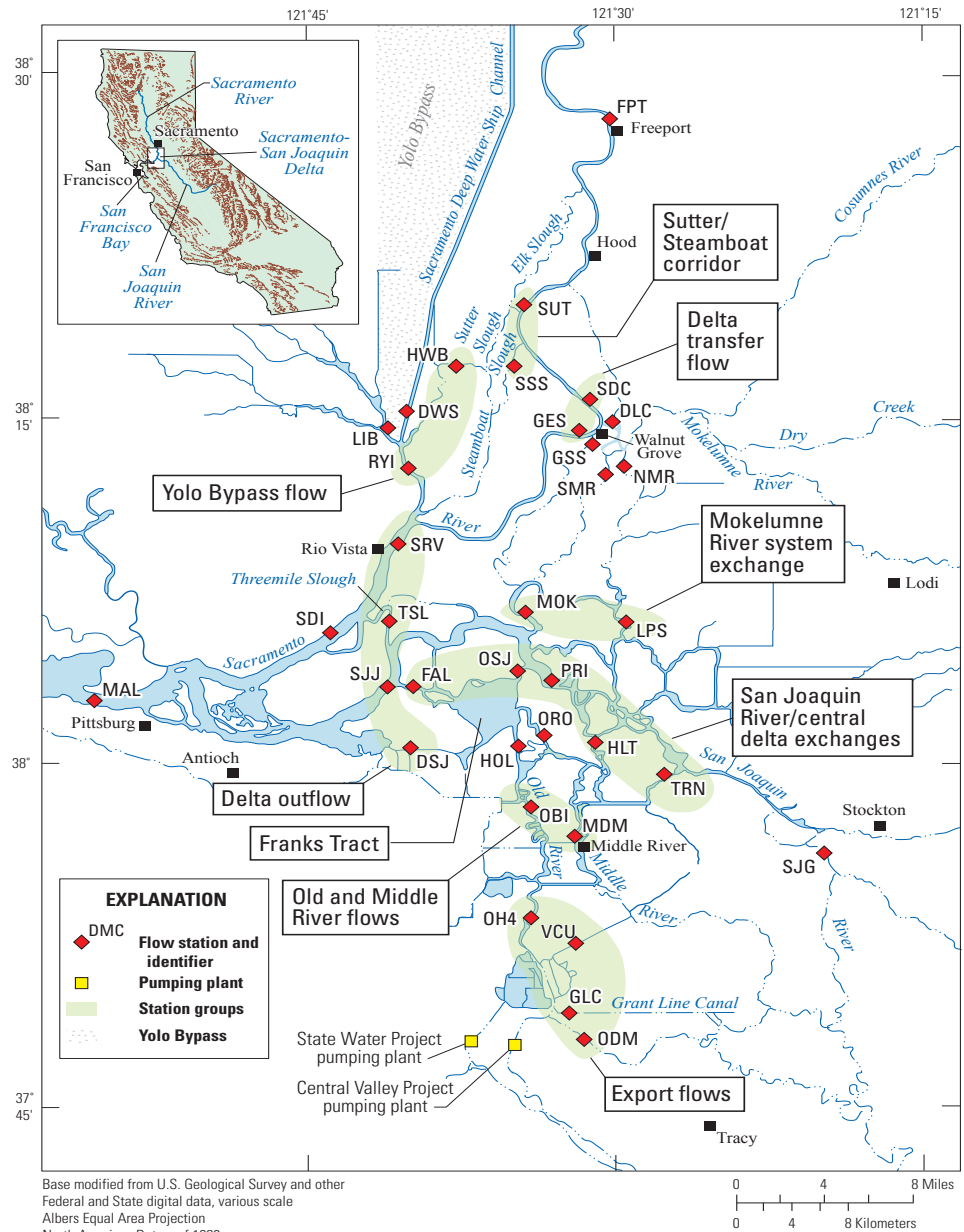


# Innovation in Monitoring: The U.S. Geological Survey Sacramento–San Joaquin River Delta, California, Flow-Station Network

The U.S. Geological Survey (USGS) installed the first gage to measure the flow of water into California’s Sacramento–San Joaquin River Delta (figs. 1, 2) from the Sacramento River in the late 1800s. Today, a network of 35 hydro-acoustic meters measure flow throughout the delta. This region is a critical part of California’s freshwater supply and conveyance system. With the data provided by this flow-station network—sampled every 15 minutes and updated to the web every hour—state and federal water managers make daily decisions about how much freshwater can be pumped for human use, at which locations, and when. Fish and wildlife scientists, working with water managers, also use this information to protect fish species affected by pumping and loss of habitat. The data are also used to help determine the success or failure of efforts to restore ecosystem processes in what has been called the “most managed and highly altered” watershed in the country.

Understanding flow would be less challenging if managers and scientists were only trying to measure the outflow of the watershed’s myriad rivers and streams into San Francisco Bay and the ocean. However, the delta also receives a large amount of seawater that exchanges with the Pacific Ocean; peak tidal flows of 1.7 million cubic feet per second are exchanged into and out of the estuary by the tides through the Golden Gate. Twice every day, tides surge into the delta, causing reversed flows as far upstream as Freeport, less than 15 miles downstream from the city of Sacramento, before ebbing back to the ocean. It is a challenge to measure the amount of fresh water flowing through the delta’s labyrinth of channels because it is so strongly influenced by tides. Yet in the last few decades, the USGS Bay–Delta hydrodynamics team has measured delta flows successfully (fig. 3) by pioneering techniques for improved measurements of tidal currents and freshwater inflows (Simpson and Oltmann, 1993; Simpson and Bland, 2000; Simpson, 2002; Ruhl and Simpson, 2005; Dinehart and Burau, 2005a, 2005b) to reflect real-time conditions in the delta more accurately.



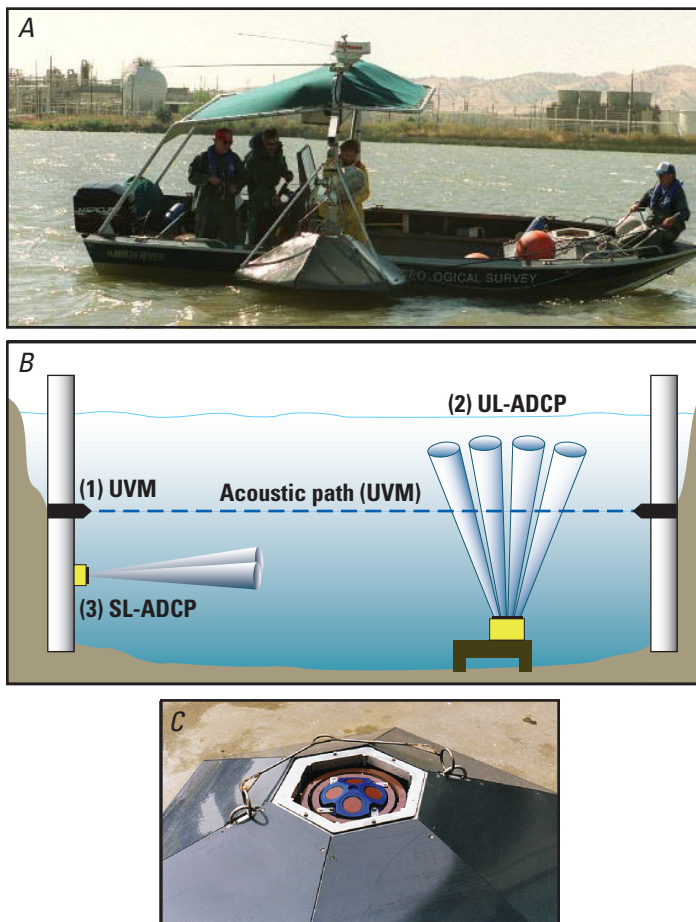
**Figure 1.** The Sacramento–San Joaquin River Delta showing the location of U.S. Geological Survey-operated sites.

The modern-day flow station employs technology similar to sonar, with hydro-acoustic devices (fig. 4) and other monitoring tools that are attached to pilings on the edges of delta channels. Measurements from these stations are telemetered to computers through cell-phone modems, which upload the data to the Internet within minutes (Sauer and Turnipseed, 2010). Many stations include sensors for measurement of components

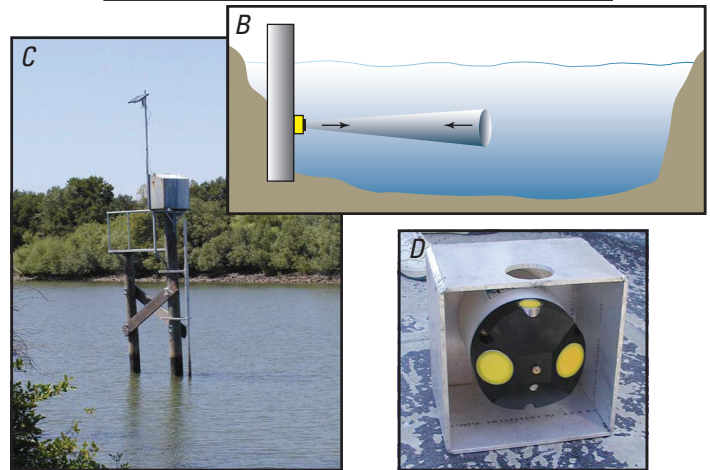
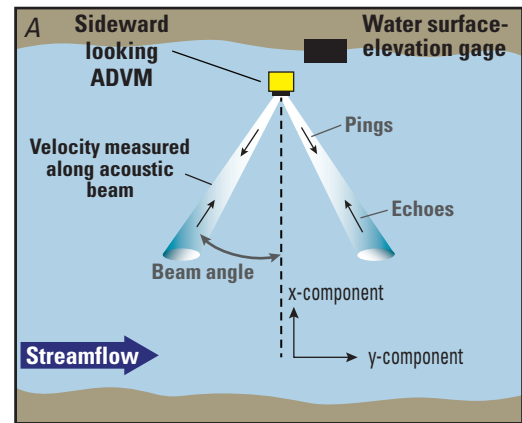


**Figure 2.** Aerial view of Sacramento–San Joaquin River Delta. Photo courtesy of California Department of Water Resources.

of water quality such as salinity, turbidity, contaminants, chlorophyll, and nutrients. By combining water-quality related data with hydrodynamic conditions—measured at the same time, place, and frequency—a more complete understanding of changes in the delta’s physical, chemical, and biological environment is emerging.



**Figure 3.** Suite of hydroacoustic instrumentation used to monitor flow in the flow-station network. *A*, Deployment of an upward-looking acoustic Doppler current profiler (UL-ADCP) from a small research vessel. *B*, Schematic of a river cross section showing three different hydroacoustic technologies that were used in the flow-station network: (1) an ultrasonic velocity meter (UVM, a time of travel device no longer in commission); (2) an UL-ADCP; (3) a sideward-looking acoustic Doppler current profiler (SL-ADCP), which is currently in use. *C*, An UL-ADCP in a trawl-resistant mount.



**Figure 4.** Typical modern-day flow-station configuration for a sideward-looking acoustic Doppler current profiler (SL-ADCP). *A*, Aerial view of river with a SL-ADCP affixed to a piling, such that acoustic beams project across the river. *B*, Cross section of a river channel with the SL-ADCP affixed to a piling, such that acoustic beams project across the channel. *C*, A typical flow station set above the water, with gage house and solar panel. *D*, An SL-ADCP.

The data generated by the delta flow-station network are available not only to water managers, regulators, and scientists, but also to the public, from the National Water Information System (NWIS; <http://waterdata.usgs.gov/nwis>), where real-time data and data that have gone through quality-assurance checks are both available, and from the California Data Exchange Center (CDEC; <http://cdec.water.ca.gov/>), which contains real-time data only. Indeed, with this sophisticated flow-station network, the effects of existing dams, canals, and other delta modifications on flow patterns and water quality can be assessed. The flow-station network is a foundation for understanding the Sacramento–San Joaquin River Delta water-management system because of the importance of flow on many ecosystem processes and aquatic resources.

### Measuring Net Flows in a Tidal Environment

The Sacramento–San Joaquin River Delta is a tidal system in which water, and the organisms and constituents in the water, are in constant motion. The water can move rapidly, more than 2 miles per hour, and travel long distances over each 12-hour flood-ebb tidal cycle. For example, a water parcel residing on Liberty Island (station LIB) at high tide can end up downstream from the Rio Vista Bridge (8–9 miles down estuary, station SRV) in 6 hours with an outgoing tide.



The density of flow stations in the network is necessitated, in part, by the dynamic nature of transport processes in the Sacramento–San Joaquin River Delta. Calculating net flows (freshwater discharge) by using measured tidal flows is a classic signal (net flows) to noise (periodic tidal flows) problem. Because the net flows are small and tidal flows large, calculating the net flow places rigorous demands on the accuracy of tidal-flow estimates and every aspect of the data-collection process.

For example, at the San Joaquin River at Jersey Point station (SJJ), the daily peak tidal flows can be on the order of 150,000 cubic feet per second (cfs), whereas the net flows can be 2,000 cfs or less. Thus, estimates of net flows require that the tidal flow data be accurate to better than 1 percent, a challenging requirement. Even a small bias, on a percentage basis, in either the flood or ebb tidal discharge estimates can result in erroneous calculations of net flow, possibly in the wrong direction.

## Network History

The flow-station network developed over time to address a series of specific questions. The first question, how much freshwater was flowing into the Sacramento–San Joaquin River Delta from the Sacramento River, was answered with the installation of the first hydro-acoustic meter at Freeport (Station FPT in [fig. 1](#); see [table 1](#) for NWIS station numbers) in 1978. A decade later, water managers and scientists wanted to quantify the influence of water-export facilities on the north-to-south movement of water from central to southern regions of the delta. In response, the USGS installed two more acoustic velocity meters at Old River (station OBI) by Bacon Island and at Middle River near Holt (HLT, 1987). In the early 1990s, the

USGS installed two stations in the Walnut Grove area, so water-project operators could find out how much water was flowing from the Sacramento River into the central delta through the Delta Cross Channel (DLC) and Georgiana Slough (GSS), the so-called delta transfer flow. Finally, a combination of four stations in the south delta, just upstream of the export pumps, was installed to estimate delta export flows (stations Old River near Byron, OH4; Victoria Canal, VCU; Great Line Canal, GLC; and Delta Mendota Canal, ODM). As of November 2015, the USGS operated 35 stations throughout the Sacramento–San Joaquin River Delta.

## Technological Advances

Until the 1970s, getting just a snapshot of the net flows required campaigns over 30-hour periods employing multiple boats, multiple current meters (Price AA<sup>1</sup>), and long tag lines stretched across wide channels. It was difficult to routinely collect a time series of the net flows, the type of data that managers now take for granted. Today, most of the flow stations employ sideward-looking acoustic Doppler current profilers (SL-ADCPs) attached to pilings or channel markers ([fig. 4](#)). Measurements of velocity, cross-sectional area, and stage are used to compute volumetric discharge (for example, cubic feet of water per second). In 2008, “robot boats,” unmanned vessels equipped with acoustic devices, were introduced. More recently, new systems have been set up that enable scientists to repair or reset stations remotely ([fig. 5](#)). Such improvements greatly reduce the costs of running the flow-station network.

<sup>1</sup>Use of trade names in this manuscript is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey.

**Table 1.** Delta flow-station network.

[Abbreviations: CDEC, California Data Exchange Center; NWIS, National Water Information System]

Name (CDEC abbreviation)	NWIS station number	Name (CDEC abbreviation)	NWIS station number
Sacramento River at Freeport CA (FPT)	11447650	San Joaquin River at Jersey Point (SJJ)	11337190
Sutter Slough at Courtland CA (SUT)	11447830	False River near Oakley CA (FAL)	11313440
Steamboat Slough near Walnut Grove CA (SSS)	11447850	Old River at Franks Tract near Terminous CA (OSJ)	11313452
Miner Slough at Hwy 84 bridge CA (HWB)	11455165	San Joaquin River at Prisoners Point near Terminous CA (PRI)	11313460
Sacramento River Deep Water Ship Channel near Rio Vista CA (DWS)	11455335	Middle River near Holt CA (HLT)	11312685
Cache Slough at south Liberty Island near Rio Vista CA (LIB)	11455315	Old River at Quimby Island near Bethel Island CA (ORQ)	11313434
Sacramento R at Delta Cross Channel CA (SDC)	11447890	Holland Cut near Bethel Island CA (HOL)	11313431
Delta Cross Channel near Walnut Grove CA (DLC)	11336600	Dutch Slough below Jersey Island Road at Jersey Island CA (DSJ)	11313433
Sacramento River below Georgiana Slough CA (GES)	11447905	Turner Cut near Holt CA (TRN)	11311300
Georgiana Slough near Sacramento River CA (GSS)	11447903	Old River near Bacon Island CA (OBI)	11313405
South Mokelumne River at New Hope bridge near Walnut Grove CA (SMR)	11336680	Middle River at Middle River CA (MDM)	11312676
North Mokelumne River near Walnut Grove CA (NMR)	11336685	San Joaquin River below Garwood bridge at Stockton CA (SJJ)	11304810
Mokelumne River at Andrus Island near Terminous CA (MOK)	11336930	Old River near Byron CA (OH4)	11313315
Little Potato Slough at Terminous CA (LPS)	11336790	Victoria Canal near Byron CA (VCU)	11312672
Cache Slough at Ryer Island CA (RYI)	11455350	Grant Line Canal near Tracy CA (GLC)	11313240
Sacramento River at Rio Vista CA (SRV)	11455420	Old River at Delta Mendota Canal CA (ODM)	11312968
Three Mile Slough near Rio Vista CA (TSL)	11337080	Sacramento River at Mallard Island CA (MAL)	11185185
Sacramento River at Decker Island near Rio Vista CA (SDI)	11455478		



**Figure 5.** Electronics inside a flow-station gage house.

## Station Groups

Scientists specifically selected the station locations to assess transport (the movement of water and everything in it) at a variety of spatial scales, from the individual channel to regional scales and to the Sacramento–San Joaquin River Delta as a whole. The stations are grouped, as shown in [figure 1](#), to calculate and verify localized inputs and outputs of water and localized storage. The eight groups are described here.

### Delta Outflow

The sum of the measured flows from stations at Rio Vista (SRV), Three Mile Slough (TSL), San Joaquin River at Jersey Point (SJJ), and Dutch Slough (DSJ) are used to estimate delta outflow. Delta outflow is a key ecosystem metric because it is a measure of water flowing into San Francisco Bay (that is, inputs less exports and consumptive use within the delta).

### Delta Transfer Flow

Delta transfer flow is the difference between the flows measured at stations in the Sacramento River upstream from the Delta Cross Channel (SDC) and the Sacramento River downstream from Georgiana Slough (GES). The calculation is used by water managers to estimate the amount of Sacramento River water that flows into the central delta through the Mokelumne system, including the Delta Cross Channel and Georgiana Slough. The water associated with the delta transfer flow is used by state (the State Water Project) and federal (Central Valley Project) water-project operators to meet salinity standards in the central delta. The delta transfer flow can now also be calculated by summing the flow in the Delta Cross Channel (DLC) and Georgiana Slough (GSS) directly.

### Old and Middle Rivers Flows

The sum of the flows at stations OBI and Middle River at Middle River (MDM), referred to by the regulatory agencies

as OMR (Old and Middle River flow), represents the flow of water toward the export facilities from the north. The data from these stations currently are used to adjust water management to comply with a variety of court decisions and biological opinions under the Endangered Species Act. The OMR flow parameter used for regulatory purposes is a 14-day average of the measured (tidal) flows.

### Sutter-Steamboat Corridor

Sutter and Steamboat Sloughs are important conveyance channels that carry half of the water that flows past the city of Sacramento at high water. Sutter Slough carries the bulk of the net flow; Steamboat Slough is more tidally dominated. The flows in both of these channels are strongly influenced by Sacramento River flows and Delta Cross Channel gate operations. Hydrodynamic data collected at Sutter (SUT) and Steamboat (SSS) Sloughs are also important for the study of salmon outmigration (Perry and others, 2013; Romine and others, 2013).

### Yolo Bypass

The flows entering the Sacramento-San Joaquin Delta from the Yolo Bypass are computed by subtracting the flow in Miner Slough (HWB) from the flow in Cache Slough (RYI). This computation also defines the tidal and net exchanges into the Liberty Island/Cache Slough region, an area slated for large restoration efforts. Moreover, this region is one of the few places where delta smelt are found year round (Sommer and Mejia, 2013).

### Mokelumne River System Exchange

Most of the Sacramento River water that is exported flows through the Mokelumne River system. When the Delta Cross Channel gates are open, this region is essentially riverine. Conversely, when the gates are closed, this system is primarily tidal. The data from the Mokelumne (MOK) and Little Potato Slough (LPS) stations also are relevant to salmon migration, because salmon outmigrants that take this route have lower survival (Perry and others, 2013), and are critical for monitoring the system's response to the proposed restoration of McCormack–Williamson Tract and Staten Island.

### San Joaquin River/Central Delta Exchanges

Exchanges of water from the San Joaquin River into the central delta are important for understanding how salinity and turbidity (from suspended sediments and organic matter) change in the system. The four stations used to calculate this exchange are Turner Cut (TRN), Middle River north of Mildred Island (HLT), Old River north of Frank's Tract near the confluence of the San Joaquin and Mokelumne Rivers (OSJ), and False River (FAL). These exchanges strongly influence the rate of entrainment of San Joaquin River salmon outmigrants into the central delta (Holbrook and others, 2008; Buchanan and others, 2013).

### Export Flows

The volume of water entering the federal and state export facilities from the various "feeder" channels is calculated by using data from the following stations: Old River at Highway 4 (OH4), Victoria Canal (VCU), Grant Line Canal (GLC), and Delta Mendota Canal (ODM).

## Uses of Network Data

Data from the network are used by scientists and by managers of the area who make decisions and plans for the future. The data are also used for calibration and validation of numerical computer models that can estimate water levels, flow speeds and discharges, and even the spatial and temporal evolution of salinity in the delta and San Francisco Bay (Resource Management Associates, 2005; MacWilliams and others, 2008; DSM2 User Group Portal, 2014). Measurements from the network are required input for models of this type.

In addition, the flow-station data, and the USGS California Water Science Center hydrodynamics team, have played an important role in numerous interdisciplinary investigations of subjects such as sediment transport processes, the behavior of the low-salinity zone in the delta, and the outmigration of Chinook salmon and the upmigration of delta smelt. The flow-station network was the foundation for the process-based, large-scale, adaptive-management experiments undertaken by the CALFED Science Program, and in the future, it could support the projects envisioned by the Delta Stewardship Council (the Delta Plan) and the Bay Delta Conservation Plan (BDCP). This network can provide the base-line data to help document the effects of proposed changes in conveyance (for example, the tunnels proposed as part of the Bay Delta Conservation Plan) and of restoration efforts in the future, for which the data collected now document baseline (pre-project) conditions.

## Uncertainty about New Facilities and Habitats

Decades of hydrodynamics monitoring, modeling, and special studies indicate that restoration or changes in water conveyance in one area can substantially affect basic hydrodynamic processes and transport in others. Many changes are proposed for the Sacramento–San Joaquin River Delta to meet the State’s goals of “providing a more reliable water supply for California and protecting, restoring, and enhancing the delta ecosystem” (Delta Stewardship Council, 2013). Documenting how these changes affect flows in the delta is important. The proposed flooding of Sherman Island, for example, could affect hydrodynamics and transport processes, including salinity intrusion, throughout the delta. Withdrawing water from the system into an isolated water-conveyance facility, such as the currently proposed twin tunnels, would also alter transport throughout the delta. If built, net flows throughout the north and western Sacramento–San Joaquin River Delta would be proportionately reduced by the amount withdrawn into the conveyance facility, increasing the influence of the tides throughout the delta. If the conveyance facility is built, the north-to-south draw of water across the delta that has existed for decades would likely be reduced as a result of compensatory reductions in pumping from the south delta, creating much longer average residence times. Longer residence times are associated with higher rates of algal growth, which could fuel eutrophication in some regions, including increased blooms of nuisance algae, such as *Microcystis*, which is toxic to humans and other organisms (Lehman and others, 2013). In the coming decades, the flow-station network can provide data that address uncertainty concerning the location of proposed water-conveyance facilities and that, after they are built, document the effects of these new

water-conveyance facilities, management actions, and habitat-restoration efforts.

## Climate Change and Endangered Species

The comprehensive coverage of the flow network provides valuable data for developing responses to any new endangered species listings and ecosystem changes, as well as to flooding, droughts, and hydrodynamic changes due to earthquakes, storms, and sea-level rise.

## Taking the Network to the Next Level

The dynamic nature of the delta system makes it very difficult to understand the transport and fate of constituents. Indeed, efforts are currently being made to add technology to existing flow stations that can measure and report in real time a broad suite of physical, optical, particle, and water-quality parameters. This multi-analytical approach allows for better integration of information across disciplines and for more powerful diagnostic tools. It allows scientists and water managers to continuously characterize parameters related to nutrient uptake, phytoplankton community structure, and zooplankton and fish-foraging efficiency at the same time as more common water-quality information (for example, dissolved oxygen, nutrients, and pH) in the context of the existing flow and turbidity monitoring network. When further coordinated with monitoring of biological organisms, such as fish, birds, and invasive species, these simultaneous data sets can also help scientists gain a better understanding of the influences of flows on the extent of estuarine and riparian habitats and on the distribution of species in the Sacramento–San Joaquin River Delta.

## Acknowledgements

The flow-station network would not have been possible were it not for the generous support, throughout the years, of a variety of agencies and individuals. Jerry Johns, during his tenure with the State Water Resources Control Board, provided the initial funding for the installation of the acoustic velocity meter (AVM) at Freeport and funded the installation and initial operation of ultrasonic velocity meters (UVMs) at Old and Middle Rivers. Randy Brown, with the California Department of Water Resources (DWR), and Ken Lentz, with the U.S. Bureau of Reclamation (USBR), provided much of the support for the development of acoustic technologies to measure tidal flows in the delta and supported the operation of the flow network. The Interagency Ecological Program (IEP) continues to support the flow-station network substantially, and we thank Ted Sommer, Karen Gehrts, and others for their ongoing support. The conveyance branch at the California Department of Water Resources (DWR) funded the installation, operation, and maintenance of 16 sites in the north and central delta for a period of 5 years under the auspices of the Franks Tract Project until bond funds were cut as a result of the State’s fiscal crisis. The USBR, through Erwin Van Nieuwenhuysse and others, took over support of these stations. Finally, support from the city of Stockton, Sacramento County and the Contra Costa Water District (CCWD) over the years is gratefully acknowledged.



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## USGS Data Repository

### (National Water Information System, NWIS)

<http://waterdata.usgs.gov/ca/nwis/>

### California Data Exchange Center (CDEC)

#### Delta flow stations

<http://www.cdec.water.ca.gov/>

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