slips that occurred along the canal banks. During very wet years that include large-scale flooding and overtopping events, it is reasonable to expect that lateral sources will dominate, especially when the Headworks is closed to minimize turbid water inflows from Lake Solano. However, the frequency of lateral sediment inputs from storm events similar to the December 31, 2005 and January 4, 2008 storms may be on the order of once every 10 to 20 years or more. During dry years, when no overbank flooding occurs, approximately similar contributions from lateral sources and Lake Solano can be expected. Based on the present results and data, the range of the average annual contribution from lateral sources can be on the order of 60-90% of the total loading to the canal. However, accurate long-term average sediment contributions from the major sources (Lake Solano and lateral inflow) cannot be accurately determined at this time based on only three years of data.

The following sections discuss the relative importance for each source from a long-term average perspective. It is important to note that under present conditions sediment loading from Lake Solano occurs all year long at different rates depending on the season and water diversion rate, while all lateral inputs, except for atmospheric (wind blown) deposition, side casting from road maintenance, and sediment residuals left in the canal after each fall cleanout, are created only during the rainy season.

8.1. Lake Solano

Based on flow and turbidity monitoring data collected during WYs 2006, 2007, and 2008, Lake Solano produced approximately 900 tons of suspended sediment during WY 2006, which is approximately 7-17% of the estimated total annual sediment load entering the PSC. During WY 2007, approximately 540 tons of suspended sediment came from the lake, or approximately 38-57% of the total annual load entering the PSC. In WY 2008, an estimated 900 tons of sediment (13-31% of the total annual load) was derived from the lake.

8.2. Lateral Sources

8.2.1. Atmospheric Deposition: Chronic, Minor

Atmospheric sediment deposition (primarily from wind blown particles) is a chronic, but relatively minor source of sediment loading to the canal that is difficult to measure. For example, in Lake Tahoe, which has been intensively studied, atmospheric particulates from wood smoke and fugitive dust produces approximately 830 tons/year, or 4.34 tons/mi^2 of lake surface area (Roberts and Reuter 2007). Applying this same atmospheric loading rate to the average top width (40 ft) and total canal length of 33 miles yields an estimated annual atmospheric sediment load into the canal of approximately one ton/year on a long-term annual basis. This probably underestimates atmospheric loading (wind-blown sediment) from tilled agricultural areas near the PSC. Nevertheless, the assumed loading rate illustrates that atmospheric loading is several orders of magnitude less than the total sediment loads from Lake Solano or from lateral sources, and is deemed to be not significant.

8.2.2. Surface Erosion from Canal Banks: Chronic, Minor

Surface erosion (sheet and rill erosion) from the canal banks is chronic but not static in that the amount of erosion is roughly proportional to the amount of rain received each year, along with a host of other factors, including time between storms, storm duration and intensity. There is a large body of research on surface erosion and the role of groundcover (live plants, litter, and gravel or larger particles) in controlling its occurrence (Coleman 1953, Bailey and Copeland 1961, Marston 1952). In general, where groundcover exceeds 70-80%, marginal erosion rates asymptotically approach zero with further increases in groundcover. From a practical perspective, vegetated portions of the canal banks probably function at near their maximum potential in controlling surface erosion. This is evident from field inspections of the canal, wherein no sediment was observed on the concrete edge of the canal where the banks were vegetated except in cases where there were recent landslides. In contrast, sediment was commonly observed all along the canal edge where broad-spectrum herbicide was being applied.

Although no field-plot studies of surface erosion from the canal banks were performed during this study, it is still possible to perform a comparative analysis between the levels of turbidity generated from the canal banks versus those associated with inflows from Lake Solano. Figures 8.4 and 8.5 illustrate levels of turbidity generated from local canal bank contributions versus those from turbidity plumes that originated from inflows from Lake Solano. These data come from annual real-time turbidity monitoring data produced by the SCWA. These data may have some minor discrepancies due to local effects occurring near the turbidity probe during storm events, but for the most part these data are reliable and show how the two different sources of sediment and turbidity enter the canal and affect local turbidity in the canal during storm events.

The measured turbidity results shown in Figures 8.4 and 8.5 are summarized in Table 8.1. The table compares observed maximum turbidity readings form local lateral sources versus Lake Solano and/or overtopping sources. While this analysis is not a mass-balance approach, it is a close proxy, because Figure 3.30 in Chapter 3 shows an excellent relationship between turbidity and suspended sediment measured in the canal. Based on this simple analysis, canal banks and other lateral sources, usually represent less than 10% of the total sediment introduced into the canal during significant storm events when turbid inflows are allowed to enter the canal from Lake Solano or from overtopping flows. What these data do not show is the amount of additional sand and gravel associated with sediment materials that are larger than fine silt and clay-sized materials and quickly settle in the canal. The turbidity data is only capable of monitoring those sediment fractions that stay in suspension for a long period of time. The only way to measure contributions from the larger sized fractions is to perform field-plot studies and/or estimate the amount of coarse-grained materials from sediment deposits observed in the bottom of the canal prior to fall cleanout.

Therefore, based on the available data, it is reasonable to conclude that direct erosion from canal banks is largely confined to those areas where broad-spectrum herbicides are being applied. Presently, 21 miles out of 64 miles of canal bank are sprayed to maintain a barren condition. These barren banks are annual chronic sources of sediment. The absolute magnitude of eroded sediments tends to be minor compared to other sources, but the relative contribution can be high during dry years.

8.2.3. Direct Drains: Chronic, Major (Most Occur Downstream from Serpas Check)

On a unit area basis, direct drains introduce far more sediment than the canal banks even if the banks have been treated with herbicide, because blading of the native surface of access roads generates a new "source or crop" of easily eroded fine sediments that are easily washed into the canal during the winter months. In contrast, banks treated with herbicide develop at least to a limited type of protective crust (armor layer) which reduces the erosion rate relative to freshly disturbed surfaces.

Table 8.2 gives an approximate sediment yield ranking for the direct drains shown in Figure 4.1 (Chapter 4), from the estimated largest sediment yield to the smallest. The ranking is based on the information presented in Table 4.2 (Chapter 4). Drain #6 receives the number one ranking because of its large watershed and routine cultivation such that nearly the entire surface is freshly disturbed prior to the rainy season. It should be noted that the actual watershed size may be larger than the estimate listed in Table 4.2 (Chapter 4). Drain #5 ranked second because of its smaller watershed area but similar land use. Drains #2-4 receive a high ranking, even though they do not drain off right-of-way lands, because the native surface access road is routinely bladed throughout the reach which disturbs and exposes fine sediments to erosion during each subsequent rainy season. Although drains #7-13 drain the largest cumulative area, the land is open space (and may no longer be grazed) and is relatively undisturbed. Sediment yields from this area are likely to be less than 1% of sediment yields from lands with cultivated agriculture. In addition, the native surface access road is not routinely bladed, such that fine sediment production on it is a smaller fraction of what would be produced if the road were bladed. Drain #1 receives the lowest ranking, because it has a very small source area.

The relative importance of direct drains as a lateral sediment source is best evaluated in the context of "water supply disruption potential" due to high turbidity and with respect to their "contribution relative to canal cleanout." The majority of winter municipal water supply use occurs above the Serpas Check. In addition, the water treatment plants located downstream of the Serpas Check have greater flexibility to bypass turbid PSC flows. For that portion of the canal above the Serpas Check, the contribution from drains #1-4 to total lateral source inputs is estimated to be smaller than the contribution from canal banks during non-flood years, although on a lineal foot basis, the erosion rates exceed those of the canal banks, even those treated with broad spectrum herbicide. During flood years, the relative contribution from drains #1-4 is minor compared to lateral sources such as canal bank slides and possible overtopping inflows.

Below the Serpas Check, the situation is different. Direct drains are estimated to be the primary source of chronic sediment loading to the canal, and their relative importance increases during wet years up to the point where overtopping inflows occur. During all years except the most extreme, drains #5 and #6 are estimated to be the largest sources of sediment input into the canal below the Serpas Check. Even during dry years, these drains act as sediment sources because they drain the native surface access road, which are disturbed each year by road maintenance and blading activities.

Figures 8.6 and 8.7 illustrate the influence on turbidity from direct drains as measured at the Terminous Check turbidity sensor. The drains do contribute broad peaks in turbidity which may be greater than contributions from the canal banks. However, relative to the overtopping of McCune and Sweeney Creeks or turbid inflows from Lake Solano, inputs from the direct drains in Suisun Valley during 2008 were modest, but this is largely explained by the fact that the storm of January 4, 2008 was relatively minor in Suisun Valley compared to the rainfall received at the upper end of the canal. Figure 8.6 provides an example of the effect of wash-off sediment from the native surface access road from Drain #10 on the west side of Suisun Valley, one half day following the peak of the storm on January 4, 2008.

8.2.4. Mass Wasting along Canal Banks: Minor, Rare

Mass wasting of canal banks, which occur nearly exclusively on the vegetated portions, is associated only with major floods during very wet years, and so constitutes a relatively rare, episodic source of sediment (see example in Figure 2.16 in Chapter 2). No records are available to accurately judge the relative frequency of landslide and soil slip occurrence. Table 8.3 gives the total number of sides and estimated volumes of sediment delivered to the canal during the three water years (WYs 2006, 2007, and 2008) investigated during this study. Dimensions for each slide were estimated in the field. Typically, the toe along the canal edge acts to limit the amount of material delivered into the canal. Based on field observations, we estimated that the average delivery ratio is about 0.30.

During WY 2006, a record flood occurred over a widespread area of Vacaville, Fairfield and Winters, and the entire canal was affected. WY 2007 was very dry, without significant storm events. During WY 2008, a very localized severe event occurred which exceeded the average intensity of the December 31, 2005 event (8.83 inches of rain recorded for the event at the Sweeney Check), but it was isolated to the area north of Midway Road. Based on field observations, the overall frequency of landslide occurrence within the area affected by the January 4, 2008 event appeared to be far less than during the December 31, 2005 event, in spite of the equal or greater rainfall intensity, perhaps because the antecedent rainfall in WY 2008 was significantly less than that prior to the WY 2006 event.

Based on professional judgment, we suspect that landslide occurrence is typically limited to storms with a recurrence interval in excess of 20-25 years. Also landslides and soil slips are not likely to contribute significantly to lateral source inputs during storm events with recurrence intervals of less than 50 years unless the watershed has experience significant rainfall prior to the event. A further consideration is that typically only a small fraction of the sediment delivered contributes to turbidity in the canal during the event. Most of the landslide volume (90% or more) is likely to slip into the canal and remain there as a large local sediment deposit and only contribute a small portion of its volume toward turbidity observed in the canal. Post winter storm landslide deposits are also much easier to remove with traditional mechanical equipment than settled fine materials associated with turbidity plumes.

8.2.5. Overtopping into Canal: Major, Rare

Overtopping events are estimated to be the largest source of lateral sediment inflow to the canal. Sediments are delivered into the PSC with sediment-laden overbank flows, as well as from eroded canal banks at the locations where these overbank flows spill into the PSC. Such overflows occur during major floods and introduce sediment volumes and turbidity levels typically matching or exceeding those observed in Lake Solano during storm events. Table 8.4 compares maximum turbidity levels from overtopping sources and from Lake Solano for the December 31, 2005 and January 4, 2008 events. During major floods, the Headworks is typically closed for a day or longer to avoid taking high turbidity flows into the canal. Also important is the flow rate that may be carrying highly turbid flows. Typical winter flows through the Headworks may range from 20 to 60 cfs, depending on urban and municipal needs. Rates of lateral inflow from overtopping events can be significant and easily exceed the normal winter flow rates in the canal. As a result, when overtopping occurs, it is typically the single largest source of introduced sediment and turbidity to the canal. In addition, much of this sediment load consists of fine sediments from watershed sources upstream, such that it tends to settle out over the entire length of the canal bottom downstream from the point of entry.

Overtopping has occurred most frequently at McCune and Sweeney Creeks. There have been recent improvements at both locations to reduce the frequency and magnitude of impacts. At Sweeney Creek, a flap gate was installed on the release gate to Sweeney Creek, which has prevented reverse flows of sediment laden stormwater back into the canal from the creek. This improvement has not reduced the frequency of overtopping there, but it has now eliminated an important source of sediment that previously occurred during high flows on Sweeney Creek.

On McCune Creek the installation of a second overchute flume which doubled the discharge capacity significantly reduced the discharge volume into the canal during the January 4, 2008 event, over what would have otherwise occurred, although it did not eliminate overtopping during this rare event. There has also been more frequent overtopping into the canal through the bottom of Suisun Valley, due to the limited capacity of Ledgewood and Suisun Creeks in combination with a relatively low height of the upslope canal access road.

Table 8.5 provides the estimated number of overtopping events that have occurred at major stream crossings along the PSC during the last 20 years (personal communication with Stan Walker from SID, June 3, 2008). These events represent Mr. Walker's off-hand recollections and are not presumed to be precise. This information does, however, provide some context for approximating the frequency of overtopping that has occurred in the past 20 years. Note that only those locations listed in the table are those where overtopping events occurred and that recent improvements at McCune Creek will reduce the frequency of overtopping there in the future. It is difficult to assess the degree to which overtopping may occur at the numerous smaller flumes, siphons, and underdrains. No overtopping was observed at any crossings other than McCune and Sweeney Creeks during the January 4, 2008 event centered north of Sweeney Creek. Overall, overtopping on these secondary crossings seems to be unlikely. This information does indicate that additional improvements at these sites may reduce sediment loading into the canal if rare events occur in the future.

8.3. Summary of Sediment Sources

Table 8.6 provides estimated long-term annual contributions from the major sources of sediment that enter the Putah South Canal. The numerical values are approximate order-of-magnitude estimates, based on the data gathered during the project and professional judgment and are intended to help prioritize the importance of different sources. While sediment influx into the canal is roughly related to the total seasonal rainfall (higher rainfall amounts = higher sediment loads) and rainfall intensity, the mass or volume contribution from lateral sources of sediment tend to be less significant during dry years, although they may still represent a significant component relative to inflows from Lake Solano. Based on the three years of data that are presently available, the sum of all lateral sources of sediment (including fine and course grained materials) contributes approximately 60 to 90% of the total sediment loading into the 33-mile long length of the PSC annually. Lateral sources can be the dominant sources of sediment during major flood events which produce overtopping flows and canal bank landslides, especially in canal reaches located upstream from the Serpas Check. Below the Serpas Check the situation is much different since the two direct drains in Suisun Valley can routinely discharge sediment laden runoff originating on approximately 90 acres of cultivated land.

Although overtopping events are relatively rare, they likely represent the majority of the total lateral source sediment load at a decadal time scale. Above the Serpas Check, canal bank landslides are estimated to be the second largest lateral source, followed by surface erosion from the canal banks, which is largely limited to those maintained in a barren condition through the application of herbicides. Below the Serpas Check, the primary sources of sediment come from Lake Solano, drains #5 and #6, and periodic overtopping events upstream. The duration and persistence of turbid conditions in the canal downstream from the Serpas Check is related to the winter-long delivery of turbid runoff from direct drains as the single largest chronic source of turbidity followed by barren canal banks that are sprayed annually with herbicides.

Table 8.1. Relative contributions of turbidity from canal banks and lateral sources, compared to Lake Solano and overtopping sources.

Storm event	Turbidity station	Maximum turbidity from canal banks and other lateral sources (NTU)	Maximum turbidity from Lake Solano and overtopping sources (NTU)	Relative proportion of canal bank and lateral sources (%)
1/4/2008	Eldredge Plant	31	471	7
1/4/2008	Serpas Check	39	794	5
1/25/2008	Eldredge Plant	15	323	5
1/25/2008	Serpas Check	127	450	28

Table 8.2. Sediment yield ranking for direct drains.

Drain # (see Figure 4.1 in Chapter 4)	Ranking (1 represents the highest estimated sediment yield)
6	1
5	2
2-4	3
7-13	4
1	5

Table 8.3. Canal bank landslide occurrence and delivered volume.

Water year	Estimated relative frequency (years)	Slides (occurrences)	Estimated soil delivered volume* (yd^3)
2006	200 or greater	180	435
2007	<1	0	0
2008	100 or greater**	35	66

* Estimated average delivery ratio of 0.30.
** Storm limited to areas north of Midway Road.

Table 8.4. Relative contributions of turbidity from overtopping sources, compared to Lake Solano.

Storm event	Turbidity station	Maximum turbidity from overtopping sources (NTU)	Maximum turbidity from Lake Solano (NTU)	Relative proportion of overtopping sources (%)
12/31/2005	Eldredge Plant	340*	>500	<68
12/31/2005	NBR WTP	6,610**	670	987
12/31/2005	Waterman WTP	2,598**	580	448
1/4/2008	Headworks	1,580***	3,220	49
1/4/2008	Eldredge Plant	180****	471	38
1/4/2008	Serpas Check	208****	794	26

* Turbidity plume from McCune Creek overflow at MP 0.47.
** Turbidity plume from Alamo Creek overflow near MP 14.0.
*** Measured in McCune Creek flume at MP 0.47.
**** Turbidity plume from Sweeney Creek overflow near MP 6.15.

Table 8.5. Anecdotal observations on overtopping events that entered PSC during past 20 years (according to Stan Walker from SID).

Overtopping location	Estimated number of overtopping occurrences (events) in past 20 years
McCune Creek	3-4
Sweeney Creek	5-7
Alamo Creek	1
Suisun Valley	3-4

Table 8.6. Estimated long term contributions from different sediment sources.

Sediment source	Type	Estimated year-to-year variation in total sediment load (%)	Estimated long-term mean sediment load contribution (%)
Vegetated canal banks	Chronic	<1-5	<1
Bare canal banks	Chronic	0-40	5
Native surface access roads	Chronic	15-30	<5
Off-right-of-way direct drains*	Chronic	40-60	40
Canal landslides	Episodic	0-30	<10
Overtopping	Episodic	0-70	20-40**
Lake Solano	Chronic	10-80	20-40**

* All off-right-of-way direct drains are below Serpas Check.

** Estimated contribution range assumes no major improvements have been made to reduce effects of periodic overtopping.

Figure 8.1. Flooding in Vacaville near Putah South Canal from Alamo Creek during December 31, 2005 storm. Photo from http://www.vacavilleflood.com.

Figure 8.2. Lateral inflow to Putah South Canal in Vacaville during December 31, 2005 storm. Photo from Internet.

Figure 8.3. Flooding in Vacaville (Citrus Ave) during December 31, 2005 storm. Photo from http://www.vacavilleflood.com.