Advancement of Salinity and Flow Monitoring in the San Francisco Bay Delta

San Francisco Bay Delta Action Plan Implementation Support

FINAL REPORT

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EXECUTIVE SUMMARY

This report evaluates the cost and utility of adding coupled surface and near-bottom salinity monitors along the axis of the San Francisco Estuary, and the types of equipment and approximate costs of this additional monitoring effort. Expanding the monitoring network by adding downstream monitoring stations, adding stations at depth, and increasing the resolution of monitoring stations along the axis of the estuary will generate data that capture tidal dynamics and may be used to derive equations that predict salinity and other hydrodynamic endpoints with greater precision than currently possible. The proposed monitoring is expected to enhance the hydrodynamic modeling of the salt field and the accuracy of compliance and prediction methods in the estuary.

Springtime outflows through the San Francisco Estuary are managed through the position of the 2 parts per thousand bottom salinity isohaline (X2) along the center-line of the estuary, measured in kilometers relative to the Golden Gate Bridge. X2 is calculated from surface salinity measurements with a constant vertical conversion factor. The current framework of sampling stations does not collect near-bottom salinity along the estuary center-line, does not extend far enough down-estuary to adequately characterize X2 during high flows, and the separation of monitoring locations limits the precision with which the position of X2 can be calculated.

Near-surface and near-bed salinity and turbidity sensors and ancillary hardware could be added to the estuary for an estimated cost of ~ $780K in capital costs and $500K/yr in operation, maintenance, and data processing costs based on a proposed addition to an existing surface salinity network in San Francisco Estuary operated by the US Geological Survey. While this document does not recommend a particular plan for implementation, the compiled information provides rough costs for planning considerations. Data collected through a network of this kind could improve precision of compliance methods with the existing Delta outflow standard. With data collected over time, it would support modifications to a new/modified Delta outflow standard, improve our ability to assess the effectiveness of water quality standards, and improve protection of water supply and aquatic life habitat. These data would also improve the salinity modeling capability and accuracy for future predictions and past evaluations. Expanding the monitoring network

also provides a platform to connect hydrodynamic and biological measurements which is necessary for integrating biological and hydrodynamic modeling and advancing knowledge of estuarine mechanisms that influence fish population trends. The specific design of a monitoring network and whether or not the improvements can be optimized for their potential outputs was beyond the scope of the present document and needs to be based on a broader discussion among science experts, regulators, and the regulated community.

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1 INTRODUCTION

1.1 PURPOSE

The purpose of this report is to evaluate the need for and benefits of improving the monitoring network that supports the Delta outflow objective. The US Environmental Protection Agency (EPA) identified strengthening water quality standards and advancing regional water quality monitoring programs as the two highest priority actions that EPA could take to accelerate restoration of aquatic life and ensure a reliable water supply for cities and farms in the San Francisco Estuary watershed (EPA Action Plan 2012). California is in the process of updating federal and state water quality standards for the San Francisco Estuary and the upper watershed. The Delta outflow objective is one of several water quality standards in the San Francisco Bay/Sacramento-San Joaquin Delta Estuary Water Quality Control Plan. The State Water Board is evaluating changes to the Delta outflow objective (and several other objectives) in an effort to improve protection of aquatic life. It is timely and useful to consider changes to the monitoring network as the state considers updating and implementing the Delta outflow objective and other standards.

This report evaluates the cost and utility of adding coupled surface and near-bottom salinity monitors along the axis of the San Francisco Estuary and the types of equipment and approximate costs of this additional monitoring effort. Technological advances in monitoring equipment have occurred since the Delta outflow objective was first implemented in the 1990s; however, the monitoring network has not changed substantially in more than twenty years. Modern instruments and higher spatial resolution can greatly increase the precision and utility of monitoring data for determining compliance with standards, advancing forecasting tools, and evaluating the effectiveness of water quality standards in protecting water quality for aquatic life and water deliveries.

1.2 REPORT GOALS

1. Summarize knowledge of the salt field and freshwater outflow in San Francisco Estuary and identify the data limitations.

2. Evaluate the feasibility of adding coupled surface and near-bottom salinity measurements in the estuary to ongoing continuous monitoring programs.

3. Evaluate the feasibility of improving flow measurements enough to accurately measure and calculate net freshwater outflow with existing technology.

4. Describe an improved salinity monitoring design and methods for incorporating it into existing monitoring programs.

5. Estimate the cost of improving the existing monitoring system to measure coupled surface and near-bottom salinity and to improve flow measurements.

In the following chapters, we summarize existing scientific and regulatory knowledge of the salinity field in San Francisco Estuary, including the current regulatory framework and reporting requirements (Chapter 2). An overview of the monitoring currently being done is presented in Chapter 3. We identify desired improvements in the monitoring network (Chapter 4) based on our understanding of salinity behavior in the estuary. And, we provide an estimate of installation, operation, and maintenance costs for a coupled, surface and near-bottom salinity monitoring array based on preliminary plans developed by the US Geological Survey (USGS) (Chapter 5). Considerations for monitoring system design, going beyond the preliminary USGS proposal, are presented in Chapter 6.

A comprehensive evaluation of costs and performance of available instruments for monitoring salinity and flow is reported in Appendix A and B. Conceptual ideas for potential deployment options, based on our prior experience in other water bodies, are provided in Appendix C. While the instrument selection in the estuary may have been narrowed down based on ongoing or planned efforts, as described in this document, the information in the Appendices provides a reference for cost and performance comparison for other instruments that are available commercially at this time.

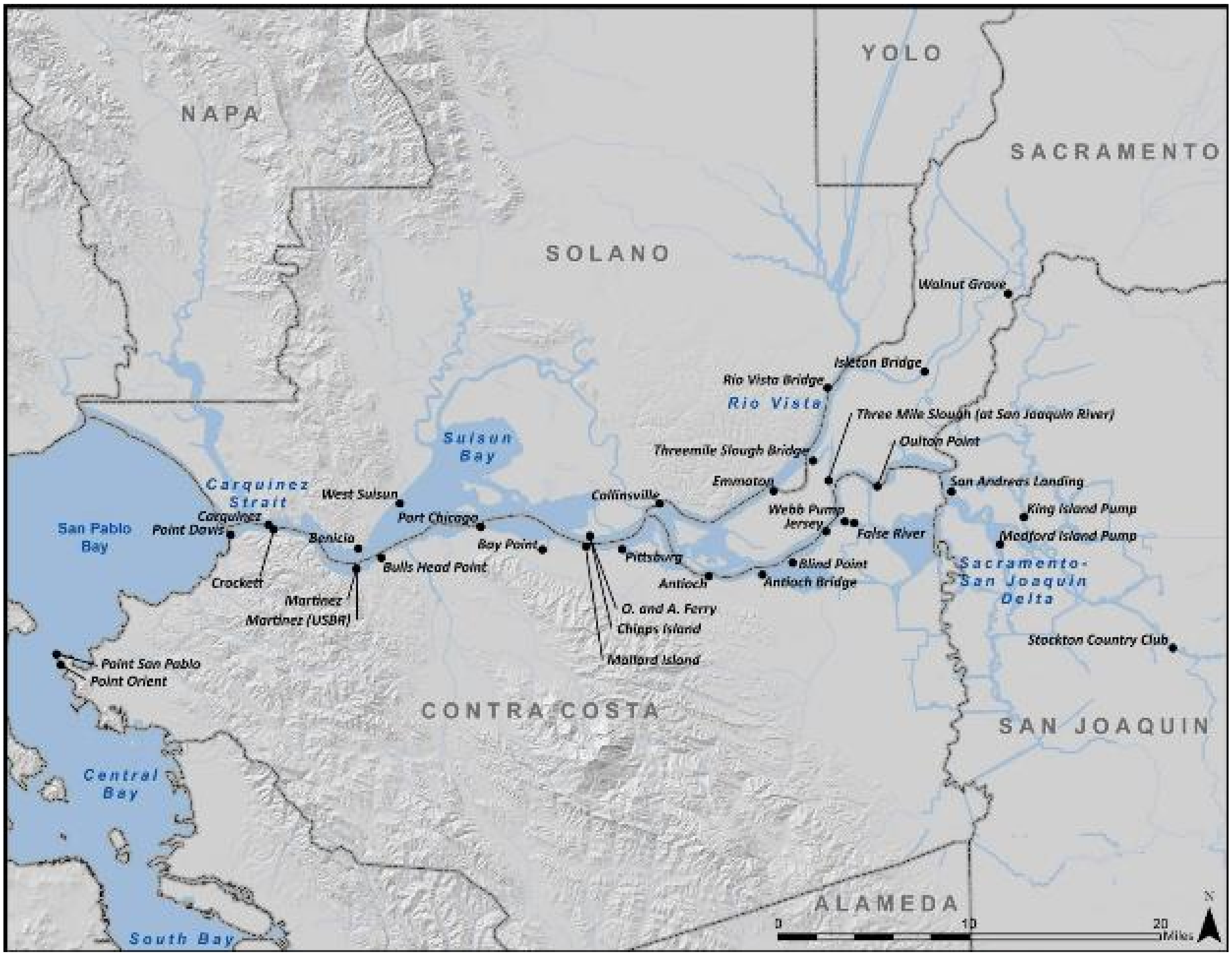

Figure 1-1 Stations with Records of Salinity Data in the North San Francisco Bay and western Delta.

2 FLOW AND SALINITY IN SAN FRANCISCO ESTUARY

2.1 BEHAVIOR OF THE SALT FIELD AND DELTA OUTFLOW IN SAN FRANCISCO ESTUARY

Freshwater inflows into SF Estuary vary strongly by season and by year, creating a time-varying salinity gradient that has been related to the abundance of various marine, estuarine, and freshwater fish species. The horizontal and vertical salinity profile in the northern part of San Francisco Estuary—including San Francisco, San Pablo, Richardson, Suisun and Grizzly Bays, Suisun Marsh, and the Sacramento-San Joaquin River Delta—is primarily affected by freshwater flows from the contributing watershed and exchange with ocean water through Golden Gate. Secondary drivers include wind and spring-neap tidal variations. The actual salinity distribution in time and space is a function of these drivers and the complex bathymetry of the estuary. Salinity is managed at key locations in the northern part of the estuary to support multiple aquatic species and drinking water and irrigation water uses.

The movements of the salt field and Delta outflow are coupled. When Delta outflow increases, the salt field moves downstream in response, primarily due to advection by the net flow. In other words, saltier water is pushed toward the sea by freshwater flow from tributaries, a relatively straightforward process. However, when freshwater flows from tributaries decrease and Delta outflow decreases, the salt field moves upstream, but, in this case, the physical processes are more complex and depend on gradients in the salt field interacting with the tidal currents and the geometry of the estuary.

Large changes in the position of the salt field occur in the winter in response to the uncontrolled run-off events associated with wintertime storms. During low flow periods (typically late spring through early winter), the salt field remains relatively stable because Central Valley Project (CVP) and State Water Project (SWP) operators adjust reservoir releases and/or export rates to maintain salinity standards at Jersey Point, and occasionally at Emmaton (Figure 1-1). During these periods, project operators make adjustments in Delta outflow primarily in response to spring/neap tidal variations in the strength of salinity intrusion, and occasionally to make adjustments for atmospheric pressure changes and sustained westerly winds.

Downstream movements of the salt field can be relatively quick in response to an increase in Delta outflow, following an advective timescale. Upstream movements of the salt field are often slower depending on the suite of dispersive processes that are primarily controlled by the position and structure of the salt field in the estuary and the timing of tidal forces (spring/neap cycle) relative to when an outflow event occurred.

The horizontal salinity gradient is the primary driver of salinity intrusion. The horizontal salinity gradient is the spatial change in salinity along the axis of the estuary, which varies from oceanic salinity (roughly 35 psu) near the Golden Gate Bridge to fresh water (zero) at Rio Vista on the Sacramento River. One of the best ways of thinking about the horizontal salinity gradient is to think of it as a spring. Compression of the horizontal salinity gradient occurs when Delta outflow increases, expansion of the gradient occurs when Delta outflow decreases. Compression of the horizontal salinity gradient increases the rate of salinity intrusion through a host of mechanisms that include gravitational circulation (tidally averaged two-layer exchange flow that is driven by a horizontal density gradient created by the difference in salty water in the bay and fresh water), tides, and winds. Dilation, or relaxation of the spring reduces the rate of salinity intrusion due to the same mechanisms. The greater the increase in Delta outflow, the farther the salt field is pushed downstream and the more compressed the spring becomes. For example, when the salt field is pushed downstream of the Benicia Bridge, it moves back very rapidly, because: (1) the salt field is highly compressed when it is seaward of the Benicia Bridge, and (2) Carquinez Straight is deep, which enhances gravitational circulation. Once the salt field is fully in Suisun Bay or the western Delta, the horizontal salinity gradient is relaxed and the depth in the channels is shallower.

The movements of the salt field can appear complicated, especially given the complexities of the bathymetry in Suisun Bay and in the western Delta. However, for the most part, we understand how the salt field works, at least at the time and space scales necessary for the proposed work. In this regard, the basic physics of the process is relatively mature. Unlike Delta outflow, the position of salt field can be accurately measured, provided the monitoring program has sufficient spatial resolution.

A conceptual model of freshwater/saltwater mixing in San Francisco Estuary is shown in Figure 2-1. Seaward of the approximate 2 parts per thousand isohaline (X2), both barotropic (water surface slope driven) and baroclinic pressure gradients (pressure differences due to a density difference between salt and freshwater) exist. The baroclinic pressure gradient is created in estuaries by the horizontal salinity gradient which drives periodic, density driven circulation cells on a tidal timescale. This can be visualized as upstream flow at the bed and a downstream flow at the surface. These density-driven circulation cells are strongest near slack water (a short period before the reversal of tidal direction in which water is not moving in either direction), especially during neap tides when vertical mixing is weakest.

The current framework of sampling stations does not extend far enough down-estuary and monitoring locations are too far apart to capture the tidal dynamics that determine the position of X2. Pulses of density driven 2-layer exchange flows typically occur near slack water twice a day which create varying degrees of periodic stratification throughout the brackish water regions of the estuary. Importantly, the salt field, including its vertical and horizontal structure and the density-driven two-layer exchange flow (when it is occurring near slack water) are all advected by the tidal currents long distances with each tide, a distance known as the tidal excursion. In Suisun Bay the tidal excursion is on the order of 21 km (roughly the length of Suisun Bay), and 13 km in the western Delta. This two-layer exchange flow occurs downstream of the 2 psu isohaline in a reference frame which traverses up to 21 km every ~6 hours. Expanding the monitoring network by adding downstream monitoring stations and increasing the resolution of monitoring stations along the axis of the estuary will generate measurement data that capture tidal dynamics and are then used to derive equations that predict X2 and other hydrodynamic endpoints with greater precision.

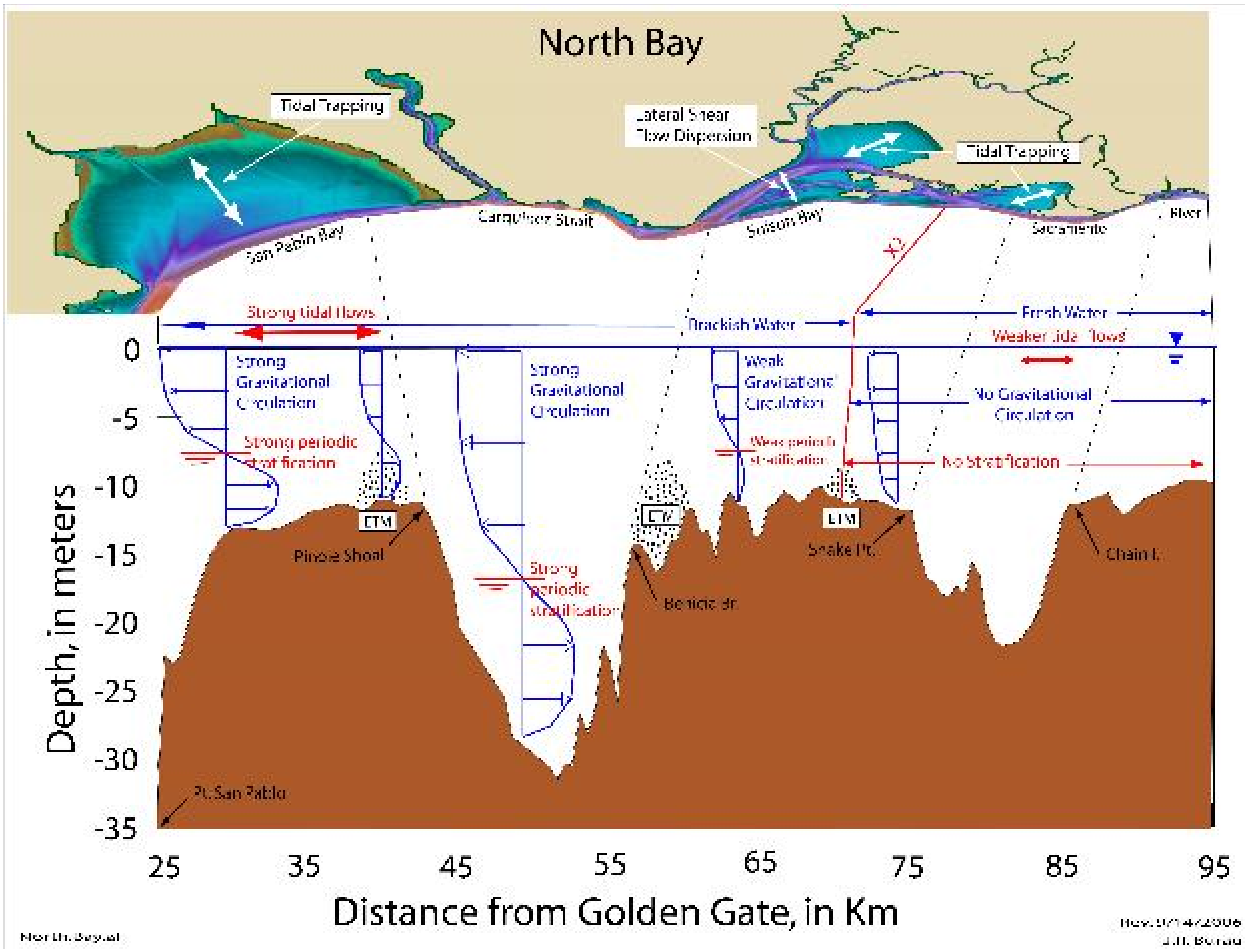

Figure 2-1 A Conceptual Model of Gravitational Circulation, Estuarine Turbidity Maximum (ETM) Formation, Salinity Stratification and Intrusion in the North Bay and Western Delta.

2.2 SUMMARY OF DELTA OUTFLOW OBJECTIVE AND X2

The State Water Resources Control Board (State Water Board) sets water quality objectives under the Porter-Cologne Water Quality Control Act and delegated authority of the Clean Water Act to protect beneficial uses of water in the SF Estuary. The Delta outflow objective was adopted by the State Water Board and approved by USEPA in 1995 to protect resident and migratory fish that use the SF Estuary. The relationship between fish species abundance and X2, the near-bottom 2 parts per thousand (ppt[1]) salinity isohaline as described in Jassby et al. (1995), is the scientific foundation of the flow and salinity-based Delta outflow objective which has controlled regulation of springtime freshwater flows in the estuary over the past two decades. During that time scientific research has continued to evaluate the relationships between salinity and biology (Feyrer et al., 2007, 2011; Kimmerer et al., 2009) and between salinity and flow (e.g., Monismith et al., 2002; Gross et al., 1999; MacWilliams et al., 2015). Nevertheless, the basic approach and tools for

[1]In current usage, ppt and practical salinity units (psu) are equivalent.

measuring, managing, and calculating salinity and freshwater flow outlined in 1995 are still in use.

The Delta outflow objective includes flow and salinity targets for compliance, dependent on location and seasonal hydrology and precipitation. Delta outflow targets of 7,100 cubic feet per second (cfs), 11,400 cfs, and 29,200 cfs are established at specific compliance locations of Collinsville, Chipps Island, and Port Chicago, respectively (Figure 1-1). These compliance locations correspond to X2 values of approximately 80 km, 75km, and 65 km respectively. Compliance with the flow objective is determined using the Net Delta outflow Index (NDOI), a tidally-averaged, daily estimate and not a direct observation. The NDOI has large, known inaccuracies at low freshwater flows.

A surface salinity target in the form of specific conductance of 2.64 mmhos/cm[2] is established at Collinsville, Chipps Island, and Port Chicago to approximate a near-bottom salinity of 2 ppt or psu (3.8 mmhos/cm) at 80 km, 75 km, and 65 km from the Golden Gate Bridge respectively. A constant factor is used at all three compliance locations to represent vertical salinity stratification (fixed ratio between surface and bottom salinity), yet we know that salinity stratification varies significantly with the tides, the spring/neap cycle and the position of the salt field (Stacey et al. 2010; MacWilliams et al., 2015). Near-bottom salinity measurements are not routinely measured, and are not part of the compliance calculation.

2.3 ESTIMATING, MEASURING, AND ERROR IN DELTA OUTFLOW

Delta outflow on a daily average basis is reported as the Net Delta outflow Index (NDOI). The NDOI is calculated as the sum of all Delta inflows minus exports through aqueducts, and minus the net channel depletion in the Delta, which accounts for consumptive use and precipitation. Inflows are measured at five locations: Sacramento, San Joaquin River, Cosumnes and Mokelumne Rivers, and the Yolo Bypass; with a term for other miscellaneous flows. Exports are summed for four aqueducts that transfer water outside the Delta: CVP, SWP, North Bay Aqueduct, and the Contra Costa Canal. The NDOI is a daily, tidally-averaged estimate and not a direct observation. Actual Delta flows change rapidly over the course of tidal cycle, and this tidal variation is not part of NDOI. Moreover, variations in the net flow and dispersive mixing associated with the spring/neap cycle and changes in atmospheric pressure can significantly alter the position of the salt field.

Forecasting methods for flow targets contain errors which result in small to large differences between predicted and actual ecological conditions and water supply export volumes. For example, comparisons of measured Net Delta outflow using USGS acoustic Doppler measuring instruments at four locations near the confluence of the Sacramento

[2] Note that continuous salinity measurements in modern sensors are obtained as electrical conductivity, and reported at a standard temperature of 25° C, termed *specific conductance*. Electrical conductivity and specific conductance are typically reported units of millimhos/cm or mmhos/cm.

and San Joaquin Rivers to estimates of NDOI show significant differences because both methods are imprecise, for different reasons. For example, NDOI estimates are based on a mass balance approach, where all of the measured inflows and outflows into and out of the Delta are summed. Therefore, NDOI includes the sum of all the inaccuracies in the measurements that make up the NDOI estimate. Moreover, net Delta island consumptive use is an estimate based on cropping patterns. When inflows and exports are both high, the net Delta island consumptive use is a relatively small component of the NDOI estimate. However, when inflows and exports are low, the net Delta island consumptive use can make up a significant portion of the NDOI estimate, and errors in the estimate translate to errors in NDOI.

Measuring net Delta outflow with the USGS acoustic Doppler instruments is also challenging at low Delta outflows. Measuring net Delta outflow in the field is characterized by a classic signal to noise problem. The tidal signals are orders of magnitude greater than the net flows. Daily peak tidal flows in the western Delta can be on the order of 150,000 cubic feet per second (cfs) (Department of Water Resources, 2016) while net freshwater flow in dry periods is often 5,000 cfs or less and sometimes negative during strong spring tides or during prolonged wind events. The measured net Delta outflow is actually a calculation including the sum of the tidal average of the measured data at four locations using a tidal filter (Walters, 1984). Tidal filters basically subtract the flood and ebb discharges to compute the net. Therefore, the combined tidal discharge at four stations must be measured with an accuracy of < 3% (=100*5,000/150,000) to compute Delta outflow when the outflow is 5,000 cfs or lower. The technology to measure Delta outflow to this level of accuracy does not exist. Not surprisingly, given the imprecision in both estimates of net Delta outflow (measured and NDOI), analysis by Monismith shows that there is no relationship between these estimates when Delta outflows are less than 10,000 cfs (Monismith, personal communication). A similar analysis by the Department of Water Resources (2016) indicates a significant difference between NDOI and measured Delta outflow.

2.4 Estimating, Measuring, and Error in Salinity and the X2 Isohaline

X2 is computed by interpolation from salinity at fixed stations and using different predictive equations that are primarily driven by flow history. Estimates of X2 are based on surface salinity measurements because near-bottom salinity is not routinely measured. The reason bottom salinity is the ecological variable of choice over surface water measurements is that in the brackish estuarine environment salinity stratification associated with gravitational circulation fluctuates with the tides (weak during the tidal current magnitudes and strong during near slack water periods) can make surface measurements problematic. Moreover, the location of the estuarine turbidity maximum is more closely physically associated with the position of the 2 psu isohaline (Arthur and Ball, 1978; Burau et.al., 1998) because X2 is roughly the location where the strength of the horizontal salinity gradient becomes dynamically insignificant.

The original analysis supporting the use of X2 as an estuarine water quality standard assumed a constant vertical salinity gradient of 0.24 ppt such that a bottom salinity of 2 ppt corresponded to an average surface salinity value of 1.76 ppt; this was based on a limited amount of observed data at the surface and bottom. For regulatory purposes, this bottom salinity was assumed to be equivalent to a surface electrical conductance (standardized to 25 °C) of 2.64 mmhos/cm or mS/cm (2,640 μS/cm). Specifically, Jassby et al. (1995) wrote:

"Where the bottom salinity was near 2‰ (specifically, between 1.5 and 2.5‰), the difference between bottom and surface salinity was unrelated to flow, except at very high flow. The median difference (bottom minus surface) was 0.24±0.06 (mean and 95% confidence interval), implying that a bottom salinity of 2‰; corresponded to a surface salinity of 1.76‰."

Since the development of the original regulation, X2 has been characterized using surface salinity measurements and an equation using a constant ratio between the bottom and surface salinity, as in the above quote. However, the exact value of the ratio is different in other X2 calculation approaches (Reed et al., 2014).

Bottom salinity data in the estuary are limited because of the challenges of supporting continuous long-term sensors at depth, related to maintenance, access, and fouling by near bottom sediments. A small number of stations have been monitored at the bottom, but they are usually near shore. Nearshore bottom salinity measurements often more closely represent the near surface measurements because shallow regions do not support gravitational circulation and salinity stratification. Moreover, most of the salt flux associated with salinity intrusion and brackish water habitats occurs at depth, in the shipping channels in Suisun Bay (Burau et al., 1998, 1999; Stacey et al. 2010). Despite the challenges, measurement of near-bottom salinity is consistent with the X2 standard and aquatic habitat knowledge that supports the Delta outflow objective.

2.4.1 X2 Model-based Calculations

Over the past two decades, various modeling frameworks (equations or sets of equations) have been applied to the prediction of the X2 position and of the salinity patterns in the Delta and San Francisco Bay, ranging from simple statistical models (a log-linear equation) to complex three-dimensional hydrodynamic models. A widely used statistical approach is the autoregressive equation between Delta outflow and X2 position, termed the K-M model (Kimmerer and Monismith, 1992; Jassby et al., 1995). This equation was calibrated using salinity data in the Bay and Delta from October 1967 to November 1991, the most complete data set available at the time of publication. The monthly flow-X2 relationship (Kimmerer and Monismith, 1992) was expressed in the original document as:

$$X2(t) = 122.2 + 0.328X2(t-1) - 17.65 \log_{10}(Q_{out}(t)) \quad \text{Eq. 1}$$

where Q_{out} is the mean monthly Delta outflow in terms of cubic feet per second (cfs) and X2(t-1) is the previous month isohaline position expressed as km from Golden Gate.

A recent review and evaluation, including discussion with the original authors, of the above equation being presented with different coefficients, suggests a slightly modified set of coefficients (Reed et al., 2014):

$$X2(t) = 10.16 + 0.945X2(t-1) - 1.487 \log_{10}(Qout(t)) \quad \text{Eq. 2}$$

Both equations are in units of cfs for flow. The standard error computed for Eq. 2 is 6.11 km (Reed et al., 2014, based on a presentation provided to the Delta outflows and Related Stressors Panel by Michael MacWilliams). Several variations of the original equation, with different coefficients, have been reported, as summarized in Muller-Solger (2012).

Most available formulations use a limited subset of the data that are available today. For example, Mueller-Solger (2012) reported that even if one retained the original formulation of the X2 equation, an additional 20 years of data have become available (Jassby et al., 1995 used data from 1967-1991).

In more recent work (Roy et al., 2014), the Jassby et al. (1995) model was recalibrated and the constants in the autoregressive equation (A, B, and C) were obtained:

$$X2(t) = A + B\,X2(t-1) - C\log(Qout(t)),$$

This was done for each river branch using data for several different time periods:

- the entire record of observed salinity data at fixed stations (Hutton et al., 2015), October 1921 to September 2012;
- the period with only historical grab sample data, October 1921 to June 1964;
- the period with only continuous data, July 1971 to September 2012; and,
- the period for which the original estimate of Kimmerer and Monismith was computed, October 1967 to November 1991.

Results are shown in Table 2-1. Note that the logarithmic term in the K-M equation precludes its use for negative outflows that occurred during some periods of the historical record. In all cases, equations that are broadly similar to the original K-M equation provide reasonable fits, with coefficients that are approximately in the same range for the flow term.

The flow-X2 equation has also been proposed using an exponent form of the Q_{out} term, rather than the logarithm, using the same surface salinity dataset as in the original analysis (Monismith et al., 2002), as well as with other coefficients for flow added to the basic structure of Eq 2 (MacWilliams et al., 2015). A review of the equations incorporated in Reed et al. (2014) is reproduced in Table 2-2.

In addition, there are several published one-, two- and three-dimensional numerical model applications for salinity in the region, each of which has been applied for research or to understand mechanistically the effects of specific system changes, such as changes in inflows and Delta operations or external effects such as sea level rise (e.g., Mierzwa and Anderson, 2002; Anderson et al., 2008; Gross et al., 2007, 2010; MacWilliams et al., 2015).

Table 2-1
Recalibration of KM-equation with Monthly Interpolated X2s.
Coefficient Columns are Displayed as Estimate +/- One Standard Error. (SAC= Sacramento River Branch; SJR = San Joaquin River Branch)

River	Period of Regression	r^2	Standard Error of Regression (km)	A	B	C
SAC	10/01/1921 to 09/01/2012	0.930	3.51	114. +/- 1.80	0.418 +/- 0.0106	-17.3 +/- 0.291
SAC	10/01/1921 to 06/01/1964	0.923	3.95	112. +/- 2.65	0.432 +/- 0.0158	-17.2 +/- 0.439
SAC	07/01/1971 to 09/01/2012	0.939	3.07	119. +/- 2.63	0.392 +/- 0.0153	-17.9 +/- 0.418
SAC	10/01/1967 to 11/01/1991 (K-M period, as used in Jassby et al., 1995)	0.948	2.79	110. +/- 3.36	0.419 +/- 0.0198	-16.2 +/- 0.517
SJR	10/01/1921 to 09/01/2012	0.923	3.92	119. +/- 1.92	0.425 +/- 0.0107	-18.5 +/- 0.321
SJR	10/01/1921 to 06/01/1964	0.912	4.57	119. +/- 2.91	0.433 +/- 0.0162	-18.8 +/- 0.506
SJR	07/01/1971 to 09/01/2012	0.935	3.31	120. +/- 2.75	0.410 +/- 0.0155	-18.4 +/- 0.445
SJR	10/01/1967 to 11/01/1991 (K-M period, as used in Jassby et al., 1995)	0.946	3.00	110. +/- 3.52	0.439 +/- 0.0201	-16.5 +/- 0.551

Table 2-2
X2 auto-regressive equations and RMS errors. (Adapted from M. MacWillams presentation with citations revised and all equations converted to units of flow in cfs). Table courtesy of Reed et al., 2014: Panel Summary Report on the State Water Resources Control Board's Workshop on Delta outflows and Related Stressors, May 5, 2014.

Citation	Autoregressive Equation (X_2 in km, Q in cfs)	RMS Error (km)[1]
1.) Schubel et al. (1993), Appendix A, (DAYFLOW)	$X_2(t) = 10.16 + 0.945 \cdot X_2(t\text{-}1) - 1.487 \cdot \log_{10}(Q_{cfs}(t))$	6.11
2.) Jassby et al. (1995) (not plotted in Figure 2)	$X_2(t) = 10.3 + 0.945 \cdot X_2(t\text{-}1) - 1.5 \cdot \log_{10}(Q_{cfs}(t))$	7.33
3.) Jassby eq. as cited by Monismith et al. (2002)	$X_2(t) = 13.76 + 0.945 \cdot X_2(t\text{-}1) - 2.3 \cdot \log_{10}(Q_{cfs}(t))$	9.22
4.) Monismith et al. (2002)	$X_2(t) = 0.919 \cdot X_2(t\text{-}1) + 22.43 \cdot Q_{cfs}(t)^{-0.141}$	7.47
5.) Gross et al. (2010)	$X_2(t) = 0.910 \cdot X_2(t\text{-}1) + 36.16 \cdot Q_{cfs}(t)^{-0.182}$	5.31
6.) MacWilliams et al. (in review) with flow-dependent α	$X_2(t) = \alpha \cdot X_2(t\text{-}1) + (1-\alpha) \cdot 644.9 \cdot Q_{cfs}(t)^{-0.230}$	Constant α 4.17 Variable α 3.10

[1] RMSE based on differences with X2 calculations using UnTRIM 3D hydrodynamic model for 4/94 to 4/97

2.4.2 X2 Calculation by Interpolation

In 2007, the California Data Exchange Center (CDEC) started reporting the X2 value as a linear interpolation for the 2.64 mS/cm EC isohaline location from the following four stations (with distances from Golden Gate): Martinez (56 km), Port Chicago (64 km), Chipps Island (74 km) and Collinsville (81 km). By this definition, the value is not reported when the X2 falls outside the 56-81 km range. This is available online at: http://cdec.water.ca.gov/cgi-progs/stationInfo?station_id=CX2. Each of these 4 monitoring stations has upper and lower measuring probes, although the lower probes are not currently used for X2 determination. This is because they have shorter records and generally do not measure salinity at the bottom along the center-line of the estuary, but rather at a location corresponding to the surface salinity observation point (Reed et al., 2014). Importantly, the surface salinity data are used as a surrogate for bottom salinity with a constant difference of 0.64 (Reed et al., 2014, based on M. MacWilliams, workshop presentation), which is different from the value of 0.24 used by Jassby et al. (1995) and discussed in the introduction of this chapter.

Another related approach is to use log-linear interpolation, as employed in the original Jassby et al. (1995) approach. In this approach, log salinity versus distance interpolation is performed across two stations that bound a specific isohaline level, i.e., for the X2 or 2.64 mS/cm isohaline. This can be generalized to any position within the estuary, and the interpolated X2 can be outside of the 56-81 km range, which does occur frequently.

Similar to net Delta outflow, measurement and prediction methods describing the estuarine salinity gradient and near-bottom salinity are characterized by significant error. One reason for the error is poor spatial resolution in the data (measurements separated by at least 10 km) because some of the dynamics that determine the position of the salt field occur at spatial scales than are less than the distance between the salinity monitoring stations. A second reason is that bottom salinity is not directly measured, but estimated as a constant factor of the surface salinity, which is a coarse simplification of the underlying process.

Large water costs may occur due to insufficient monitoring resolution and subsequent large errors in predictive equations. Equations to estimate X2 described above have standard errors that range from 3 to 9 km. The difference in the estimate for X2 could result in substantially different water costs to municipal and agricultural water users and represent a significantly different index of the aquatic habitat available for resident and migratory fish species for a given X2. For example, if an X2 equation predicts a value of 75 km, but X2 is actually 70 km (as measured near the bottom), more freshwater would need to be released from reservoirs than necessary or export pumping would be restricted more than necessary to meet the 75 km requirement. The subsequent water cost to water users is approximately 300,000 acre feet per month (Schubel Report, 1993, Appendix A, table 2, page A-10). Alternatively, if an X2 equation predicts a value of 70 km, but X2 is actually 75 km, then the aquatic habitat loses approximately 300,000 acre feet of freshwater per month and more importantly the habitat and abundance benefits associated with an X2 location of 70 km over 75 km in the estuary.

These well-known deficiencies in salinity and flow measurement and prediction methods led to a Delta Stewardship Council panel suggestion of installing salinity monitoring instruments at “both the surface and bottom of the water column on channel markers at regular intervals along the axis of the estuary,” as a method for generating new field data that can be used to increase the precision of equations that predict salinity and X2 (Reed et al., 2014). Instruments that directly measure near-bottom salinity are now widely available. In addition, new technology is in development to measure a continuous vertical salinity profile in the water column at a given location and measuring multiple water quality elements at these locations will provide important habitat quality information.

3 EXISTING MONITORING NETWORK

The Delta outflow objective, along with other flow and salinity objectives, is implemented by the State Water Board in a water rights decision issued to the Department of Water Resources (DWR) and U.S. Bureau of Reclamation (USBR) for the operation of the State Water Project (SWP) and the Central Valley Project (CVP) water delivery projects. Water quality standards (objectives) were last amended under the 1995 Water Quality Control Plan and Water Right Decision 1641 (D-1641) established in 1999. The SWP and CVP are currently operated to comply with the monitoring and reporting requirements described in D-1641. D-1641 requires both agencies to conduct a comprehensive environmental monitoring program to determine compliance with water quality standards and also to submit an annual report to SWRCB discussing data collected.

Continuous water quality monitoring is one element of the Bay-Delta Monitoring and Analysis Section (EMP) conducted by DWR and USBR with support from the USGS under the Interagency Ecological Program (IEP). The overall objective of the water quality monitoring program is to provide information for water resource management in compliance with flow-related water quality standards set forth in the Water Right Decision 1641 described above. These decisions permit the USBR and DWR to deliver water by operating the CVP and the SWP. In return, the two agencies are required to monitor the effects of diversions and flow manipulations resulting from project operations and ensure the compliance with existing water quality standards and protection of the most sensitive beneficial uses.

This chapter presents a general description of the ongoing monitoring programs and the different approaches for computing X2 that are based on these programs. Monitoring programs in place include:

- Continuous Multi-parameter Monitoring (IEP Environmental Monitoring Program), operated by the Department of Water Resources
- Continuous Recorder Sites, operated by the Department of Water Resources and the U.S. Bureau of Reclamation

- Delta-Mendota Canal Water Quality Monitoring Program, operated by the U.S. Bureau of Reclamation
- Municipal Water Quality Investigations (real-time sampling), operated by the Department of Water Resources
- State Water Project Water Quality Monitoring (continuous sites), operated by the Department of Water Resources

Continuous monitoring focuses mainly on flow and general water quality characteristics such as salinity, temperature, and turbidity with limited coverage of a few other parameters such as chlorophyll fluorescence, organic carbon, and nutrients (Jabusch and Gilbreath, 2009). An overview of the continuous monitoring sites is shown in Figure 3-1.

3.1 Interagency Ecological Program – Environmental Monitoring Program

The DWR Environmental Real Time Monitoring (RTM) and Support section monitors Delta water at nine continuous water quality monitoring stations from Martinez in Suisun Bay to Hood on the Sacramento River and Vernalis on the San Joaquin River (Figure 3-2).

DWR-RTM water quality instruments are all manufactured by YSI. The instruments presently in use include the YSI 6600 and EXO2. The YSI 6000 is deployed 3 feet below water surface, and the EXO1 is deployed the 5 feet above river bottom. Bottom salinity (reported as specific conductance) is currently collected at only three locations, Martinez, Mallard Island, and Antioch, of the nine multi-parameter stations in support of X2 monitoring. Bottom specific conductance is also collected by USBR at 2 sites, Collinsville and Antioch, within the Sacramento-San Joaquin Delta. RTM is currently in process of upgrading from the YSI 6600 series to the new YSI EXO platform with improved calibration and related performance characteristics (instrument details are presented in Appendix A.

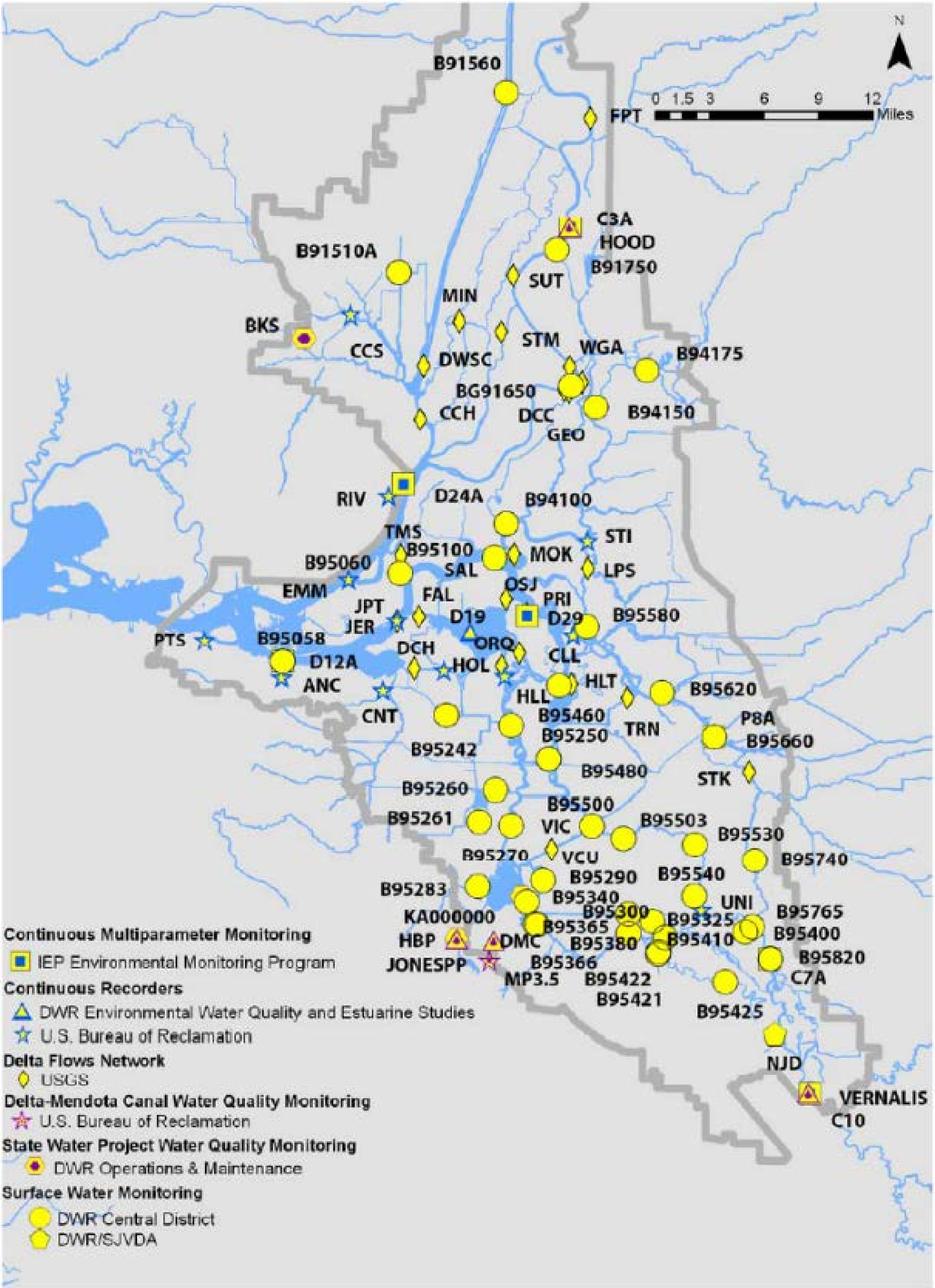

Figure 3-1 Bay Delta Continuous Monitoring Sites (Reproduced from Jabusch and Gilbreath, 2009)

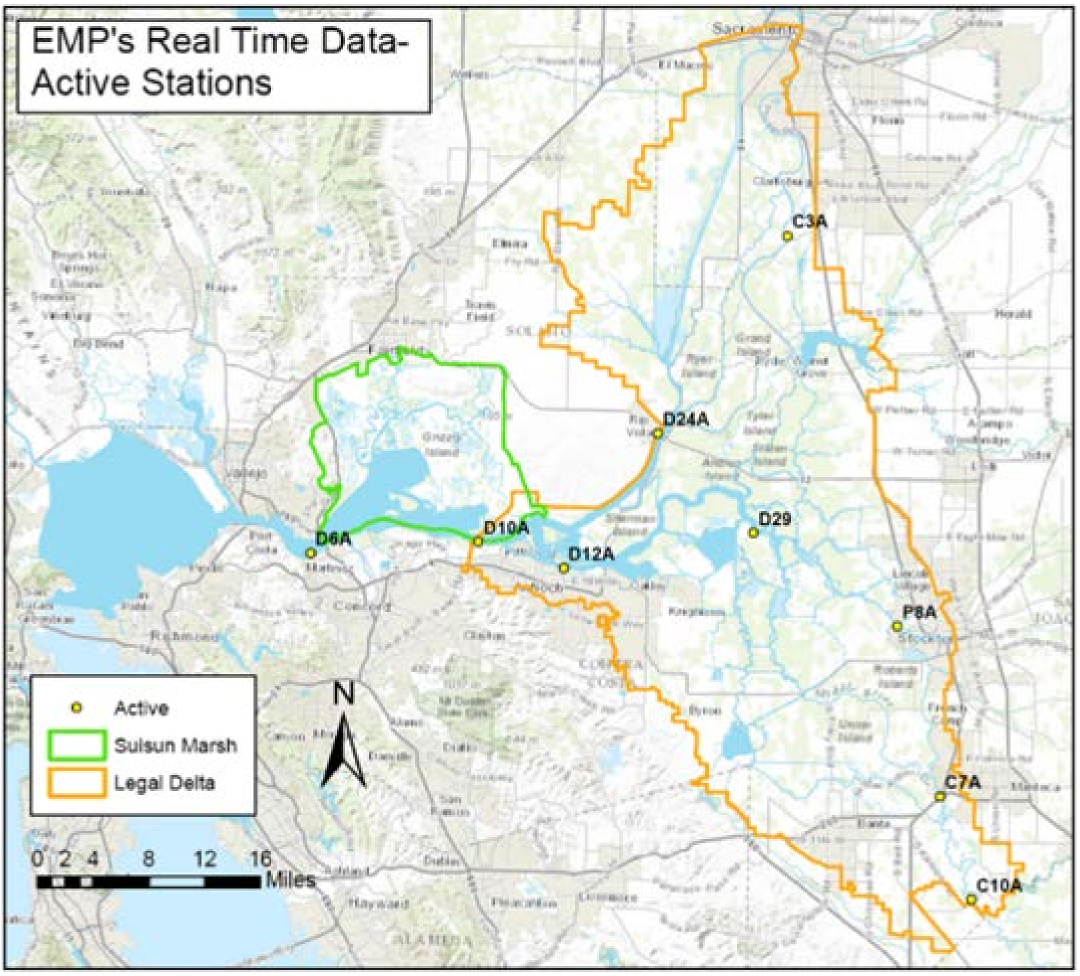

Figure 3-2 EMP's Real time Monitoring Stations

The calibration intervals vary depending on the parameter being measured and the type of the instrument being used. Handheld devices are used as a way to cross-check the data collected at monitoring stations. All calibration is done in the lab with the exception of dissolved oxygen (DO).

Data are transmitted to State Water Project operations via wireless telemetry real-time to provide information on Delta conditions. Publically available data are posted to the CA DWR Real Time Monitoring web site (http://www.water.ca.gov/rtm) and the California Data Exchange Center (CDEC) web site (http://cdec.water.ca.gov).

3.2 US Geological Survey (USGS) Monitoring Network

The San Francisco Bay Hydrodynamics project, managed by USGS California Water Science Center (CAWSC), conducts hydrodynamic transport investigations in the Bay and Bay Delta, with financial support from the DWR and USBR and in collaboration with a broad coalition of state and federal agencies (SWRCB, CDFW, and USFWS).

The USGS CAWSC has standardized flow and water quality monitoring methods in the Bay and Delta for data collection instrumentation, equipment configuration, telemetry protocols and data QC and reporting. This approach allows multiple individuals to work on station servicing and maintenance without the need for site specific knowledge of any particular setup or instrument configuration. By using standard methods, it is relatively easy for USGS to add additional monitoring stations, with identical equipment configurations, while only incrementally increasing annual maintenance costs for the monitoring network.

The USGS owns multiple vessels configured for field measurements and maintenance of the fixed monitoring stations. Each vessel is stocked with equipment spares, sampling equipment and a permanently installed Acoustic Doppler Current Profiler (ADCP) for flow monitoring and to update index ratings of installed discharge monitoring stations.

The USGS maintains a network of 38 flow and water quality stations across the Delta (Figure 3-3). This project began measuring the flows in the Delta in 1987. The network has been expanding since then, and now is comprised of 21 continuously operating flow stations and 32 continuous water quality monitoring stations. Plans are to expand the flow measurement network from 21 to 29 stations, with additional stations in the Deep Water Ship Channel and Liberty Island Cache Slough region. (http://ca.water.usgs.gov/projects/sf_hydrodynamics.html). Collection of salinity, temperature, and water level time series began in 1988; collection of turbidity and suspended sediment concentration (SSC) time series began in 1991; and collection of dissolved oxygen time series began in 2012 (Buchanan, 2014).

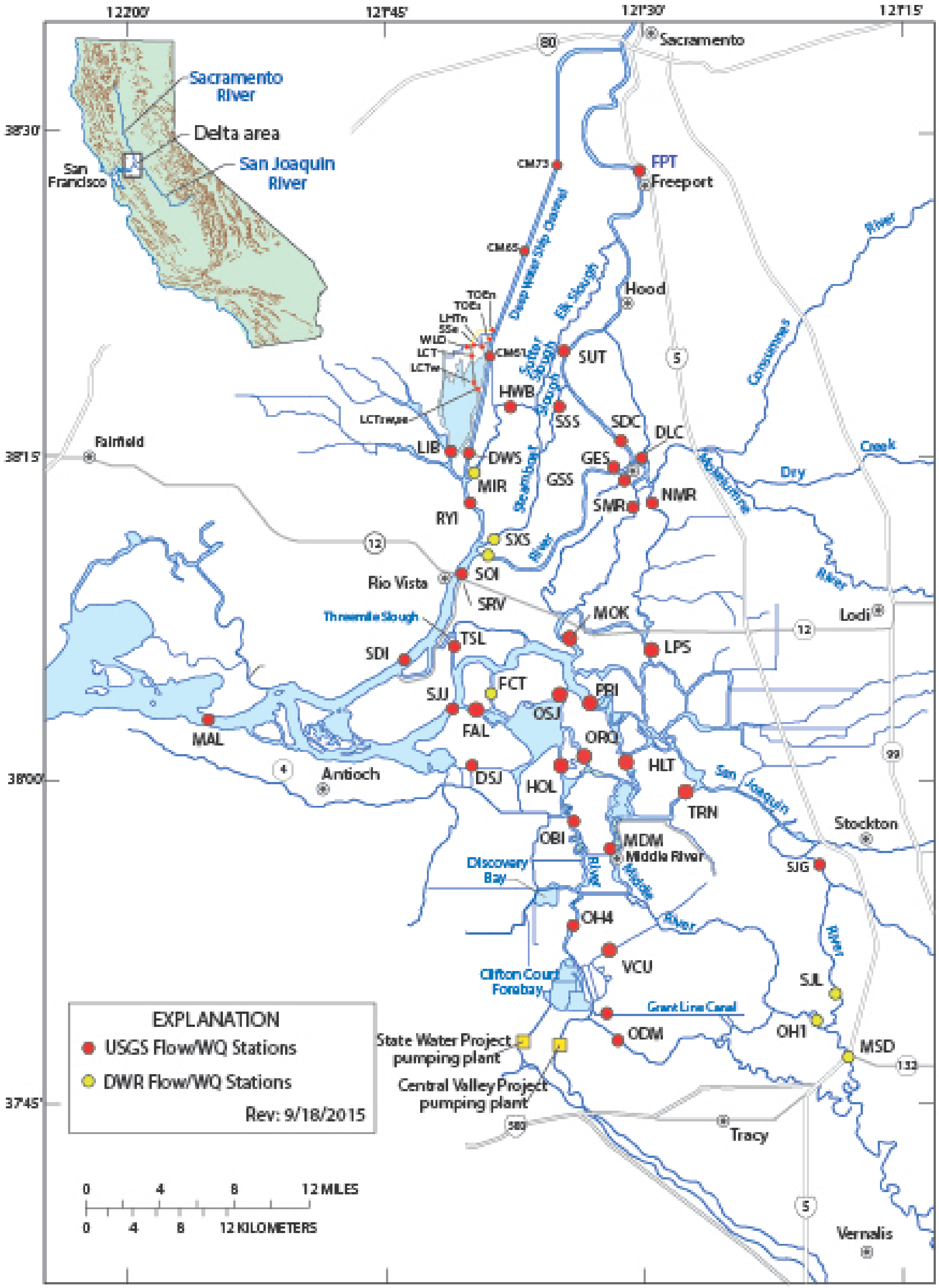

Figure 3-3 USGS Continuous Monitoring Stations in SF Bay (Blue) and the Bay Delta (Green)

3.2.1 WATER QUALITY MONITORING

Continuous water-quality measurements are collected at stations throughout the San Francisco Bay and Delta using multi-parameter water quality sondes. The sondes are usually deployed in the water by suspension from a stainless-steel cable anchored to the bottom (Figure 3-4 and Figure 3-5) or in plastic pipes strapped to pilings. The sondes are equipped with sensors that measure water level (pressure sensor), temperature, specific conductance, turbidity (optical), Chlorophyll-a (optical), fluorescent dissolved organic matter (FDOM, optical) and dissolved oxygen. Data are recorded every 15 minutes and are retrieved either real time via cellular telemetry or by manual download during routine station visits
(http://ca.water.usgs.gov/projects/baydelta/methods.html).

Biological activity and growth (biofouling) interfere with sensor readings, requiring regular servicing intervals and that data affected by biofouling to be corrected or deleted. Biofouling increases with time and generally is greatest during spring and summer; the degree of biofouling is site dependent, causing data return to vary among stations. Biofouling is mitigated by routine sensor cleaning and anti-fouling sensor equipment such as wipers for optical sensors. Self-cleaning sensors have proven to reduce data loss only in relatively fresh water because they are ineffective when fouling is excessive and they are prone to leak and malfunction in saltier water (Buchanan and Ruhl 2001), though wiper technology has greatly improved in the last 5 years. Every 2-5 weeks, each station is visited to clean, calibrate, and download the instruments. The CAWSC hydrodynamics project checks their data every day and sends out crews on an as needed basis when sensors are fouled. Sensor performance is also ensured by comparing sensor output with nearby stations in real-time and known values; such comparison is used to identify sensor drift, calibration errors, or malfunction. For example, for temperature, sensor output is compared to that from a NIST traceable thermistor. For specific conductance and turbidity, sensor output is checked against and, if needed, calibrated to, solutions of known value (standards). For dissolved oxygen, sensor output is checked in water-saturated air.

Water samples are collected from the same depth as the sensor to calibrate the turbidity data to the suspended-sediment concentrations. For stations that compute water discharge and cross-sectionally averaged SSC, water samples are collected periodically at points across the channel by using the equal-discharge-increment method, and velocity is measured by ADCP.

Specific conductance (reported in micro-Siemens per centimeter at 25° Celsius) and water temperature (reported in degrees Celsius) have been measured by using a YSI, Inc., conductance/temperature sensors. Two types of optical sensors have been used to monitor turbidity: the DTS-12, manufactured by Forest Technology Systems, and the model 6136, manufactured by YSI, Inc. Dissolved oxygen has been measured by using the optical model 6150, manufactured by YSI, Inc.

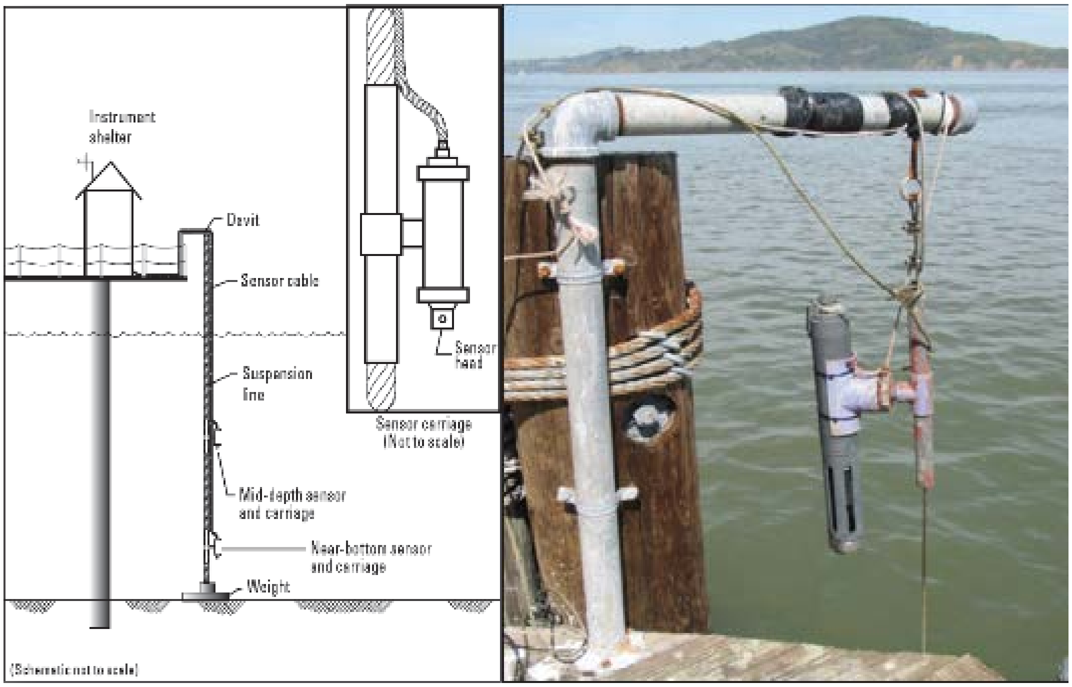

Figure 3-4 Typical monitoring installation, San Francisco Bay study (Buchanan 2014)

Figure 3-5 Example of USGS WQ Monitoring Station (using YSI 6920V2 internal logging Sonde)

3.2.2 Flow (Discharge) Monitoring

The network is comprised of 21 continuously operating flow stations (Figure 3-3). These stations measure flows in the Delta in channels as well as at Chipps Island. (http://ca.water.usgs.gov/projects/sf_hydrodynamics.html). Discharge is calculated from velocity data in a two-step process (Ruhl and Simpson, 2005). First, the cross-sectional area of the channel is computed from measured water levels and the mean cross-sectional velocity is computed on the basis of the measured index velocity. The discharge is calculated as the product of the channel cross-sectional area and mean velocity.

4 DESIRED IMPROVEMENTS IN SALINITY AND FLOW MONITORING

4.1 DEFICIENCIES IN EXISTING MONITORING DATA AND FOR PREDICTING X2

Given the importance of flow and salinity in the San Francisco Estuary, we are fortunate to have an extensive long term record of salinity, spanning more than nine decades (data summarized in Hutton et al., 2015). However, most of the historical salinity data in San Francisco Bay are based on measurements made near the surface, and were originally motivated by upstream withdrawals and salinity intrusion in the Delta (e.g., Department of Public Works, 1931).

The present-day monitoring setup generally pre-dates the understanding of the role of near-bottom salinity on estuarine physics and habitat and hence for outflow management. This limitation was known at the time of the development of the X2 approach (Jassby et al., 1995), and the method of predicting X2 used surface measured salinities as a surrogate for bottom salinity with a correction factor. The top –bottom salinity difference was assumed to be constant at 0.24 psu in Jassby et al (1995), but appears to have been modified to 0.64 psu in more recent reporting of X2 by DWR (Reed et al., 2014). The basis for the 0.64 psu correction is not clearly documented in the literature. Given the dynamic nature of stratification in partially mixed estuaries like San Francisco Bay (Stacey et al., 2010), the assumption of a constant factor decreases the accuracy and precision of X2 time series based on this assumption, although it may also give a systematic downstream bias to the X2 estimate at very high flow rates when stratification can be significantly stronger than 0.24 psu (Monismith 2002). The development of X2 relationships has continued, with different auto-regressive formulations in the literature (summarized in Reed et al., 2014 and as described in Chapter 4).

Some of the modified fits for X2 and flow appear to perform better than the original formulation reported in the X2 publication (Jassby et al., 1995) because of the incorporation of additional parameters, and/or with the use of a larger data set. In the final analysis, we do not expect the relationships to improve if they are based on surface measurements taken at a small number of locations roughly 10 km apart. The current monitoring is inadequate given our current understanding of the physics of salt transport in this estuary (Burau et.al. 1998, 1999; Stacey et. al, 2010, Monismith et.al., 2002). More detailed analysis of existing data, collected by the current monitoring network, may not substantially improve the accuracy and predictive capability of these relationships.

Besides X2, another way of looking at the salinity management problem is to use the net Delta outflow as a predictor for the position of the low salinity zone. However, recent work shows that measurements of Delta outflow are problematic in strongly tidally-influenced channels with weak net currents. For example, there are major differences between NDOI estimates reported by DWR and direct measurements made by USGS using acoustic Doppler (Monismith, 2015, personal communication; DWR, 2016).

Based on above discussion, it appears that a better estimate of X2, or the low salinity zone in general, could be obtained by using a set of top and bottom salinity recorders that will give us a more complete picture of the salt field, including along-channel variability in the horizontal salinity gradient (or barotropic pressure gradient - the driver of gravitational circulation and salinity intrusion) and vertical salinity gradient (as also noted by Monismith et al. 2002 and Reed et al. 2014). This information would not be available retroactively, of course, but methods could be developed to allow translation using surface salinity and flow data that may permit more effective hind-casting of the bottom low salinity than the use of constant difference between top and bottom salinity. Or, more simply, a relationship may be possible that is not only based on improved measurements of the position of the salt field but data on the dynamics of the salt field, such as the along-channel and internal structure of the salt field, the spring/neap cycle, and possibly atmospheric pressure changes. Analytical methods based on the physics of the salt field with data collected at the appropriate resolution could then be developed to more accurately predict X2 which would allow evaluation of the water costs under different scenarios with greater accuracy.

4.2 DESIRED MONITORING DATA AND ACCURACIES

While past experience and efficiency of existing methods and equipment are of significant value, this effort is aimed at evaluating ways to improve the quality, accuracy, resolution, and usefulness of the salinity and flow data without unnecessarily constraining ourselves to existing practices and methods. Previous sections of the report outline and support the primary reasons to improve the monitoring network. They include: 1) improve precision of compliance methods for water quality standards, 2) improved ability to accurately evaluate the effectiveness of water quality standards and management actions, 3) increase precision of modeling equations used for forecasting and hindcasting, and 4) establishing a framework for connecting hydrodynamic and biological measurements and exploring the mechanistic drivers of biological outcomes in the estuary.

It is important to evaluate how specific scientific and regulatory data requirements can be better addressed through the use of existing state-of-the-art technology before constraining the monitoring program design by choosing specific equipment, sampling methods, and locations. In addition to more monitoring stations, we suggest reviewing newer instrumentation, antifouling technology and deployment methods that might provide more robust data, decrease data loss and maintenance costs and decrease the uncertainty in the estimated X2 position. Key issues to be addressed are discussed below. In Chapter 4, we present an alternative plan developed by Jon Burau of the USGS that addresses some, but not all, of these issues.

4.2.1 Preferred Salinity Monitoring Design

An ideal monitoring network for X2 measurement and interpolation, and for the other biologically relevant constituents would have the following design criteria:

Spatial Measurement Criteria:

- Monitoring locations spaced at intervals of no greater than 1/4 the tidal excursion. Within reason, the closer the spacing, the more accurate the estimate of X2. For example, a target spacing of 5 km has been proposed (Monismith, 2015, personal communication)
- Near-bottom (1m height) measurement of temperature, salinity, turbidity and DO
- Near-surface (1m depth) measurement of temperature, salinity, turbidity and DO
- Optional, full vertical water column profiles of all parameters, technology is still in development

Temporal Measurement Criteria:

- Sampling interval not greater than 15 minutes
- Real-time reporting of near-bottom salinities (and additional water quality parameters)
- Real-time reporting of near-surface salinities (and additional water quality parameters)
- Daily reporting of tidally averaged near-bottom salinity

Instrumentation and Installation Requirements:

- At a minimum must measure conductivity, temperature
- Preferably measure conductivity, temperature depth, turbidity, DO
- Resistant to biological fouling for periods of at least 1 month and preferably longer
- Deployment method must protect communication/power cables from debris damage

- Instrumentation must be easily recoverable from a surface structure or vessel (no divers)
- Instrumentation must have sufficient batteries and PV panels to operate at 1sample /15min

Data Quality Criteria:

- Daily QC of all real-time station data to highlight outliers and trigger site visit
- Greater than 95% of time with no data loss for instrument fouling/failure
- Monthly QC of all data sets before posting to USGS/ NWIS

4.2.2 Flow Monitoring Design

4.2.2.1 OVERVIEW AND BASIS FOR DATA NEED

Outflows in the San Francisco Estuary are strongly tidally influenced with large positive (toward the ocean) and negative (toward inland) flows occurring over a tidal cycle. Tidal flows are often much larger than the freshwater flows exiting the estuary (e.g., +/- 150,000 cfs for tidal flows, compared to freshwater outflows that are typically 10% of this value, and often much lower in dry periods). For this reason, it is challenging to measure the freshwater outflows directly, and there are programs that report data based on inflows into the Delta at upstream non-tidally influenced locations (the DAYFLOW program used by the Department of Water Resources; http://www.water.ca.gov/dayflow/). In reporting the NDOI values of Delta freshwater outflow, besides the observed values of inflows and out-of-Delta exports, DWR also makes an estimate of the in-Delta consumptive use, a quantity that is not directly measured. When freshwater outflow is low, during the driest months of the year and/or drought periods, the estimated consumptive use is often of the same magnitude as the Delta outflow, and the overall estimate may be less accurate. For this reason, there is a need to measure the outflows as directly and accurately as possible.

4.2.2.2 DEFICIENCIES IN EXISTING FLOW MONITORING DATA

Net Delta outflow is considered extremely challenging to measure. This is based on the following current constraints:

- Existing installed flow monitoring stations
- Existing Acoustic Velocity Meter/Acoustic Doppler Current Profiler (AVM/ADCP) technologies, methods and accuracies.
- Difficulty in determining net daily outflow from measured bi-directional velocity profiles resulting from tidal flow and gravity driven flow.
- Availability of resources

All of the methods currently used to measure flow in open channels in the Delta are based on an Index Velocity Method (Levesque and Oberg 2012). Where an index velocity of a portion of the total flow is measured (with AVM or ADCP) and that index velocity is related to mean channel velocity through an index equation. The index equation is developed by measuring the total channel flow with a moving boat ADCP while also measuring the index velocity with the fixed instrument. The moving boat ADCP method has errors of its own, and index ratings vary with flow and stage (water elevation).

In short, when attempting to measure a very small net daily outflow (NDO) (<10,000cfs) by using a combination of flow meters at multiple locations, the combined instrument/calibration errors of the flow measurements and the errors in calculating net outflow from the total measured flow over a tidal cycle exceed the accuracy required.

4.2.2.3 POSSIBLE SOLUTIONS TO IMPROVE FLOW MONITORING ACCURACY

Measuring these net daily outflow under low-flow conditions will require more than adding measurement locations or better index velocity meters at existing locations. It will take a concerted effort and perhaps new technology and research to develop a measurement system with sufficient accuracy to measure the desired flows, if it is possible at all.

One possibility might be a “large transect” approach where multiple meters at one location (Chipps Island) could be used to fully characterize the velocities across the entire cross-section and the index calibration for each small portion of the flow could be accurate enough to characterize the low outflow periods. The feasibility of AVM flow measurement at Chipps Island has previously been studied (Hoffard 1980), but no recent publications were found that address the possibility of measuring Chipps Island channel flow with currently available measurement technology.

While the AVM instruments installed in the Delta in the 1980s have now become difficult to service and antiquated, their utility and proven technology could be used as a stepping stone to a newer acoustic measurement system which might take advantage of the substantial improvement in transducers, electronics and digital signal processing technologies in the past 30 years.

The older AVM transit-time acoustic technology has been largely supplanted by the newer acoustic Doppler (ADCP) technology due to cost, availability and utility of using ADCP in fixed, side-looking, up-looking and boat mounted configurations. ADCP technology is now off-the shelf and has instruments from several manufacturers (Appendix B) which are specialized in physical configuration, electronics and processing capabilities for oceanographic, hydrologic and industrial applications.

However, there has not (apparently) been sufficient market and financial incentive for manufacturers to develop systems for large (wide) rivers which provide a high level of accuracy which is now desired for the Bay Delta. This is not to say that it is not possible in future, given the economic value associated with this measurement.

4.3 SUMMARY

In general, salinity measurement at the bottom could help to define X2 more accurately, or another similar metric that adequately represents the position and volume of the low salinity zone. These measurements could be made with commercially available sensors although they have not been routinely made at most locations in the estuary. Direct measurement of flow with commercially available instrumentation, on the other hand, are considered much more difficult at this time, and will need much greater development effort than bottom salinity measurements.

In support of this discussion, we performed a review of commercially available technologies, including performance specifications and costs, for salinity and related water quality measurements and for flow measurement (Appendices A and B, respectively). Discussion of conceptual installation considerations are represented in Appendix C. These appendices are intended to serve as a resource for available instrumentation and installation, as further definition on the spatial and temporal accuracy as well as monitoring goals, is obtained.

5 USGS MONITORING PROPOSAL

Here we present three monitoring options of varying degrees of complexity and costs, see Table 5-1. The options, developed by Jon Burau of the USGS, incorporate salinity, turbidity and velocity measurements that fit within the existing monitoring framework. Of relevance to this proposal are installation, operation, data processing, and maintenance costs associated with each plan. In the first option, requiring the greatest investment, measurements are made at the spatial scales needed to resolve the physical processes that drive salinity intrusion and ETM (estuarine turbidity maximum) formation. This plan would generate data to forecast and hind-cast the position and character of the salt field. The budgets associated with these plans are given as a point of reference in Section 5.3.

The monitoring options presented employ existing technologies that involve point measurements of water quality constituents in the vertical (e.g. near-surface and near-bed measurements of conductivity, temperature and turbidity). We know that these constituents vary considerably in the vertical in the brackish portions of the estuary at seasonal, spring-neap and tidal timescales depending on the strength of vertical stratification. Measurements of complete vertical profiles of these constituents would be ideal for developing the relations that capture the physics rather than using the near-surface and near-bed measurements suggested here, because with point measurements we have to infer/estimate the position and strength of the stratification within the water column.

A prototype instrument has been developed that can make continuous measurements of vertical salinity profiles from an instrument mounted on the seafloor (Szuts et al., 2015). This type of instrument would provide the invaluable resolution in the vertical because it is mounted on the seafloor and can be deployed in the center of the channel. This is an advantage over equipment deployed in the water column (e.g., a near-surface sensor) which is not located in the center of the channel due to likely collisions with ship traffic in the area. Moreover, since the strength of the gravitational circulation scales with depth, obtaining a profile in the shipping channel where the depths are greatest is critical in being able to correctly capture, calculate and model the rate of salinity intrusion.

5.1 Overview

USGS has developed three (3) options for increasing the accuracy of salinity, flow, and X2 estimates by deploying and maintaining a number of additional salinity/turbidity sensors in the channels in Suisun Bay and the western Delta as is shown in Figure 5-1. All of these options provide, to varying degrees, data that will also provide the temporal evolution of the along-channel spatial structure of habitat features for estuarine pelagic organisms such as salinity, temperature and turbidity fields, in unprecedented detail in the region that has the greatest abundance of adult Delta smelt in the summer through winter period (Moyle et al 2016).

These data will give us the ability to calibrate and validate numerical models in this region, which are increasing in sophistication and predictive capability. Additionally, these data could be used to reformulate and evaluate the efficacy of the X2-abundance relationships computed at a variety of times scales (daily, weekly, fortnightly and monthly).

Lastly, these monitoring designs are a platform to connect biological, ecological, and hydrodynamic data and models. Adding biological monitoring at these sites would produce a data set that could be used to identify and better describe the connection between the physical processes (of which X2 is a bulk metric) and the biology and ecology of the estuary. Hydrodynamic and biological data collected at these sites can then be used to make the first tangible steps toward integrating biological and ecological models with hydrodynamic models.

5.2 Instrumentation and Deployment Details

Three monitoring options of varying degrees of usefulness and rigor are outlined below. These plans represent the extremes in effort (and cost), or bookends, ranging from the most complex to the simplest. Variants of these options are also possible.

5.2.1 Option 1- Monitor X2 and the ETM with Greater Precision and Capture the Physics

Beginning with the most extensive plan, which will allow us monitor X2 and the estuarine turbidity maximum (ETM) with greater precision and to capture the physics, 11 stations are proposed (Figure 5-1). In addition to deploying new instruments to collect both near-surface and near-bed salinities at these 11 new monitoring stations, four upward-looking acoustic Doppler current profilers (V-ADCP) will be deployed at the locations with the red icons in Figure 5-1, to evaluate the contribution of gravitational circulation to salinity intrusion, vertical stratification and ETM formation in the western Delta (Schoellhamer and Burau, 1998).

The V-ADCP’s will be deployed seaward of X2 to measure gravitational circulation during periods when salinity has intruded into the Delta as far as salinity standards at Emmaton and Jersey point will allow, a condition that typically occurs from mid-summer to the onset of winter storms, November-January, in a typical year. Gravitational circulation contributes to salinity intrusion, and, hence the water cost associated with maintaining salinity standards in the Delta, and the formation of an ETM immediately downstream of X2. The placement of the V-ADCP's can be adjusted (up or down-estuary) as data collection starts and we refine the positioning of X2 and our understanding of gravitational circulation.

All of the data will be telemetered in real-time and made available on CDEC and NWIS-web.

The YSI sondes associated with all of these plans will be mounted on Channel Markers – out in the channel – potentially avoiding bias associated with measurements made on the channel edge where lateral variability in constituents can exit.

The ADCPs will be deployed toward center channel to maximize the depth and cabled to the data-loggers and telemetry systems on the channel markers.

Option 1 involves monitoring the near-bed and near-surface conductivity, temperature and turbidity at 11 stations, which, when combined with 4 ADCP results in a total of 70 15-minute time series that would be collected annually.

5.2.2 Option 2 - Monitor X2 and the ETM with Greater Precision Only

Option 2 is built on a significantly smaller deployment footprint at 9 stations (Figure 5-2) and measurements of near-bed conductivity, temperature and turbidity only (e.g. no surface measurements will be made) and no ADCP's, resulting in 27- 15-minute time series collected annually.

5.2.3 Option 3 - Monitor X2 with Greater Precision Only

Option 3 is built on the same footprint as in plan 2 with 9 stations (Figure 5-2) and measurements of near-bed conductivity and temperature (e.g. no turbidity measurements and no surface measurements will be made) and no ADCP's, resulting in 18 15-minnute time series collected annually.

5.3 Cost Estimates Developed by USGS

Table 5-1
Cost Estimates of Three Monitoring Advancement Plans/Options

X2 Monitoring Budgets		(1)	(2)	(3)
rev: 1-31-17 (JRB)	Plan ->	Monitor X2 **and** ETM with greater precision **and** capture physics	Monitor X2 **and** ETM with greater precision	Monitor X2 with greater precision
	Stations	11	9	9
	Sensors per station	2	1	1
	CT Sondes	22	9	9
Number of	Turbidity Probes	22	9	0
	ADCP's	4	0	0
	Time series	70	27	18
	Unit costs			
	CT Sonde	$13,000		
	Turbidity Probe	$2,070		
	ADCP	$34,500		
	Instrument Shelter and ancillary equipme	$9,540		
	O&M (CT) -- Data Program	$13,000		
	O&M (CT -- Existing Station) -- Data Progra	$9,000		
	O&M (Turbidity) -- Data Program	$8,400		
	O&M (ADCP) -- Data Program	$9,000		
	Equipment	$574,480	$221,490	$202,860
	Installation labor	$27,500	$22,000	$22,000
	Backup sondes (for full replacement during fiel	$180,840	$75,350	$65,000
	TOTAL INSTALLATION COSTS	**$782,820**	**$318,840**	**$289,860**
	CT (O&M based on data program)	$143,000	$117,000	$117,000
O&M Costs	)&M existing station based on data prog	$99,000	$81,000	$81,000
ised on Data Progra	Turbidity (O&M based on data program)	$184,800	$75,600	$0
	ADCP (O&M)	$36,000	$0	$0
	ANNUAL O&M COSTS (Data Program)	**$462,800**	**$273,600**	**$198,000**

Figure 5-1 USGS Locations of Proposed Temperature, Salinity and Turbidity Monitoring Equipment. All of the stations proposed are new (circle icons), except at MAL(s), RIO and JPT (square icons), which are long-term monitoring stations run by the DWR-RTM.

Figure 5-2 USGS Locations of Proposed Temperature, Salinity and Turbidity Monitoring Equipment. All of the stations proposed are new (circle icons), except at MAL(s), RIO and JPT (square icons), which are long-term monitoring stations run by the DWR-RTM.

6 REPORT SUMMARY AND CONSIDERATIONS FOR MONITORING SYSTEM IMPROVEMENT

The USGS approach presented in Chapter 6 is one possibility, and while it will considerably improve the understanding of the physical system, this is also the time to address broader concerns related to X2 position accuracy targets and other goals related to the scientific need for the characterization of the low salinity zone. For example, the basic concept of X2 was developed as a monthly index, although new research shows the importance of changes at much smaller time scales (Reed et al., 2014). A plan for monitoring should ideally address, as far as possible, the requirements of monitoring (temporally and spatially) given the current understanding of estuarine biology.

Based on our understanding of the current systems in place, and work with similar systems in other locations, we provide some general recommendations that could be considered.

6.1 CHALLENGES IN MEASURING NEAR-BOTTOM SALINITY

- Most of the USGS, DWR IMP-EMP water quality measurement sites are located on fixed structures, piers, docks, etc. In many cases these platforms probably don't extend over the deepest parts of the channel and thus may not provide access to a salinity measurement location with appropriate depth.
- One of the biggest logistical issues in installing real-time near-bottom salinity measurement instrumentation is the requirement for and vulnerability of the instrument power and communications cable. Internally powered data logging instruments overcome the cable limitation but lack the real-time reporting ability (with a few possible exceptions presented in Appendix C).
- Most near-bottom salinity measurement solutions will be constrained by a) access to and platform installation at an appropriate location for near-bottom measurement and b) maintaining power and communications to the instrument.

- High-velocity currents make it difficult to maintain a floating mooring and instrument power/communications cabling from the surface to bottom.
- Vessel navigation requirements or channel size may not allow a platform in the deepest part of the channel or the platform would be a navigation hazard.
- Reversing tidal currents and deep water prohibit dual or multipoint mooring, which is necessary to eliminate instrument cable entanglement.
- Excessive sedimentation, bed morphology changes, etc. may affect the long-term operation of the system.
- Other concerns that need to be kept in mind include: Excessive floating debris that would interfere with instrumentation or platform; vandalism; biofouling, maintenance and data degradation; and instrument Power/ communication cable vulnerability.

6.2 STATION LOCATION OPTIONS

While the fixed (pile) navigation aids proposed by USGS are convenient locations for installing the monitoring equipment, limiting the installation to these structures does not allow monitoring at some desirable center-channel locations. As an example, there are no US Coast Guard fixed navigation structures for a distance of approximately 6 km between the east end of Middle Ground channel (km ~71) and the mark North of New York Slough (km ~77). Within this reach the monitoring stations are placed near the shoreline at Mallard Island.

Consideration of buoy mounted systems, perhaps with integrated mid-channel ADCP might provide benefits for both salinity and flow monitoring over some of the selected pile locations or the addition of another fixed shoreline station (MAL) on the North side of the channel.

6.3 TECHNOLOGY AND METHODS TO CONSIDER

Possible solutions for near-bottom salinity measurement include:

- Installation of equipment on stationary pilings located in deep water with fixed-cable top and near-bottom CTD sensors (although Aid-TO-Navigation (ATON) pilings, day-marks and other structures, are typically located outside of the channel).
- Floating multi-point mooring with fixed-cable top and near-bottom CTD sensors.
- Floating single or multi-point mooring with an automated mechanical vertical profiling system and a single CTD sensor. This would provide even more detailed salinity data and help to define the X2 location vertically in the water column.

- Floating single or multi-point mooring with an internally-powered near-bottom CTD sensor and a wireless inductive mooring cable modem for near real-time communications to the surface.
- Floating single or multi-point mooring with a pumped flow of water from the near-bottom to a flow-through CT sensor at the surface.
- Deep-water bottom-mounted platform with single CTD sensor and power-communications cables run across the bottom to shore.
- Near-bottom water intake pipe with a pumped flow of water to a flow-through CT sensor on a mooring or fixed structure.

6.4 CHANGES TO DATA ANALYSIS METHODS

As new data are envisioned to be collected, potential analysis using these data can be discussed. These include updates to the biology-low salinity zone relationships and updates to the flow-salinity relationships, both using a range of tools from data driven statistical approaches to three-dimensional models. Regardless of methods discussed at this point in time, it is also worthwhile to address how these data will be used to translate to past observations of surface salinity, which capture a long history of estuarine response to major upstream changes in land use, water withdrawals, and reservoir construction, and also to past sea level rise over the 20th century.

6.5 SUMMARY

The review of information presented above, suggests that basic improvements to the monitoring system could be put in place at a cost of ~ $1M in capital costs and $200,000/yr in annual operations and maintenance. This report does not recommend a particular implementation, but these costs are a reasonable starting point for planning purposes. These improvements could greatly improve precision of compliance methods with existing Delta outflow standard, support modifications to new Delta outflow standard, improve modeling capability and accuracy for future predictions and past evaluations, and make real progress in connecting hydrodynamic and biological measurements, integrating biological and hydrodynamic modeling, and advancing our knowledge of estuarine mechanisms that influence fish population trends. The specific needs for the monitoring network and whether or not the improvements can be optimized for their potential outputs was beyond the scope of the present document and needs to be based on a broader discussion among the science experts, regulators, and the regulated community.

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Advancement of Salinity and Flow Monitoring in the San Francisco Bay Delta

San Francisco Bay Delta Action Plan Implementation Support

APPENDIX A:
Salinity / Conductivity Instrumentation Equipment Overview, Comparison and Manufacturers' Specifications

A. CONDUCTIVITY/SALINITY INSTRUMENTATION

A.1 OVERVIEW

Water conductivity and temperature (CT) are measured directly using a submerged or flow-through sensor and conductivity is typically reported as specific conductance standardized to a temperature of 25°C (77°F). Salinity is typically calculated from the measured conductivity and temperature, depending upon the specific sensor type, the salinity standard in use and the units being used to report the data (Fofonoff, N.P.; Millard, R.C., 1983).

Conductivity probes are available from a wide range of manufacturers of oceanographic and engineering equipment and are generally referred to as CT sensors, or CTD when depth measurement is integrated. The conductivity probes are compact, as small as 4 inches long by 1 inch diameter. Measurements can be recorded over a wide range of user-defined intervals, from seconds to hours or days. The collected data are stored either internally or externally via a cable to a data logger. Instrument vendors usually provide dedicated data loggers and frequently can provide integrated telemetry systems, as well.

A.2 RESOURCES FOR SENSOR EVALUATION AND PERFORMANCE VERIFICATION

The Alliance for Coastal Technologies (ACT) is a partnership of research institutions, resource managers, and private sector companies dedicated to fostering the development and adoption of effective and reliable sensors and platforms for use in coastal, freshwater and ocean environments. Because of their unique affiliation and specific involvement with the evaluation of conductivity/salinity sensors, ACT is a key resource for identifying State-of-the-Art sensor technology. ACT serves as an unbiased, third party test bed for evaluating sensors and provides technology verifications of specific manufacturer’s instruments.

ACT conducts two levels of Technology Evaluations: Verifications and Demonstrations. Technology Verifications focus on classes of commercially available instruments to provide confirmation that each technology meets the manufacturer's performance specifications or claims and/or provides verified data on those operational parameters that stakeholders require to make a use decision. Verifications are a 25-step process, which includes community consensus on test protocols, laboratory and field-testing, and QA/QC based on Environmental Protection Agency (EPA) and International Organization for Standardization (ISO) guidelines. Field tests are carried out at no fewer than four but typically all six ACT partner sites. Technology Demonstrations involve fewer steps and focus on highlighting the capabilities and potential of pre-commercial or emerging early-stage technologies, building user awareness, and facilitating technology maturation and transition into operational observing. Working closely with developers, Demonstration field tests may be conducted at only two or three Partner sites, depending on stakeholder priority needs.

ACT Technology Evaluations also are open and transparent, free of charge for all applicants with appropriate instrumentation, and all results are released to the public in final reports. However, ACT and its Partner Institutions do not certify or guarantee performance of technologies, nor does ACT rank or directly compare the individual instruments tested.

A.3 CURRENT STATE OF SALINITY MONITORING TECHNOLOGY

When evaluating conductivity/salinity instrumentation, several things should be considered, including:

- The current state-of-the-art in electrical conductivity measurement for water quality monitoring has not changed significantly since 2000 (ACT 2007a).
- Due to the capital, installation and maintenance costs of water quality measurements, conductivity and temperature are rarely the only parameters measured at a monitoring station. (ACT 2007b)
- The selection and purchase of water quality monitoring instrumentation is often driven by the need for simultaneous measurement of parameters other than conductivity so, rather than recommending a specific manufacturer's model of instrument, specifications for required salinity accuracy should be driven by instrument conductivity specifications (i.e. accuracy, range) while allowing the user to select the most appropriate combined-sensor package if required. (ACT 2007b)
- Current development efforts related to conductivity measurement have been focused on methods to limit sensor bio-fouling, which helps to maintain measurement accuracy, ensure long term data stability, increase deployment duration and decrease maintenance costs. Some examples of these anti-biofouling methods are outlined in Table A-1.
- The Alliance for Coastal Technologies estimates that maintenance costs due to biofouling consume 50% of operational budgets. Over the years, methods for combating biofouling on submerged sensors have evolved from the use of toxic chemicals and pumps to more mechanical systems that use wipers or shutters to combination systems that use mechanical systems and technologies such as ultrasonic or chlorine generation systems. (YSI 2010)
- "Data from deployments indicated that anti-fouling hardware effectively provided viable data for deployments longer than 40 days. Without anti-fouling hardware, sensors were affected by fouling in as few as nine days. By using anti-fouling components, the monitoring program in St. Petersburg Harbor decreased its maintenance visits by 66% and saved $10,000. Overall, anti-fouling components for water quality instruments very effectively extend deployment times and collect high quality data for water managers." (YSI 2010)

Table A-1
New Developments in Anti-biofouling Technology

New Technology	Description
AML –UV•Xchange™	UV•Xchange is a subsea module that prevents biofouling during long-term, in-situ deployments. UV•Xchange inhibits marine growth by bathing critical surfaces in ultraviolet (UV) light. Comparative studies show UV•Xchange to be as effective as leading chemical protection methodologies, such as bis(tributylin)oxide (TBT), at eliminating drift due to biofouling in CTDs and multi-parameter instruments.
YSI-6-Series Copper Sensor and Sensor Guard Components	YSI Environmental has developed a copper-alloy based system to significantly slow the rate of biological fouling on water quality instruments and extend long-term instrument deployments. These “anti-fouling kits” are an affordable solution to biofouling and thereby decrease the number of site visits and maintenance needed at remote sites (YSI, 2010).
YSI-EXO series new independent Antifouling wiper and U-shape conductivity probe.	The newly designed EXO2 Central Wiper occupies the central port on an EXO2 sonde rather than being separate wipers incorporated into individual sensors as in the 6-series. To keep it from interfering with data, an EXO2 sonde can be equipped with this anti-fouling wiper to prolong deployments and improve data accuracy. Note: A biennial (every two years) wiper shaft o-ring replacement is necessary to maintain optimum performance of the EXO2 central wiper.
RBR Inductive Cell Technology	Instruments that use inductive cell technology are not as susceptible to biofouling due to the configuration of the sensor. Whereas conductivity meters have electrodes in direct contact with the water and are subject to fouling, the inductive meter requires only submersion of the sealed electrical coil, which measures the inductance of the fluid without electrical contact. (RBR, 2010).
Seabird-Coastal - WQM Technology	An instrument the water quality monitor (WQM), integrates high-accuracy sensors to measure pressure, temperature, salinity, dissolved oxygen, chlorophyll fluorescence and turbidity. The WQM design includes several synergistic anti-foulant strategies such as unique plumbing that protects the sensors from continuous exposure, passive diffusion of anti-foulant, and a copper guard installed over the sensors (Janzen, Larson and Moore, 2008).
MicroCAT/HydroCAT antifoulant-protected flow path	The Sea-Bird Coastal MicroCAT/HydroCAT measure and record conductivity, temperature and optical dissolved oxygen ensuring long term data stability. The HydroCAT has unique bio-fouling protection method using an integral pump, and unique internal flow path, and EPA-approved anti-foulant devices installed in the flow path. This configuration minimizes biological contact and flow across the sensor between samples and provides stable measurements throughout a deployment.

A.4 CONDUCTIVITY/SALINITY SENSORS FOR CONSIDERATION

Existing and newer conductivity sensors to be considered for the Bay Delta Action Plan are presented in **Table A-**.

Table A-2
Conductivity/Salinity Sensors for Consideration

Instrument	Description	Pros	Cons	Capital Cost
YSI 6-Series	These water quality sondes are ubiquitous in the measurement community. Over the past two decades 28 varieties of 6-Series instruments have been manufactured to meet the needs of customers across the globe. These sondes are used extensively by EPA, USGS, and NOAA throughout the US.	Very widely used/accepted sensor systems. Copper-based antifoulant probes. High-quality at reasonable cost.	Older electronics nearing obsolescence. Phase out 2018-2021. Self-cleaning sensors have proven to reduce data loss only in relatively fresh water because they are ineffective when fouling is excessive and they are prone to leak and malfunction in saltier water.(Buchanan and Ruhl 2001)	$3800-$7400+ depending upon sensors installed.
YSI EXO Series	The EXO2 water quality sonde are new YSI multi-parameter instruments that can accommodate up to six user-replaceable sensors, a central wiper to keep sensors clean of biofouling, and an integral pressure transducer for depth. The EXO1 can accommodate fewer sensors. **YSI EXO Conductivity Sensor (New Fall 2015)**	Newer electronics, titanium sensors and data storage technology. Smart ports on the sonde accept any EXO water quality sensor. Newer independent wiper mechanism eliminates leaks from having wiper integrated into individual sensors.	Currently fewer copper-based antifouling sensors with this compared with 6-Series	EX02 sonde with pressure: $6980 CT sensors: $820 Turb: $1800 Wiper: $1010 Cable: $ 500 **Total: ~$11,110**

Table A-2
Conductivity/Salinity Sensors for Consideration

Instrument	Description	Pros	Cons	Capital Cost
SBE-37SIP/37SMP	MicroCAT CTD family, which make measurements at user-programmable intervals. All MicroCATs: •Measure Conductivity and Temperature. •Can include an optional strain-gauge Pressure sensor. •Can include an integrated pump for improved bio-fouling protection and improved conductivity and oxygen sensor response. •Have 8 Megabyte memory. •Are available for depths to 350 meters (plastic housing) or 7000 meters (titanium housing).	Proven long-term stability and high-accuracy. Specialized antifouling with integral pump and flow path. high accuracy, long term (30-90 days) stability (<3% error) in biofouling environments. Capability to add SeapHOx and Optical DO sensors. Capability to add inductive-cable modem telemetry.	Do not incorporate a Turbidity sensor at instrument level. Has to be incorporated as an external sensor via cable.	$8000 Ext Power $8500 Internal Pwr
Sea-Bird Coastal HydroCAT	Conductivity, temperature, depth and optical dissolved oxygen sensor designed for long term deployments.	Specialized antifouling with integral pump and flow path. high accuracy, long term (30-90 days) stability (<3% error) in biofouling environments	No other sensors can be integrated directly to instrument.	$9000
Sea-Bird Wetlabs WQM	Designed specifically for long-term moored operations in biologically rich water. Sensors include fluorometer, conductivity, temperature and depth. Includes active flow control, passive flow prevention, light-blocking, active biocide injection and passive inhibitors to limit biofouling	Specialized antifouling with active injection and copper optical shutters. Has integrated fluorometer for measuring fDOM	No other sensors can be integrated directly to instrument. Slightly higher capital cost and requirement to handle biocide chemicals during servicing.	$14000

Table A-2
Conductivity/Salinity Sensors for Consideration

Instrument	Description	Pros	Cons	Capital Cost
AML Metrec X	Metrec•X is an externally-powered, multiparameter instrument that allows you to change the instrument's sensor load, in the field and on-demand.	Specialized UV•Xchange antifouling with •No toxic chemicals. •No moving parts and hence greater reliability compared to wipers. •Protects complex and delicate surfaces, for which wipers are unsuitable. •Adjustable LED sub-modules ensure effective coverage of all critical surfaces, regardless of geometry.	No internal battery	$11300
AML Plus X	Plus•X is a logger that allows you to change the instrument's sensor load, in-the-field and on-demand. With Plus•X, your CTD can become an sound velocity temperature profiler (SVTP); shallow pressure sensors can be swapped for deep; and temperature range can be extended or tightened, as needed. One single logger meets multiple deployment requirements.	Specialized UV•Xchange antifouling		$14300
RBR Concerto CTD Inductive Sensor	Inductive meter for determination of conductivity/salinity temperature. Toroidal sensor design, encased in plastic is a non-contact conductivity meter with good antifouling capability.	Testing has shown biofouling has much less effect on conductivity measurements that direct-contact conductivity probes.	No other sensors can be integrated directly to instrument.	$6,750 w/cable
APL-UW Sigma Profiler	University of Washington Applied Physics Lab's Experimental Water Column Conductivity instrument. Measures conductivity as a function of depth and time in the water column.	Longer endurance and reliability than mechanical CTD systems. Measures conductivity of water column.	Not a commercial product, In development.	N/A

Table A-3
Instrument Sensor Specification Comparison

Instrument	Range	Resolution	Accuracy	Stability	Response time OR Time constant	Maintenance Interval
YSI 6-Series Conductivity (6560) Temperature(6560) Depth (Medium) Dissolved O2 (6150)	0 to 100 mS/cm -5 to +50°C 0 – 61 m 0 to 50 mg/L	0.001 to 0.1 mS/cm 0.01°C 0.001 m 0.01 mg/L	±0.5% of reading + 0.001 mS/cm ±0.15°C ± 0.003 m 0 to 20 mg/L: ± 0.1 mg/L or 1% of reading, whichever is greater; 20 to 50 mg/L: ±15% of reading, relative to calibration gases	?	?	1-5 weeks
YSI EXO Series Conductivity (?#) Temperature Depth Dissolved O2 (Optical) Turbidity	0 to 200 mS/cm -5 to 50°C0-0 to 100 m to 50 mg/L	to 0.01 mS/cm 0.01 °C 0.01 m 0.01 mg/L	0 to 100: ±0.5% of reading or 0.001 mS/cm -5 to 35°C: ±0.01°C, 35 to 50°C: ±0.05°C ±0.04 m 0 to 20 mg/L: ±0.1 mg/L or 1% of reading, w.i.g.; 20 to 50 mg/L: ±5% of reading	?	T63<2 sec T63<1 sec T63<2 sec T63<5 sec	1-5 weeks
SBE-37SIP/37SMP Conductivity Temperature Depth	0 to 70 mS/cm -5 to +45 °C 0 to 20 m	0.0001 mS/cm 0.0001 °C 0.002%	±0.0003 S/m ±0.002 °C /± 0.01°C (over 32°C) ± 0.1%	0.0003 S/m/month 0.0002 °C/month 0.05%		1-6 months
Sea-Bird Coastal HydroCAT Conductivity Temperature Depth Dissolved O2 (Optical)	0- 70 mS/cm -5 to 45°C 0- 20 m 120% of surface saturation	0.0001 mS/cm 0.0001°C 0.002% 0.007 mg/L	± 0.003 mS/cm ± 0.002°C/± 0.01°C (over 32°C) ± 0.1% ± 0.1 mg/L or ± 2% whichever is greater	0.003 mS/cm/month 0.0002°C/month 0.05% < 0.03 mg/L/ 100,000 samples	?	1-3 months

Table A-3
Instrument Sensor Specification Comparison

Instrument	Range	Resolution	Accuracy	Stability	Response time OR Time constant	Maintenance Interval
Sea-Bird Wetlabs WQM						1-3 months
Conductivity	0- 90 mS/cm	0.0001 mS/cm	± 0.003 mS/cm	0.003 mS/cm		
Temperature	-5 to 45°C	0.0001°C	± 0.002°C/± 0.01°C (over 32°C)	0.002°C/month		
Depth	0- 100 m	0.002%	± 0.1%	0.05%		
Optical DO	120% of surface saturation	0.035% of saturation	± 2% of saturation	.5% per 1000 hours		
Chlorophyll (Several)	0- 250 µg Chl					
Turbidity (Several)	0- 250 µg Chl					
CDOM	0- 375 ppb		0.28 ppb			
AML Metrec X						
Conductivity (RA090)	0-90 mS/cm	0.001 mS/cm	0.01 mS/cm		25 ms	
Temperature (n545)	-5-45°C	0.001°C	0.005°C		100 ms	
Depth (0050)	0 to 50 m	0.02%	0.05%		10 ms	
Turbidity (Several)	1 to 3000 NTU	0.01 to 0.1 NTU	1 to 5%		<0.7s	
AML Plus X						
Conductivity (RA090)	0-90 mS/cm	0.001 mS/cm	0.01 mS/cm		25 ms	
Temperature (n545)	-5-45°C	0.001°C	0.005°C		100 ms	
Depth (0050)	0 to 50 m	0.02%	0.05%		10 ms	
Turbidity (Several)	1 to 3000 NTU	0.01 to 0.1 NTU	1 to 5%		<0.7s	
RBR Concerto CTD Inductive Sensor						
Conductivity	0-85mS/cm	~1 µS/cm	±0.003 mS/cm	~1 µS/cm/month	<100ms	
Temperature	-5°C to 35°C	<0.00005°C	±0.002°C	~0.002°C/year		
Depth	0 to 50 m	<0.001%	±0.05%	~0.1%/year		

Table A-4
Instrument Physical Specification Comparison

Instrument	Housing Material	Depth Rating	Anti-Fouling	Acquisition Time	External Power	Memory Capacity
YSI 6-Series	Plastic	200 m	Copper Alloy Accessories		12 V DC	
YSI EXO Series	Plastic	250 m	Copper Alloy Accessories			1,000,000 logged readings
SBE-37SIP/37SMP	Plastic	350 m	Expendable devices	1.0-2.9 sec/sample	0.25 to 0.5 A at 8.5 to 24 VDC	530,000 samples CTD
Sea-Bird Coastal HydroCAT	Plastic	350 m	Anti-fouling capability	2.3 – 3.2 sec/sample	0.25 A at 9 to 24 VDC	
Sea-Bird Wetlabs WQM	Plastic (Acetal copolymer, ABS, PVC, titanium, copper)	200 m	Anti-fouling capability, copper alloy	1 Hz	350 mA Peak, 9 – 16 VDC	
AML Metrec X	Hard anodized Aluminum	6000 m	Ultraviolet LED light	Scan up to 25 Hz	10 to 36 VDC	Gigabyte non-volatile memory
AML Plus X	Hard anodized Aluminum	5000-6000 m	Ultraviolet LED light	Scan up to 25 Hz	10 to 36 VDC	Gigabyte non-volatile memory
RBR Concerto CTD Inductive Sensor	Plastic	740 m		1s to 24h		30M readings

A.4.1 YSI 6-SERIES WATER QUALITY SONDES

During the early 1990's, YSI introduced what has become one of the most widely used water quality instrument systems – the 6-Series environmental monitoring sondes. Over the past two decades what started as a single sonde product evolved over 28 varieties of 6-Series instrumentation to meet the needs of customers across the globe. These sondes are used extensively by EPA, USGS, and NOAA throughout the US. The 6-Series will be phased out over the next 3-5 years and will be replaced with the YSI-EXO series (Xylem 2015).

Figure A-1

The most robust and newest of the 6-series sondes is the YSI 6920 V2 water quality logging system which is ideal for economical long-term in situ monitoring and profiling. The sonde comes in two versions:

- 6920 V2-1 has 1 optical port, 1 conductivity/temperature port, 1 Rapid Pulse Dissolved Oxygen port, 1 pH/ORP port, and 3 ISE ports
- 6920 V2-2 has 2 optical ports, 1 conductivity/temperature port, 1 pH port, and 1 ISE port

Available optical sensors include:

- ROX optical dissolved oxygen
- Blue-green algae
- Chlorophyll
- Turbidity
- Rhodamine

A pressure sensor is an option on both versions.

Additional parameters include:

- Salinity
- Specific Conductance
- Depth or Shallow Vented Level
- Total dissolved solids (TDS)
- Open-channel Flow
- Nitrate-nitrogen, Ammonia/Ammonium-nitrogen, or Chloride (ISEs)

The manufacturer's specifications for this instrument are included in Appendix A.

A.4.2 YSI – EXO SERIES WATER QUALITY SONDE

YSI's EXO sonde platform was launched in 2012. Much like the 6-Series platform, YSI plans to grow and evolve the EXO meter series to meet the needs of specific applications.

Figure A-2

The EXO2 water quality sonde is a new YSI multi-parameter instrument that collects data with six user-replaceable sensors, a central wiper to keep sensors clean of biofouling, and an integral pressure transducer for depth. Each sensor port on the sonde accepts any EXO water quality sensor and automatically recognizes it.

Newest Conductivity Sensor Option (Fall 2015)

Sensor Options:

- Conductivity and Temperature
- Dissolved Oxygen (optical)

- fDOM (Fluorescent Dissolved Organic Matter, surrogate for CDOM)
- pH or pH / ORP
- Depth (integral)
- Total Algae (Dual-channel Chlorophyll and Blue-green Algae)
- Turbidity

Data Collection Options:

- Store onboard the sonde
- Transfer data to DCP
- Relay data to PC
- Relay data to EXO Handheld

The manufacturer's specifications for this instrument are included in Appendix A.

A.4.3 SEABIRD ELECTRONICS SBE-37 MICROCAT

Figure A-3. Seabird MicroCAT SBE-37

Sea-Bird manufactures a number of instruments within the MicroCAT CTD family, which make measurements at user-programmable intervals. **All MicroCATs:**

- Measure Conductivity and Temperature.
- Can include an optional strain-gauge Pressure sensor.
- Can include an integrated pump (**P** in the model number designation) for improved bio-fouling protection and improved conductivity and oxygen sensor response.
- Have 8 Megabyte memory.
- Are available for depths to 350 meters (plastic housing) or 7000 meters (titanium housing).

Some MicroCATs also include **Dissolved Oxygen**:

- **IDO** MicroCATs include a membrane-type Dissolved Oxygen sensor.

- **ODO** MicroCATs include an Optical Dissolved Oxygen sensor.

The SBE 37-SMP-ODO MicroCAT can be integrated with a **pH** sensor to provide CTD + DO + pH:

A.4.4 SEA-BIRD COASTAL HYDROCAT

Figure A-4

The Sea-Bird Coastal HydroCAT with technology by Sea-Bird Electronics (SBE) measures and records conductivity, temperature and optical dissolved oxygen ensuring long term data stability. Depending on the application, the HydroCAT can collect high quality data for several months up to a year. Excellent bio-fouling protection is provided by US EPA-approved anti-foulant devices, integral pump, and unique internal flow path, which minimizes flow between samples and provides stable measurements throughout a deployment.

Conductivity and temperature sensors are based on field proven Sea-Bird Electronics (SBE) CTD products. The aged and pressure- protected thermistor has a long history of exceptional stability and accuracy. The oxygen sensor was designed by SBE to meet the demand for a low maintenance and high accuracy sensor for use in applications such as hypoxia monitoring. All HydroCAT sensors are built with careful choices of materials and geometry combined with superior electronics and calibration methodology to optimize field performance.

A.4.4.1 APPLICATIONS

For continuous or real-time measurement of conductivity, temperature, depth and dissolved oxygen in:

- Estuaries
- Lakes and reservoirs
- Rivers and streams

A.4.4.2 Performance Features and Benefits

- Robust - Excellent anti-fouling capability- EPA approved anti-foulant device and pumped internal flow path for maximum biofouling protection
- Accurate- High initial accuracy and low drift rate
- Cost Effective- No in-field calibrations required, common deployment duration of three plus month, reducing field costs

A.4.4.3 Additional Features

- Each instrument is factory calibrated in a temperature controlled bath that operates at 2-4 times the accuracy of the instrument.

The manufacturer’s specifications for this instrument are included in Appendix A.

A.4.5 Sea-Bird Coastal WQM X

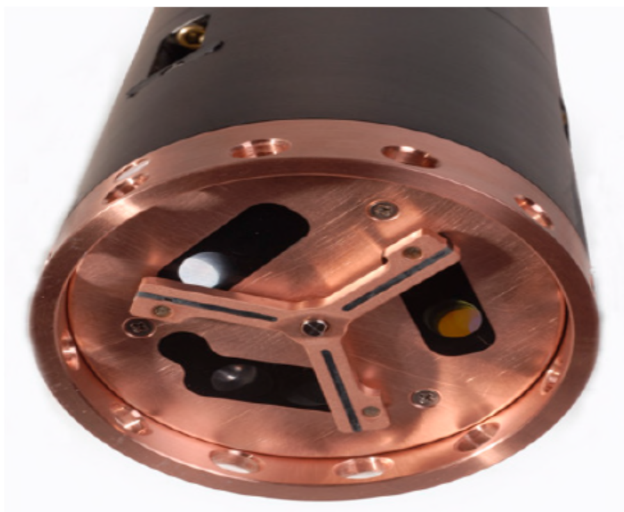

Figure A-5

The Sea-Bird Coastal WQM X with technology by WET Labs and Sea-Bird Electronics is designed specifically for long-term moored operations in biologically rich water. The WQM X combines WET Labs’ state of the art fluorometers with cutting edge conductivity, temperature, and depth technology from Sea-Bird Electronics to create a monitoring Sonde with unprecedented long-term deployment capabilities.

Ideally suited for unattended monitoring the WQM employs active flow control, passive flow prevention, light-blocking, active biocide injection and passive inhibitors to combat internal and external fouling.

The manufacturer's specifications for this instrument are included in Appendix A.

A.4.6 RBR XR-420/ XR-620 (CONCERTO) CTD LOGGERS

http://www.rbr-global.com/products/ct-and-ctd-loggers

The RBR*duo* C.T and the RBR*concerto* C.T.D are unique data loggers dedicated to the determination of salinity. Salinity is calculated by measuring the conductivity and temperature of the water. Equipped with a depth sensor, the RBR*concerto* C.T.D can also derive density anomaly and speed of sound. The RBR*duo* C.T and the RBR*concerto* C.T.D are available in configurations that support moored or profiling applications. Both loggers meet World Ocean Circulation Experiment (WOCE) accuracy and resolution standards and are NIST traceable.

Figure A-6

A.4.6.1 MAIN FEATURES:

- High accuracy measurements.
- Fast download.
- Improved instrument design.

- True USB speed and convenience
- Unique desiccant holder in the battery end cap.
- Store over 30 million readings internally (10 million C,T and D samples) .
- RS-232 and RS-485 support for telemetry and long cable usage.
- Longer deployments with eight CR123A batteries (optional extended body with 16 batteries).
- New microprocessor, real-time operating system, sophisticated power management, and USB and serial connectivity.
- Mechanical redesign to reduce the complexity of the internal parts and more efficient use of the space available.
- 6Hz and 12Hz fast sampling options for profiling
- Memory expansion to 60 or 120 million readings option

Conductivity – Measured with an inductive sensor, suitable for deployment in marine, estuarine, or fresh water. There are no exposed contacts, which avoids susceptibility to corrosion, and the housing may be frozen into ice without damage.

Temperature - The sensor is built and calibrated in-house using an aged thermistor. The temperature channel is calibrated an accuracy of ± 0.002°C (ITS-90) over the range -5 to +35°C. Extended range calibrations are available.

Pressure - Measured with a piezo-resistive transducer with nickel based super alloy diaphragm to avoid corrosion. Accuracy is 0.05% of the full scale rating and achievable resolution is 0.001%. The pressure sensor is available in a range between 10dbar to 740dbar. See the data sheet for possible sensor ratings.

The manufacturer's specifications for this instrument are included in Appendix A.

A.4.7 University of WA Applied Physics Lab (APL-UW) Sigma Profiler

http://staff.washington.edu/aganse/myresearch/sigmaProfiler/index.html

APL-UW has developed a remote sensing instrument – the "Sigma Profiler" (SP) – which measures conductivity as a function of depth and time in the water column of an estuarine environment.

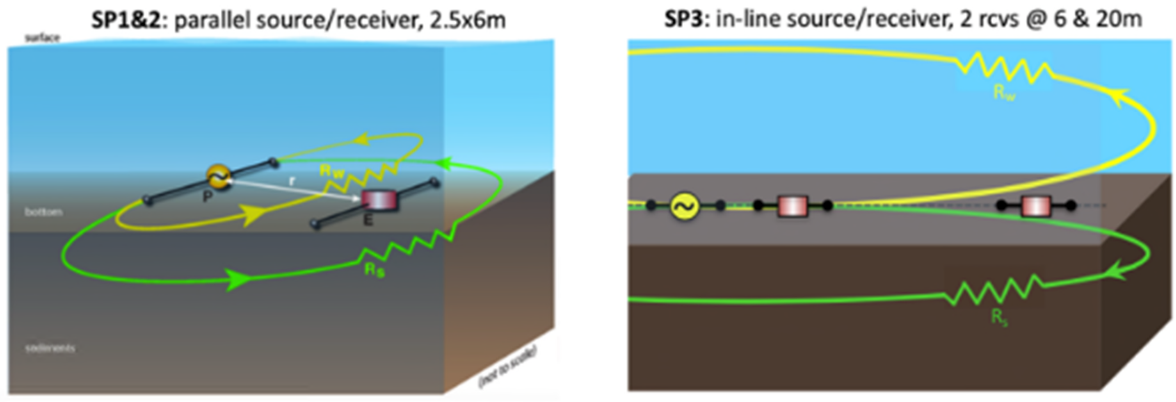

Figure A-7

The Sigma Profiler is an APL-developed instrument prototype for remotely observing estuarine salinity profiles via electromagnetic measurements. It was used repeatedly in the Columbia River estuary in conjunction with nearby CTD profiles as part of the Center for Coastal Margin Observation and Prediction program, which sponsored the instrument's initial development.

The instrument's principle of operation is that electromagnetic waves are attenuated in seawater as a function of frequency. Electrical currents at different frequencies are produced by the instrument, and the resulting electric field is measured at a nearby dipole receiver. These measurements can be combined to infer the conductivity (and hence salinity) structure in the water column. Conductivity is the variable of focus from this tool for sake of statistical rigor, but there is a nearly linear relationship to salinity in the estuarine environment, so we can measure conductivity to directly obtain salinity with low error.

Regions of strong property gradients, such as those present at fronts of salinity intrusions into a marine estuary, are of vital importance to the ecology of the estuary as well as the quality of the drinking and irrigation water sourced from it. Previous technologies to observe a salt wedge are subject to difficulties with: point sensors that are not representative, maintaining sensors in strong current, bio-fouling and sedimentation, fish attack and floating and submerged debris, damage from fishing and vessels and vandalism, and costly sensors and batteries.

Advancement of Salinity and Flow Monitoring in the San Francisco Bay Delta

San Francisco Bay Delta Action Plan Implementation Support

APPENDIX B:
Flow Measurement Instrumentation Equipment Overview, Comparison and Manufacturers' Specifications

B. FLOW MEASUREMENT - INDEX VELOCITY INSTRUMENTATION

B.1 OVERVIEW

Accurate measurement of flow in an open channel requires precise measurements of the channel cross-section area and many independent velocity measurements taken across the entire channel. Real-time flow measurements are typically taken with a type of meter that only measures a portion of the channel velocity that is referred to as in Index Velocity (Vi). An index equation is developed for the *in-situ* index velocity meter by conducting several independent measurements of channel cross-section, stage and current velocity, which is then used to calculate the average channel velocity (Va) from the measured index velocity. The average velocity is multiplied by the channel cross-sectional area, determined from measured stage, to calculate flow.

B.1.1 ACOUSTIC VELOCITY METER

Acoustic Velocity Meters (AVMs), also referred to as an Ultrasonic Velocity Meters (UVM), are time-of-travel devices that measure water velocities along an acoustic path between pairs of transducers located on a diagonal line across a channel. The transducers are connected to a central processors by cables (Figure B-1). Acoustic pulses are transmitted along the acoustic path; the upstream-moving (against current) pulses travel slower than the downstream-moving (with current) pulses. The difference in travel time between a pair of back and forth pulses provides an average velocity (Vp) across the channel at the depth of the transducers. The measured velocity (Vp) is not an average cross-sectional velocity and is referred to as an "index velocity" (Vi) that is used when processing the data to determine an average cross-sectional velocity(V_L). (Laenen, 1985).

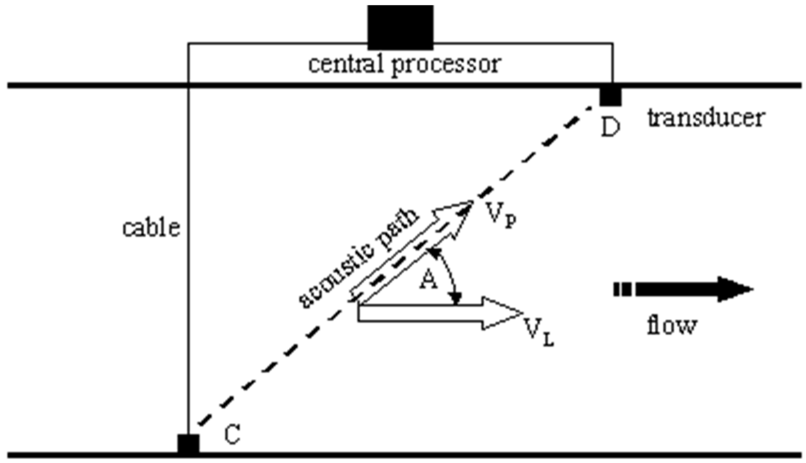

Figure B-1 Acoustic Velocity Meter (AVM) Schematic (Laenen 1985)

B.1.2 ACOUSTIC DOPPLER CURRENT PROFILERS

Acoustic profilers use the Doppler frequency shift of acoustic pulses reflected from particles in the water to measure water velocities in multiple sample cells. Profilers can be mounted in a horizontal orientation (Figure B-2a) to measure velocity profiles across a channel or mounted in a vertical orientation (Figure B-2b) to measure vertical velocity profiles. A profiler uses two to four transducers set at a known orientation to measure water velocities. Each transducer transmits sound pulses of a known frequency along a narrow acoustic beam (Figure B-2). As the pulses travel along the acoustic beam, they strike particulate matter (scatterers) suspended in the water. When the pulses strike scatterers some of the sound is reflected along the acoustic beam to the transducer. The reflected pulses have a frequency (Doppler) shift proportional to the velocities of the scatterers they are traveling in along the acoustic beam.

Profilers measure velocities in uniformly-sized cells or bins along the acoustic beams (Figure B-4). By measuring velocities in a number of bins across a channel or vertically through the water column, these instruments produce horizontal or vertical water velocity profiles, hence the designation "profiler." (Levesque 2012)

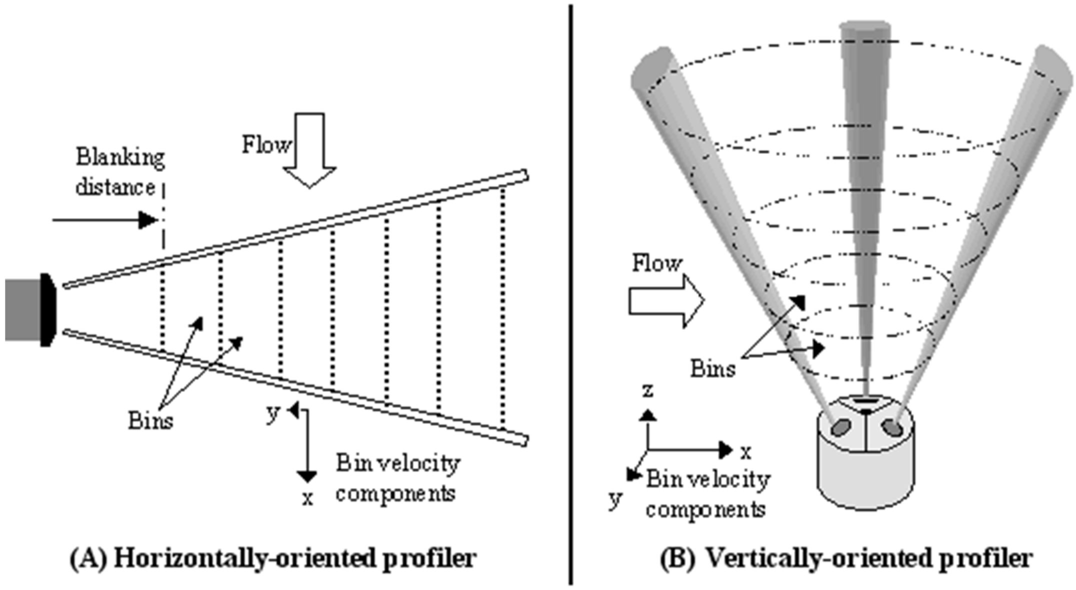

Figure B-2 Examples of Acoustic Doppler Profiler Orientations

B.1.3 Flow Measurement by Acoustic Scintillation

In the mid-1990s, ASL AQFlow developed a new method for measuring the discharge in low head, short intake power plants, the Acoustic Scintillation Flow Meter (ASFM). Originally tested in rivers and ocean channels, the method uses the scintillation of an acoustic signal transmitted along a path in a turbulent flow to measure the flow velocity.

This method may have some application in measuring the mean velocity across the channel at a location like Chipps Island. Research application of this technology has been typically applied with a single acoustic path, however the newer, well developed application of this technology for use in intakes of hydroelectric dams has employed an array of vertical sensors to provide accurate 2D velocities across short sampling paths. The application of this technology to wide-channel flow is discussed in (Di Iorio and Barton 2003) and should be considered as a possibility for future flow measurement in the Bay Delta.

Measurement principles

Acoustic scintillation drift is a technique for measuring flow in a turbulent medium by analyzing the variations in ultrasonic pulses that have been transmitted through the medium.

The Acoustic Scintillation Flow Meter (ASFM) uses this technique to measure the velocity of the water flowing through a conduit (e.g. an intake to a hydroelectric turbine) by utilizing the turbulence in the flow (e.g. small-scale turbulence generated by the intake trash racks).

With two transmitters placed at one side of the conduit, and two receivers at the other, the signal amplitude at the receivers will vary randomly in time as the distribution of turbulence along the propagation paths changes with time and the flow. If the paths are sufficiently closely spaced, the turbulence will remain embedded in the flow, and the pattern of the variations (known as "scintillations") at the downstream receiver will be nearly identical to that at the upstream receiver, except for a time delay, Δ_t (Fig 1). If these scintillations are examined over a suitable time period, this time delay can be determined. The mean flow velocity perpendicular to the acoustic path is then Δ_x/Δ_t, where Δ_x is the separation between the paths. Using three receivers in a triangular array allows both the magnitude and inclination of the laterally averaged velocity to be measured.

The average velocity is measured at several pre-selected measurement levels. Total flow rate is calculated by integrating the average horizontal component of the velocity at each level over the total cross-sectional area of the conduit.

Di Iorio, D., and A. Barton, Path-averaged ocean measurements in the deep, stratified tidal channel of Hood Canal using acoustical scintillation, J. Geophys. Res., 108(C10), 3312, doi:10.1029/2003JC001796, 2003.

Lemon D. D., S. F. Clifford and D. M. Farmer B. B. Parker "Scintillation current measurements, a new approach to real-time current measurements in channels and harbours", Applications of Real-time Oceanographic Circulation Modelling Symposium Proceedings, 1986

Lemon, D. D. and D. M. Farmer, "Experience with a multi-depth scintillation flowmeter in the Fraser estuary," Proc. of the IEEE Fourth Working Conference on Current Measurement, Clinton, MD, pp. 290-298, April, 1990.

Clifford, S. F. and D. M. Farmer, "Ocean flow measurements using acoustic scintillation," J. Acoust. Soc. Amer., vol.74 (6), pp. 1826-1832, December, 1983.

Farmer, D. M. and S. F. Clifford, "Space-time acoustic scintillation analysis: a new technique for probing ocean flows," IEEE J. Ocean. Eng., vol.OE-11 (1), January, 1986.

Farmer, D. M. and S. F. Clifford and J. A. Verrall, "Scintillation structure of a turbulent tidal flow," J. Geophys. Res., vol. 92 (C5), pp. 5396-5382, May, 1987.

B.2 Flow Measurement Instrumentation for Consideration

Table B-1
Flow Measurement Sensors for Consideration

Instrument	Description	Pros	Cons	Capital Cost
Sontek SL 	The SonTek SL(Side-Looking) is a horizontally-oriented Acoustic Doppler Current Profiler (H-ADCP) It comes in 3 Models with Range of 5,20 and 120 meters	Widely excepted and easy to use. New versions have ability to measure up to 128 velocity cells. Low power electronics	Made for irrigation and natural channels <120m wide.	$10-12K*
SonTek IQ 	Up-Looking acoustic Doppler flow meter made specifically for measuring flow in irrigation and natural channels. 3 models with single-cell and profiling capability. Measure flow, total volume, water level and velocity.	Can collect flow and volume data in as little as 8 cm (3 in) of water. Self-contained all-in-one design. Proprietary flow algorithms for irrigation canals, natural streams and pipes. SmartPulseHD adaptive sampling. Self-calibrating water level using vertical acoustic beam and pressure	Made for smaller irrigation and natural channels Up-looking design needs to be mounted on the channel bottom	$8.5K
SonTek ADP 	Up-Looking Acoustic Doppler Current Profiler (ADCP) available in several frequencies (500, 1000, 1500kHz). Can be used on a boat for real-time discharge monitoring or bottom or buoy mounted for collecting detailed vertical velocity profiles.	Measured detailed vertical velocity profiles with optional CTD integration. Can be used for moving boat as well as autonomous deployment. Pros/cons related to installation needs and location.	For autonomous deployment, Up looking design needs to be mounted on the channel bottom or a mooring. Where velocity directions are reliant on internal compass.	$22-$28K Depending on model and options.
TRDI ChannelMaster 	The compact, flexible, CHANNELMASTER is a horizontally-oriented Acoustic Doppler Current Profiler (H-ADCP) designed to collect high-accuracy water velocity, stage, and discharge data for a wide array of applications	Widely accepted. New versions have ability to measure up to 128 velocity cells. Low power electronics		1200 kHz -11K, 600kHz - $12K, 300kHz - $18K

Table B-1
Flow Measurement Sensors for Consideration

Instrument	Description	Pros	Cons	Capital Cost
TRDI- ADCP 	Up-Looking Acoustic Doppler Current Profiler (ADCP) available in several frequencies. Can be used on a boat for real-time discharge monitoring or bottom or buoy mounted for collecting detailed vertical velocity profiles. Availble in 300, 600 or 1200 kHz models	Measured detailed vertical velocity profiles. Depending on model, can be used for moving boat as well as autonomous deployment. Pros/cons related to installation needs and location.	For autonomous deployment, Up looking design needs to be mounted on the channel bottom or a mooring. Where velocity directions are reliant on internal compass.	$25-$35K+ depending on model and options.
CODAR RiverSonde 	The RiverSonde® is a non-contact radar-based monitoring system providing continuous surface cross-channel velocity profiles for streams, channels, and rivers.	With 2 systems can measure 2D velocity vectors of entire river surface	Does not measure subsurface flow. Can be affected by wind driven surface velocities. *Advertised with a range of 250 to 300m. Although Hugh Roarty from Rutgers along with the ROWG tested the unit in the Hudson (~800-1000m) and were able to get coverage by raising the antenna very high (like building height)*	$25-$??K+ for a (Single ? Dual system) depending on model and options.
ASL-AQ Flow Acoustic Scintillation				

* Approximate price for meter, cable and top-side interface module

B.2.1 SonTek Side-Looking "SL" Acoustic Doppler Current Profilers

http://www.sontek.com/productsdetail.php?SonTek--SL-Series-8

The SonTek Argonaut-SL and new SonTek®-SL Series SL1500/3000 are advanced Doppler current profilers for water velocity measurement in a horizontal layer.

The SonTek-SL (known as the Side-Looker or "SL") is used to measure water velocity and level in open channels. The SonTek-SL features accessories, mounting options, software, and a variety of integration formats. Designed specifically for side mounting on bridges, canal walls, or riverbanks, the SL can be used in small channels from a few meters to rivers several hundred meters wide.

Figure B-3 SonTek SL Series Side-Looking Acoustic Doppler Current Profiler flow meter

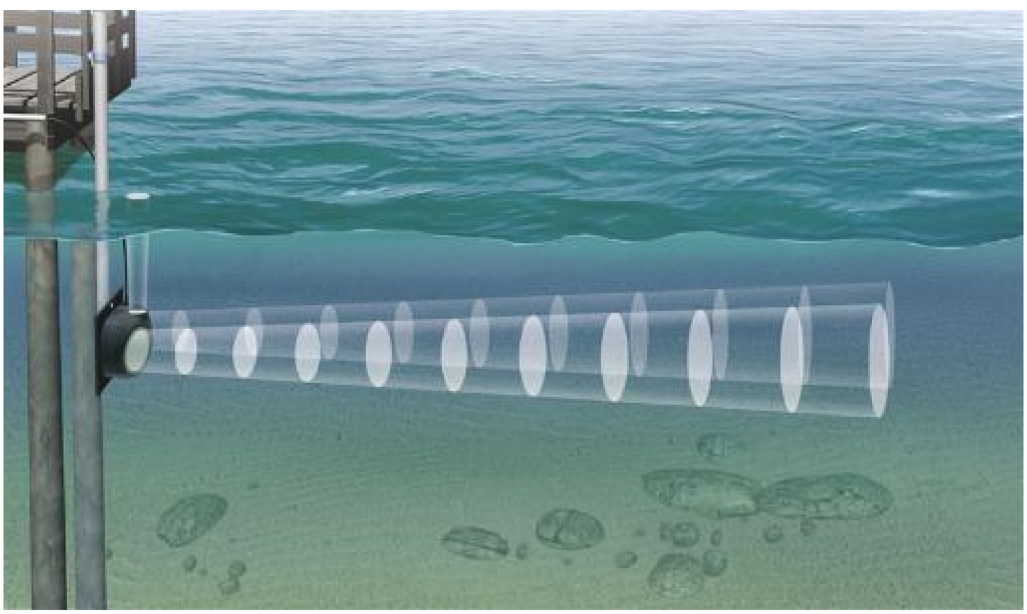

Figure B-4 Sontek SL on Pier Mount

B.2.1.1 PRODUCT FEATURES

- Water Velocity and Level: Water velocity, level, flow, and total volume-multiple parameters from one instrument. Acoustic Doppler profile of velocity data and acoustic water level offer the most accurate, reliable measurements.
- SmartPulseHD®*: An algorithm that looks at water depth, profiling range, velocity, and turbulence, and then acoustically adapts to those conditions using pulse-coherent, broadband, and incoherent techniques.
- Water Velocity Profiling: Customizable, flexible setup options to suit a variety of applications. 3G models offer 128-cells for high-resolution and detailed profiles.

The manufacturer's specifications for this instrument are included below

B.2.2 SONTEK UP-LOOKING "IQ" ACOUSTIC DOPPLER CURRENT PROFILERS

http://www.sontek.com/productsdetail.php?SonTek-IQ-Series-15

SonTek-IQ® Series flowmeters are designed for monitoring flows in canals, culverts, pipes, and natural streams. Four velocity beams profile water velocity in 3-D - both vertically and horizontally - ensuring complete coverage of the velocity field. The built-in pressure sensor and vertical acoustic beam work in tandem to measure water level. Simply input the channel geometry using the intuitive SonTek-IQ software and you are outputting flow data in minutes.

Capable of working both in man-made as well as natural channel, the SonTek-IQ can collect flow (area-velocity) and volume data in as little as 8 cm (3 in) of water. Its five-beam pulsed Doppler design is Modbus, SDI-12, RS232 and Analog ready.

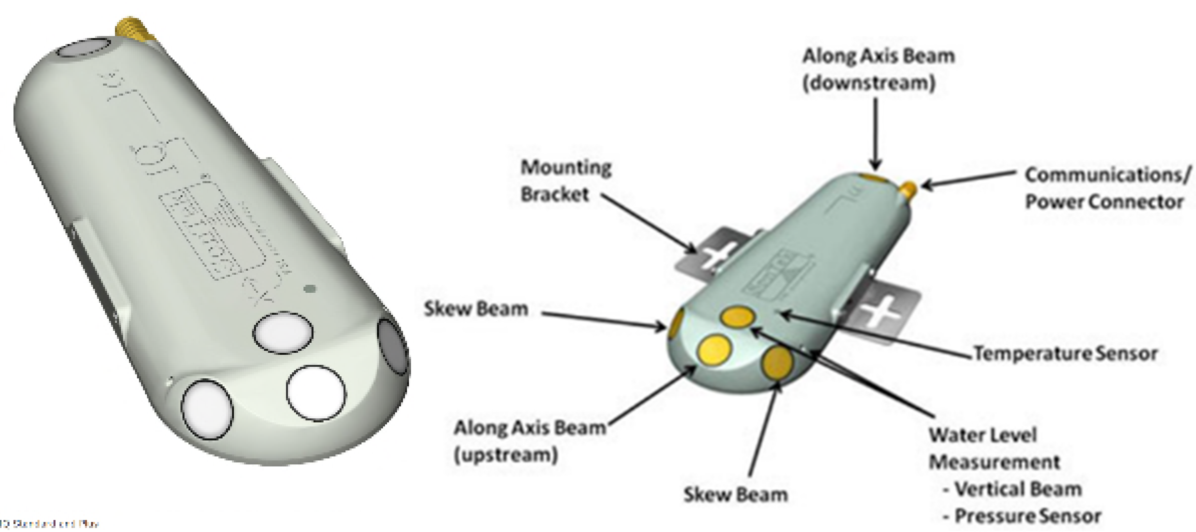

Figure B-5

B.2.2.1 PRODUCT FEATURES

- Self-contained all-in-one design
- Proprietary flow algorithms for irrigation canals, natural streams and pipes
- Uses SonTek's exclusive SmartPulseHD adaptive sampling
- Self-calibrating water level using vertical acoustic beam and pressure

The manufacturer's specifications for this instrument are included below

B.2.3 SONTEK ACOUSTIC DOPPLER PROFILER (ADP)

The SonTek ADP (Acoustic Doppler Profiler) is a high-performance, 3-axis (3D) water current profiler. The ADP uses state-of-the-art transducers and electronics designed to reduce side-lobe interference problems. This allows the ADP to make the very near-boundary (surface or bottom) current measurements critical to shallow water applications. The 1.5-MHz profiler is available as a Mini-ADP featuring a compact transducer head designed for applications where small size is critical.

Figure B-6

B.2.3.1 STANDARD FEATURES

- 0.25, 0.5, 1.0, and 1.5-MHz models

- Profiling ranges up to 180m
- Side-looking configurations for horizontal profiling
- Bottom Tracking & GPS input for moving boat applications
- Compass and 2-Axis Tilt Sensor
- Low power consumption
- Temperature sensor
- Low price
- Proven SonTek reliability

B.2.3.2 OPTIONAL FEATURES

- SeaBird MicroCat CT Sensor
- Optical Backscatter Sensor (OBS)
- Internal Recording
- Pressure Sensor (Strain Gage)
- Pressure Sensor (Frequency–RPT)

The manufacturer's specifications for this instrument are included below

B.2.4 TELEDYNE-RDI CHANNELMASTER ACOUSTIC DOPPLER CURRENT PROFILERS

Horizontal Acoustic Doppler Current Profiler

The compact, flexible, and affordable CHANNELMASTER is a horizontally-oriented Acoustic Doppler Current Profiler (H-ADCP) designed to collect high-accuracy water velocity, stage, and discharge data for a wide array of applications. By leveraging Teledyne RDI's BroadBand technology, Channel-Master allows you to obtain unmatched data quality, even in low velocities and complex flows, where a single cell cannot provide enough information.

The ChannelMaster's innovative design includes everything you need to collect high-quality data. The standard unit comes equipped with temperature, pressure, pitch and roll sensors, and a vertical beam.

Figure B-7

B.2.4.1 PRODUCT FEATURES

- Accurate: Teledyne RDI Broadband technology allows for small cells and/or short averaging sampling intervals.
- Robust: Collect highly accurate velocities even in difficult environments such as slow flow or rapidly changing flow.
- Versatile: ChannelMaster offers a range of 1-128 user selectable cell sizes from 25 cm - 8m and profiling ranges from 1m - 300m (frequency dependent).
- Sturdy: Comes standard with stainless steel mounting fixture.

B.2.4.2 APPLICATIONS

- Rivers, Streams, and Irrigation Canals: Monitor discharge and water level for a variety of applications. The ChannelMaster easily integrates with a telemetry or SCADA system, providing you with remote access to your data.
- Estuaries: Measure complex currents for environmental monitoring or circulation model calibrations or verifications.
- Port and Harbors: Monitor currents to provide velocity information for vessel maneuvering and safety

The manufacturer's specifications for this instrument are included below

B.2.5 TRDI SENTINEL ADCP

The self-contained Sentinel is Teledyne RD Instruments' most popular and versatile Acoustic Doppler Current Profiler (ADCP) configuration, boasting thousands of units in operation in over 50 countries around the world.

By providing profiling ranges from 1 to 165m, the high-frequency Sentinel ADCP is suited for a wide variety of applications. The lightweight and adaptable Sentinel is easily deployed on buoys, boats, or mounted on the seafloor. Real-time data can be transmitted to shore via a cable link or acoustic modem, or data can be stored internally for short or long-term deployments. The Sentinel is easily upgraded to include pressure, bottom tracking, and/or directional wave measurement—for the ultimate data collection solution.

Figure B-8

- Versatility: Direct reading or self-contained, moored or moving, the Sentinel provides precision current profiling data when and where you need it most.
- Precision data: Teledyne RDI's patented BroadBand signal processing delivers very low-noise data, resulting in unparalleled data resolution and minimal power consumption.
- A four-beam solution: Teledyne RDI's patented 4-beam design improves data reliability by providing a redundant data source in the case of a blocked or damaged beam; improves data quality by delivering an independent measure known as error velocity; and improves data accuracy by reducing variance in your data.

The manufacturer's specifications for this instrument are included below

B.2.6 CODAR RiverSonde non-contact Radar Surface current meter

The RiverSonde® is a non-contact radar-based monitoring system providing continuous surface cross-channel velocity profiles for streams, channels, and rivers. Data output from this system can be used as an index velocity in conjunction with other data sets or as model input for calculation of total water discharge. It can also be used for monitoring river movement during flood events and in disaster planning.

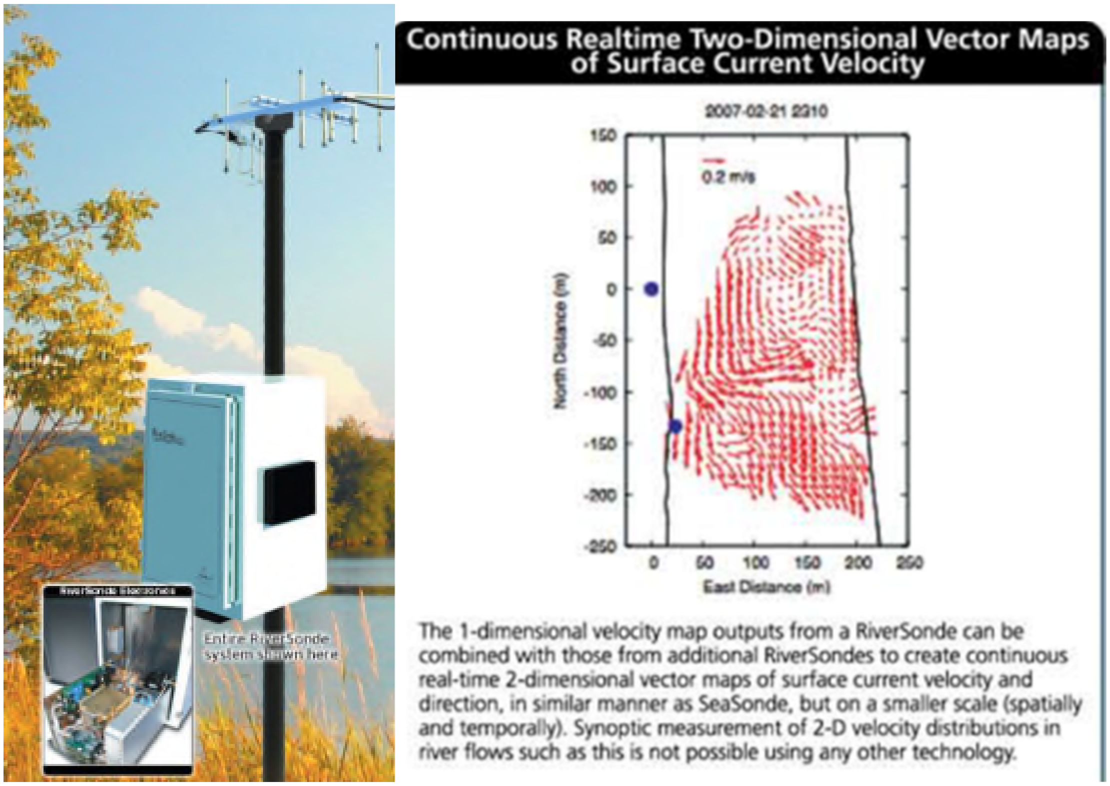

Figure B-9

This system is designed for operation at river's edge, in populated or remote locations. Robust hardware and software allow automated operation and data processing, even under extreme weather and/or vessel traffic conditions when other in-situ devices routinely fail.

B.2.6.1 RIVERSONDE FEATURES:

- Convenient: Nothing in the water: a truly non-contact sensor. All hardware is located on land close to river's edge.
- Reliable: All system hardware and software are developed by our own staff specifically for continuous, long-term field operations, and consistent data outputs.
- Remote Access: Data retrieval, system monitoring, parameter modifications and even factory support are all conducted through remote system access. (Communication link required)
- Low Power: RiverSondes low power consumption allow for working off-the-grid with alternative energy sources.
- Cross-Platform Data Format: All data products are stored as ASCII files for convenient data transfer to various computer platforms.

The manufacturer’s specifications for this instrument are included below

Advancement of Salinity and Flow Monitoring in the San Francisco Bay Delta

San Francisco Bay Delta Action Plan Implementation Support

APPENDIX C:
Deployment Equipment Options

C. DEPLOYMENT EQUIPMENT OPTIONS

C.1 PLATFORM & DEPLOYMENT METHOD

C.1.1 NAVIGATION OR MONITORING STATION PILINGS

Figure C-1. Examples of Pier Mounted Monitoring Stations

C.1.2 DOCKS AND BRIDGE PIERS

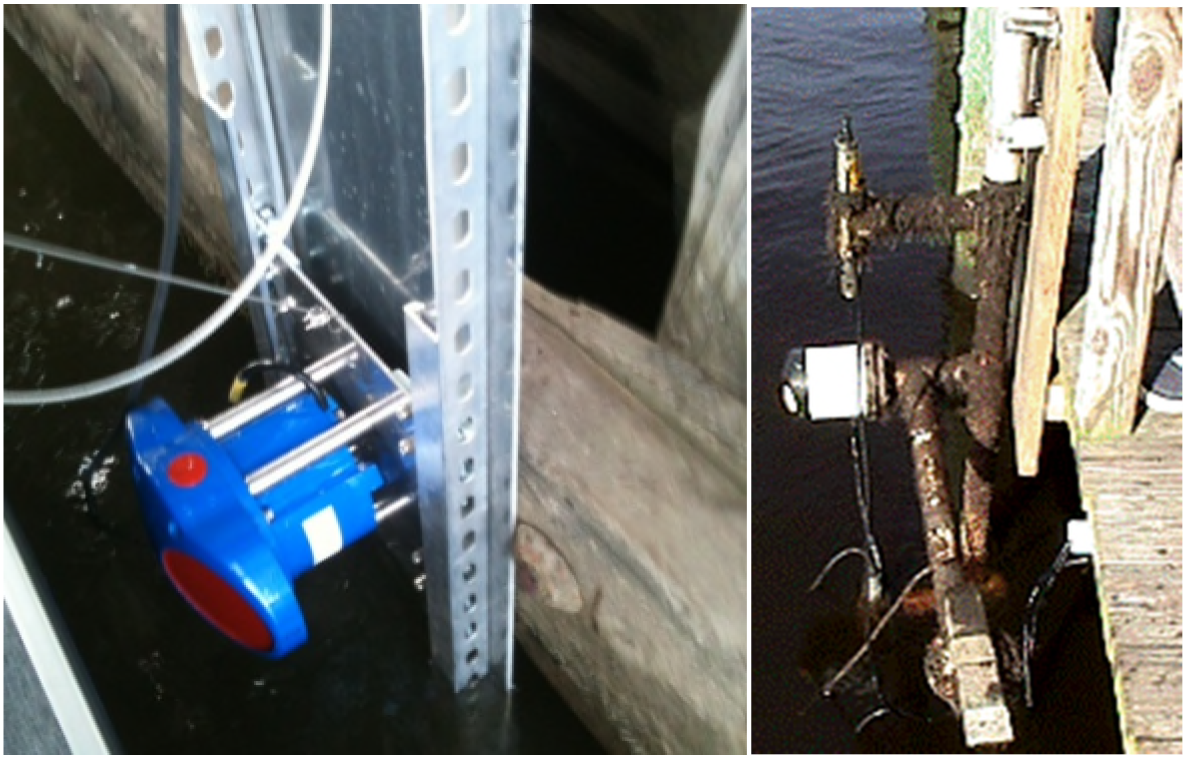

Figure C-2. TRDI and SonTek Side-Looking ADCPs mounted on movable pier mounts

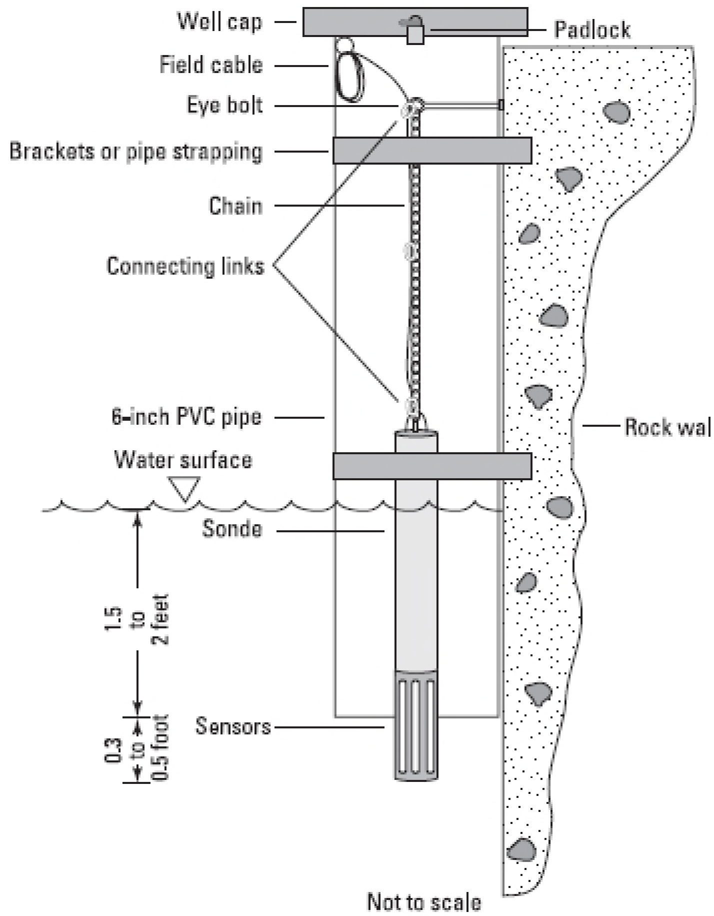

Figure C-3 Water Quality Instrument in a wall-mounted PVC pipe well

C.1.3 RIVERBANK MOUNT

Figure C-4

C.1.4 BOTTOM-MOUNTED MONITORING PLATFORM

Figure C-5. Trawl and Debris Resistant ADCP Platform with Acoustic Pop-up Buoy

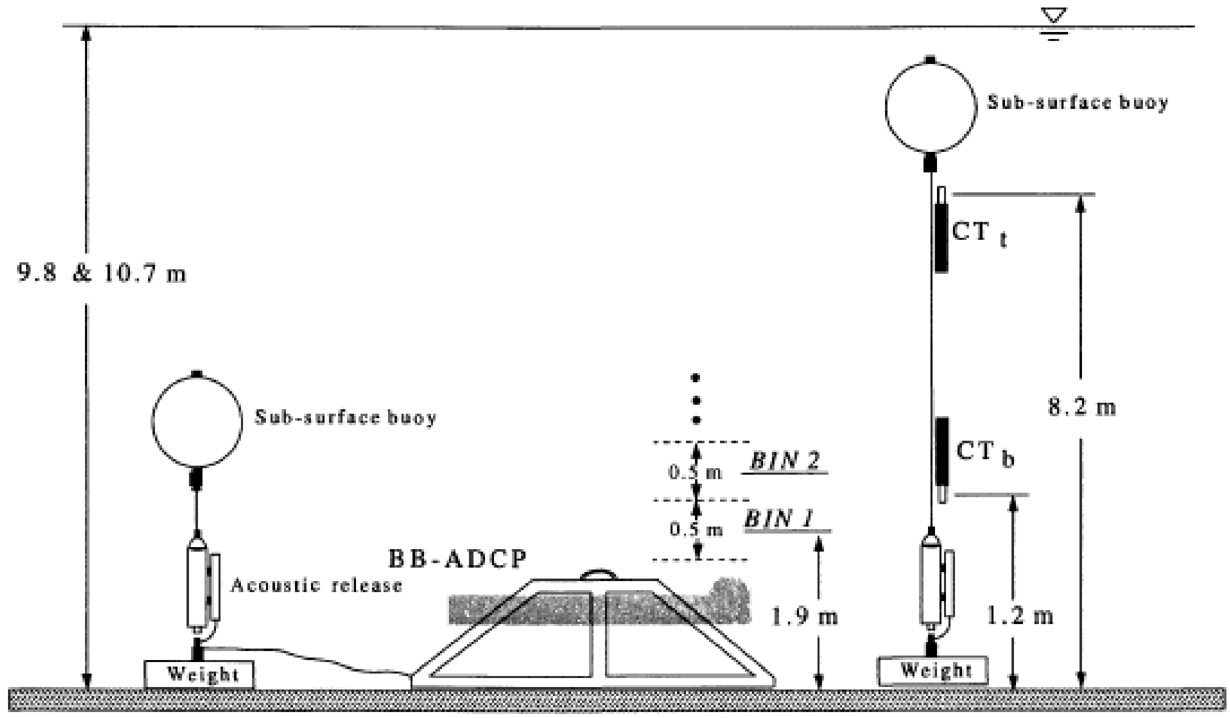

Figure C-6

C.1.5 MOORED BUOY MONITORING STATION

Buoy systems are available for various power, water depth, and onshore/offshore, lake conditions. Nexsens, YSI and Axys all make Data buoys with integrated solar panels, data telemetry and power management systems.

Figure C-7 YSI Pisces High-Velocity River Current Buoy

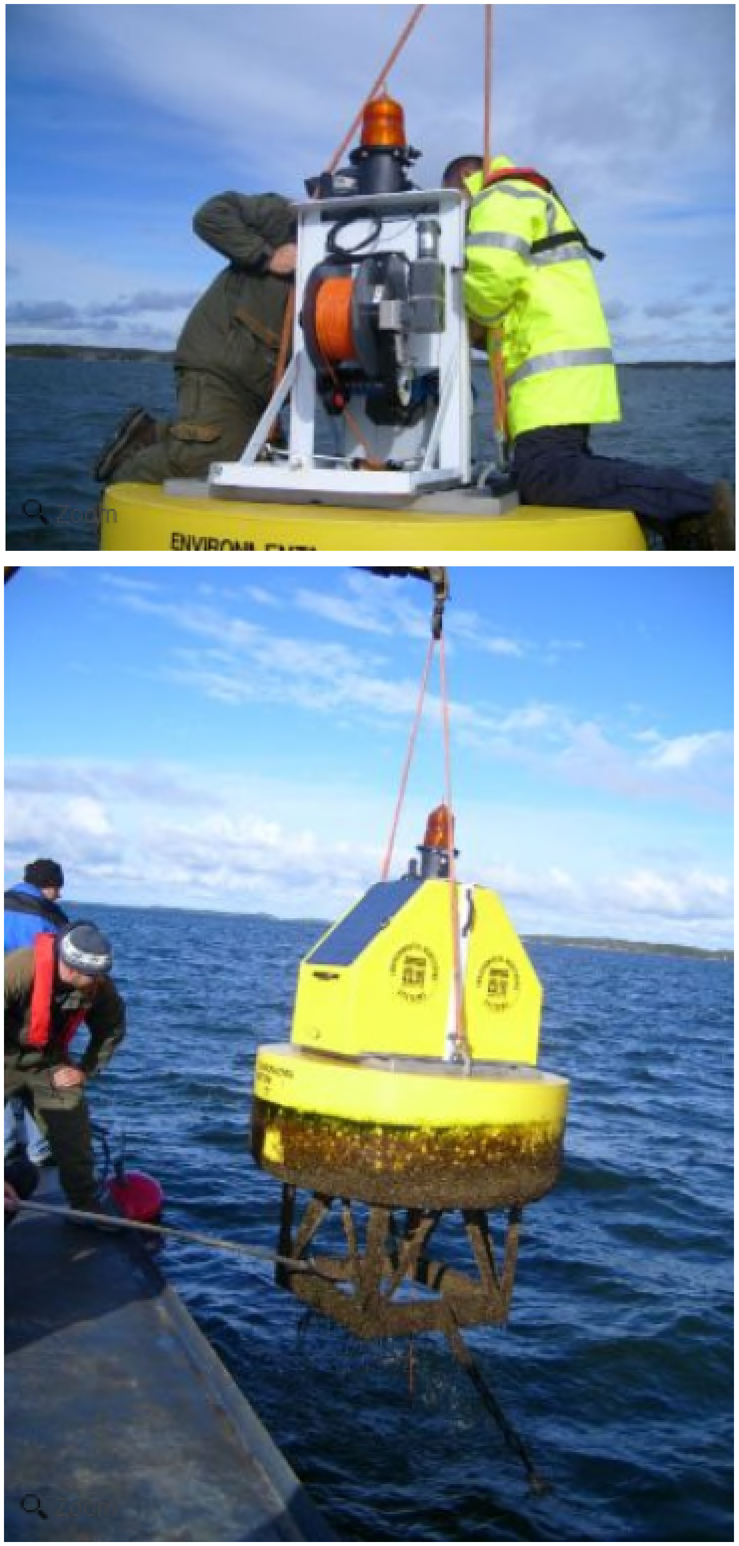

Figure C-8 YSI Buoy Vertical Profiling System

C.1.5.1 FLOW-THROUGH WATER QUALITY MONITORING STATION

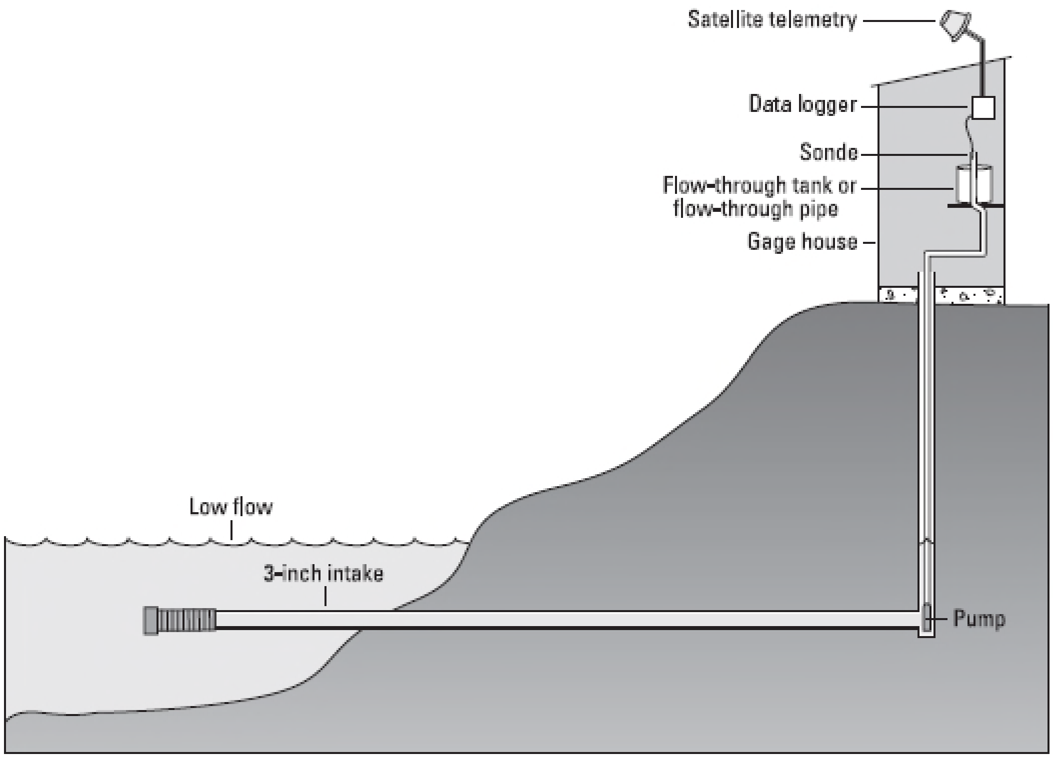

Figure C-9 Flow-Through Water Quality Monitoring Station

Table C-1
New Developments in Water Quality Sensor Deployment Methods

New Technology	Benefit	Developer
Fixed or buoy-mounted autonomous vertical profiling systems	Mechanically raise and lower CTD sensors to measure the entire water column	YSI McClane
Integrated or add-on inductive cable modems	Allow internally powered and logging sensors to communicate with the surface over the mechanical mooring cable w/o the need for an electrical power/communications cable	RBR Seabird
Add-on inductive cable modems for any Serial Sonde	Allow internally powered and logging sensors to communicate with the surface over the mechanical mooring cable w/o the need for an electrical power/communications cable	Sound9 Systems
Small, handheld CTD	Specifications are similar to standard scientific CTD but are smaller and less expensive (~$5500)	YSI Castaway
Integrated Systems	Integrated power, telemetry, instrumentation systems on pre-fabricated buoys with solar panels, batteries, radio or cellular near-real-time Internet web data display software	YSI NexSens AXYS

C.1.6 MECHANICAL PROFILERS

Mechanical profiling systems have the advantage of obtaining a complete vertical profile of the water column, enabling EC or salinity or volume to be extrapolated, and minimize some of the potential complications with having to have a cabled-bottom mounted sensor that is subject to damage.

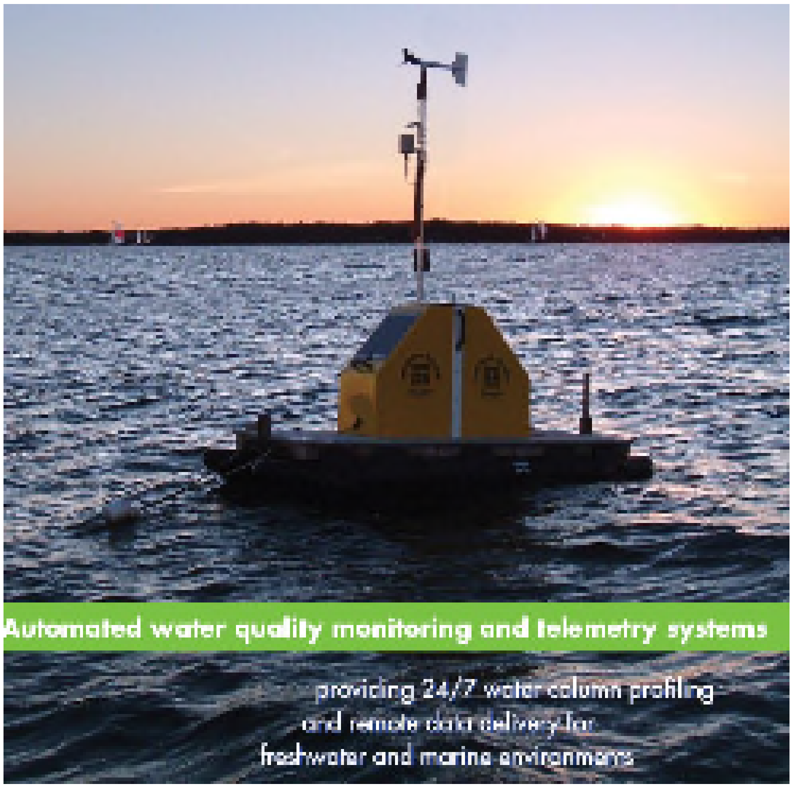

Figure C-10 Buoy and Dock Mounted Mechanical Profilers

Piling Mounted Vertical Profiler system with Solar Panels $30,000

Pontoon - Vertical Profiling System 100m profiler $75,000.00

Buoy - Vertical Profiling System $80,000.00

C.1.7 BUOY SYSTEMS

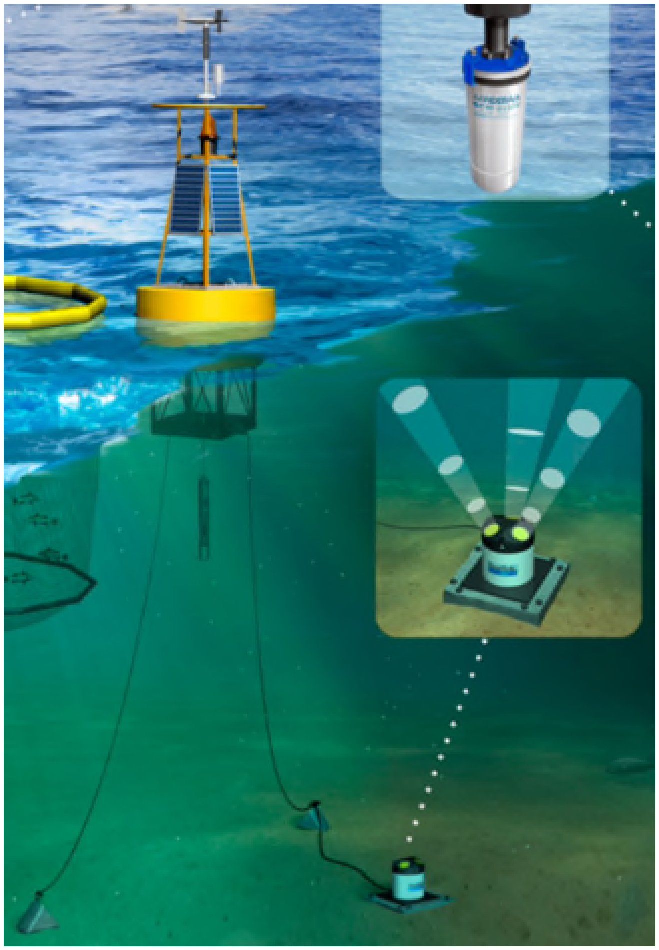

Figure C-11 Multipoint mooring buoy with CTD and up-looking ADCP

Vulnerability of a buoy to both vessel traffic and floating debris

Navigation issues with buoys: To ensure an Oceanographic Data Acquisition System ODAS buoy is compliant to IALA regulations, it has been fitted with a 3-mile visible LED navigation light displaying the Amber Gp Fl 4 (20) flash sequence and a Firdell Blipper radar reflector. Another advanced feature on a buoy that can increase awareness of this station to marine operators is the incorporation of an Automatic Identification System (AIS) transmitter. This device will transmit a unique platform ID along with buoy's GPS location and basic weather information. New shipping regulations are requiring vessels to receive this AIS data onto their navigation systems.

YSI EMM700 - Bay Buoy 2 Sondes at fixed levels $31,800.00

C.1.8 INDUCTIVE COMMUNICATION MODEMS

New technology. Allow internally powered and logging sensors to communicate with the surface over a plastic-jacketed mechanical (metallic) mooring cable without the need for an electrical power/communications cable.

An inductive modem could be used for real-time data transmission from a near-bottom sensor in locations where electro-mechanical cables would be damaged.

Figure C-12 RBR, SeaBird and SoundNine inductive cable modems

Seabird Underwater Inductive Modem Module (UIMM) is a quick way for system integrators and instrument/sensor manufacturers to adapt new or pre-existing RS-232 instruments, such as acoustic current meters, Doppler profilers, optical sensors, etc., for integration with real-time moorings using Sea-Bird's Inductive Modem (IM) telemetry.http://www.seabird.com/underwater-inductive-modem-module

The Soundnine Ulti-modem is an inductive modem with internal battery and integrated coupler. It connects any serial device to inductive telemetry, including CTDs, current meters and custom sensors. Innovative dual-mode communications allows both compatibility with inductive modem products from Sea-Bird Electronics and high speed communications (to 19200 baud) with modems from Soundnine. The plastic housing with titanium faceplate is rated to 1000 meters depth. Typical battery endurance is three years. http://www.soundnine.com/ultimodem

http://www.rbr-global.com/products/mooring-line-modem. RBR's inductive modem communication system, the MLM-1000, for XR and XRX series CTD (conductivity, temperature and depth) loggers (sonde, recorder), for the DBC2 and for OEM applications is designed to provide fast communication with loggers deployed up to a kilometre in depth. The modem uses an underwater transformer to transmit information through a jacketed mooring line without requiring cables or connectors. Essentially an unlimited number of instruments may be connected to the MLM-1000 and communication at 4800 baud is provided over an insulated mooring line of up to 1,000m length. Features include transparent link and automatic node discovery. CRC error detection is included. The MLM-1000 can drive RF, cellular, or satellite telemetry directly. The conductor loop is comprised of the steel core of a jacketed mooring cable and sea or fresh water. The ends of the steel cable are stripped of the insulating jacket and are thus in contact with the water. Between the stripped ends of the cable, the water provides a conduction path for electric current. Each system node typically uses a toroidal transformer that is clamped around the mooring line. The magnetic coupling between the toroid and the mooring cable is the medium by which information is transferred between the mooring cable and the particular system node.

Features

The ability to receive oceanographic measurement data from any one of a network of deployed RBR logger instruments in "near real-time".

The ability to alter sampling regimes for already deployed logger instruments, for example in response to changing marine environmental conditions.

The ability to gauge the status and functional health of deployed instruments.

The ability to download data from logger instrument memory while the instrument is deployed.

C.1.9 PUMPED FLOW-THROUGH CELLS

Flow through cells can be used with pumping systems to sample near-bottom water without having to have the sensor deployed at depth. They can help to greatly minimize cable damage and biofouling.

Figure C-13

C.1.10 IMPROVED WIPED CONDUCTIVITY SENSOR

599827 YSI EXO2 Wiped CT Sensor.