

The Land/Ocean Biogeochemical Observatory: A robust networked mooring system for continuously monitoring complex biogeochemical cycles in estuaries

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Abstract

An ocean observatory that consists of an array of moored sensor platforms, telemetry, and data collection and dissemination software was designed for monitoring the biogeochemistry and physical dynamics of coastal and estuarine ecosystems. The Land-Ocean Biogeochemical Observatory (LOBO) consists of robust moorings that can withstand tidal currents and weather. The moorings are highly configurable, can be deployed in waters as shallow as 0.5 m, are relatively easy to maintain, and accommodate a complete array of standard and novel sensors. The sensors communicate with an on-board controller which relays data to shore in near-real time. Up to five LOBO moorings have been simultaneously deployed and maintained in Elkhorn Slough, California, since November 2003. Continuous hourly data of biological, chemical, and physical properties are relayed to shore, processed, and disseminated to users through a web interface in near-real time. This article describes the design, implementation, and functionality of the LOBO monitoring system.

Energy and material flow through the aquatic environment are controlled by linked, biogeochemical cycles in complex and often nonlinear processes. Understanding these complex processes requires continuous monitoring to avoid undersampling high frequency and episodic events that often dominate environmental variability (Johnson et al. 2007) and long-term monitoring because of long lag times between cause and effect (Magnuson 1990). For example, the hydrological cycle, ocean circulation, and nutrient cycles at the land/ocean interface all interact to control primary production. Human alteration of these cycles can create large impacts on many marine and estuarine ecosystems. However, the impacts are not simply proportional to the nutrient flux. Moderate nutrient inputs drive eutrophication and hypoxia in the Chesapeake Bay, whereas in San Francisco Bay anthropogenic inputs that create similar nutrient levels produce low levels of eutrophication (Cloern 2001).

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Environmental sensor networks are an important tool for monitoring these processes at the appropriate spatial and temporal scales (Glasgow et al. 2004; Porter et al. 2005; Byrne and Diamond 2006; Caffrey et al. 2007). There are numerous existing environmental sensor networks that provide observations of some elements of these processes (e.g., Effler et al. 2002; Herrington et al. 2002; Bernstein and Weisberg 2003; Cole et al. 2003; Malone 2003; Tedesco et al. 2003; Zappala and Azzaro 2004; Tercier-Waeber et al. 2005; Sigleo et al. 2005). However, there are few such networks that provide capabilities for monitoring the broad spectrum of linked biogeochemical processes. Here we describe the Land-Ocean Biogeochemical Observatory (LOBO), an environmental sensor network that is capable of continuous, long-term monitoring of the critical elements of the nitrogen cycle, the hydrological cycle, and associated ecosystem processes. This system provides capability for autonomous observations of key interactions that regulate primary production, eutrophication, and hypoxia in coastal environments.

Our goal was to develop a complete biogeochemical monitoring system that consisted of a network of moored platforms that were equipped with novel chemical, biological, and physical sensors with direct dissemination to the Internet and that implemented a set of software tools that allowed processes to be visualized across all nodes of the network. The integrated observing system was required to be robust, flexible, and reliable, yet simple and cost-effective. The prototype system was deployed and tested as a multi-node sensor network in

Table 1. Functional and system design requirements

Functional requirements	System design requirements
Numerous physical, chemical and biological parameters monitored at various locations and depths on an hourly basis	Platforms need to withstand: 1.5 ms ⁻¹ tidal currents, 0.5 m short-fetch waves, 2 m tides, 0.5 m minimum water depth
Construction, deployment and maintenance of whole system should be simple and affordable	Flexible subsurface instrument cage with midwater and benthic sensor nodes
All data autonomously sent back to shore and made web-accessible in near-real time	Deployable/recoverable from small boat with 500-kg capacity A-frame
Flexible configuration for use with different and/or new sensors	Easy to maintain from small boat
Robust and reliable in estuarine and coastal environments	Reliable 2-way radio link
Bio- and geofouling resistant	Autonomous and flexible data handling and server software
Tamper and damage resistant	Optional pumping system
Technology easily exportable	3 to 6 mo service cycle
	Maximum \$20K per platform without sensors

Elkhorn Slough located at the head of Monterey Bay along the Central California coast. The system is capable of operation in a variety of estuaries and protected coastal waters.

Materials and procedures

The observing system consists of two versions of moorings, a suite of standard and novel in situ sensors, and two-way wireless communications. Software controls data collection, archiving, quality control, and dissemination via the Internet. A network of five moorings located within various environments within Elkhorn Slough has been deployed and tested since November 2003.

The mooring system was designed to fulfill criteria that include (a) holding a suite of physical, chemical, and bio-optical sensors just below the surface and, optionally, at deeper depths; (b) the ability to withstand environmental forces such as currents, waves, and fouling for sustained (~1 y) periods in typical estuaries and relatively sheltered coastal environments; (c) collection of real-time data from the sensors and relaying those values to shore; and (d) the ability to be robust, yet easy to maintain, using small boats. A list of functional and system design requirements are shown in Table 1. The design criteria resulted in two configurations of the mooring, which have either vertically or horizontally oriented instrument cages. The two moorings were designed to be deployed in waters as shallow as 3 and 0.5 m, respectively (Fig. 1 and 2). The moorings consist of foam flotation, a configurable subsurface sensor cage, a stiff tether, and anchor. Electrical cables are mated to the tether to allow connections to sensors mounted on the tether or anchor.

Vertical mooring design—For waters with depths greater than a few meters, a mooring with a primarily vertical orientation was designed to maximize instrument payload. The mooring float was limited to a diameter of 90 cm to ensure that it could be turned on its side and serviced by personnel in a small boat (typically a ~5 m Boston Whaler). This allowed direct access to all instruments for routine service without using a larger boat to lift the mooring or putting divers in the water.

Static calculations of the mooring loads were made with Buoy Version 2.43 (Specialty Devices, Inc.). The calculations

modeled drag and tension, which allowed the required flotation and anchor weight to be determined. Worst-case conditions used for modeling the mooring loads were 1.5 m s⁻¹ currents (~3 kt) and 0.5 m wave heights in waters less than 10 m depth. Model loads are shown in Table 2.

The vertical mooring frame (Fig. 1) is constructed from aluminum (6061 T6) and polyvinylchloride (PVC). An Al tube of 8 cm outside diameter (OD) with a 13 mm wall thickness runs down the center of the float and subsurface instrument cage. Two 46 cm diameter by 16 mm thick Al plates welded to the

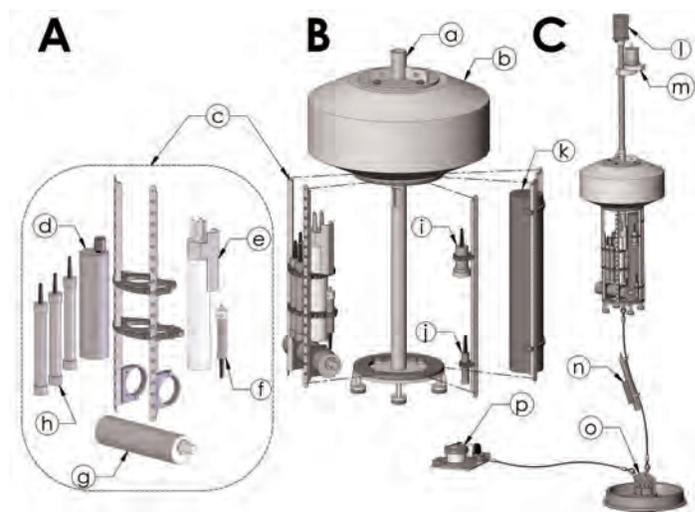


Fig. 1. The vertical mooring consists of several instrument pies (A) that are installed on the surface float (B) and deployed as complete mooring (C). The mooring frame (a) and float (b) are equipped with various “pie sections.” The standard pie (c) holds the LOBO mooring controller (d), a Seabird CTD (e) and pump (f), the ISUS nitrate sensor (g), and three battery packs (h) that power the controller, CTD and ISUS. A separate strut holds a WETlabs fluorometer (i) and an Aanderaa optode (j). A pumped chemical analyzer is also shown (k). A fully equipped mooring also includes a network radio (L), light and TrimTrac locator (m), a secondary CTD usually deployed at ~3 m (n), and anchor with SBE 50 pressure sensor (o). Several moorings are deployed with an attached ADCP (p). This configuration is designed for minimum water depths of ~2 m.

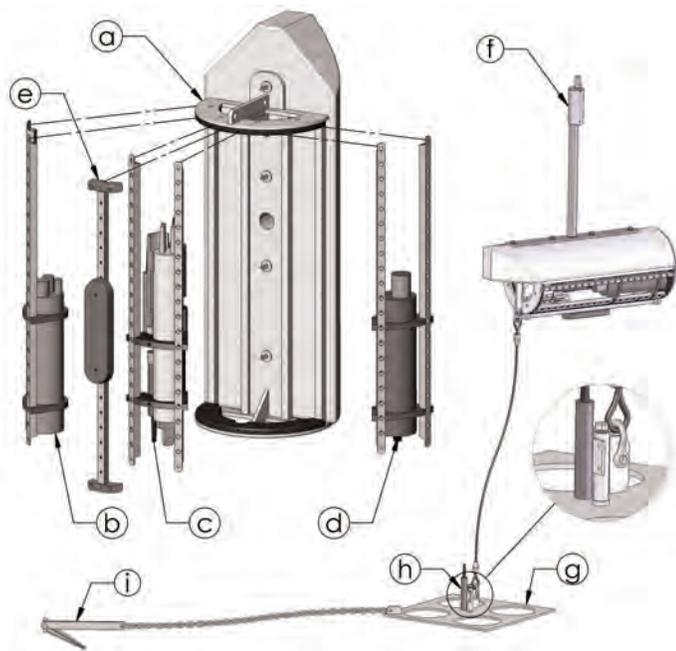


Fig. 2. The horizontal mooring uses the same pie configurations as the vertical mooring but is designed for minimum water depths of 50 cm. The mooring frame and float (a) are equipped with a LOBO mooring controller (b), Seabird pumped CTD (c), ISUS nitrate sensor (d), and lead ballast as needed for stability (e). Not shown are the fluorometer, optode, battery packs, electrical cables and tubing. A mast and network radio (f), plate anchor (g), SBE 50 depth sensor (h), and secondary claw anchor (i) are added for deployment. The inset shows the swivel mounting on the anchor plate.

central tube bracket the instrument cage. A 6-cm OD tubing with wall thickness of 5 mm is inserted into the central mooring tube and serves as mast for the network radio and light. Removing the mast allows upright assembly of major components and sensors under standard ceiling heights. All screws (316 stainless steel) are electrically isolated from the Al frame and screw into nonmetallic materials to minimize corrosion. A zinc anode (Harbor Island Supply, ZOI-4) is added to the bottom of the frame to further protect against corrosion.

Components above water are minimized to avoid potential vandalism. The only surface exposure above the float is the mast with the radio housing and optional combination light and tracking device. The network radio is connected to the subsurface mooring controller by a cable running down the center of the mast and mooring tube. Weather sensors were not included because the data are often redundant with data available from other nearby sources. All above-water screws are of a tamper-resistant design to minimize opportunities for vandalism. An electrical connector in the bottom of the radio housing allows a computer to be directly connected to the mooring controller for configuration and direct instrument access.

Buoyancy is supplied by a Softlite ionomer foam float (Gilman Corp.). The float is held in place between the upper welded plate and a top plate with four bolts. The top plate is

Table 2. Model calculation results for the standard and shallow moorings

	Vertical mooring	Horizontal mooring	Units
Drag			
Mooring scope*	1.5:1	2:1	—
Estuaries; calm			
Current	0.5	0.5	m s ⁻¹
Wave height	0.1	0.1	m
Water depth	8	3	m
Cable tension	22	10	kg
Reserve flotation†	170	70	kg
Min anchor weight‡	22	8	kg
Estuaries; stormy			
Current	1.5	1.0	m s ⁻¹
Wave height	0.5	0.25	m
Water depth	8	3	m
Cable tension	194	28	kg
Reserve flotation ²	52	60	kg
Min anchor weight [§]	228	26	kg
Protected coastal waters			
Current	1.0		m s ⁻¹
Wave height	2		m
Water depth	20		m
Cable tension	205		kg
Reserve flotation†	20		kg
Min anchor weight‡	264		kg

*The mooring scope, as used here, is the ratio of the cable length to mean high water (MHW) water depth.

†The vertical and horizontal moorings have 236 and 94 kg flotation, respectively. The drag was estimated at 40 and 12 kg/(m/s)².

‡The anchor weight needed is assumed to be twice the upward component of the mooring cable tension.

fitted with several lifting eyes for deployment and recovery. The exposed edges of the 90 cm diameter by 46 cm high float are chamfered on both top and bottom to make it difficult for marine mammals to haul out on the float and to reduce current drag. The float supplies about 140 kg static buoyancy and 52 kg reserve buoyancy under the worst case conditions. A 12 kg lead rod, encased with a heavy-walled heat shrink tubing, is placed within the bottom of the mooring's central tube to stabilize the mooring in stronger currents and weather.

The subsurface instrument cage was designed to be as compact as possible to minimize drag and the required anchor weight, yet still fit the suite of sensors that is described below. PVC disks of 19 mm thickness are bolted to the inside surfaces of the top and bottom plates. These disks provide a noncorrosive material in which to bolt instrument mounting brackets. Instruments are mounted in appropriately sized "pie sections," which are easily installed onto the mooring. Each pie section has an outside radius of 23 cm and is sized as necessary in 15° increments. Each pie section can hold one or more instruments up to 1 m long, and consists of horizontal brackets (high den-

sity polyethylene or Delrin) that attach the instruments to one or two 25 mm square tube (3 mm wall thickness) aluminum instrument struts. The assembled pie sections are screwed into the PVC plates at the top and bottom of the instrument section. New sensors can easily be added by making appropriately sized pie sections. For instrument maintenance, any pie section can be removed for access to all sides of components.

The mooring cable is a 1-cm diameter torque-balanced polyethylene jacketed galvanized wire rope (3/8" 3 × 19 from Mooring Systems) with integrated eyes at both ends. The cable is connected without swivels and is stiff enough to prevent the mooring from freely rotating, so that an armored electrical cable (Gexol by AmerCable) can be attached and connect to sub-mooring instruments. Electrical cables are attached with spaced wraps of electrical tape and protected with helical polyethylene bundling wrap. Service loops in the electrical cables at both ends of the mooring cable reduce the risk of fatigue and failure.

The moorings are anchored with surplus railroad wheels with various weights ranging from about 200 to 350 kg depending on the expected conditions. These are fitted with a welded center retainer fitted with two shackles: one for the mooring cable and another for a deployment line. The center retainer also holds a pressure sensor to monitor tides. All galvanized shackles are electrically isolated from the aluminum mooring frame with Delrin shoulder washers. Stainless steel cotter pins are also isolated with heat shrink tubing and carefully fit onto the tightened shackles to avoid damaging the isolation.

The mooring controller, surface CTD (conductivity, temperature, and depth sensor package) and ISUS (In Situ Ultraviolet Spectrophotometer) nitrate sensor are powered by separate universal battery packs. The use of individual battery packs simplifies mooring maintenance and prevents the failure of one instrument prematurely bringing down the whole mooring. Watertight housings for the battery packs are constructed from ~4 cm (1.5" Sch-80) PVC pipe and contain a string of three lithium DD-cells in series supplying 30 Ah at 10.7 VDC (Electrochem BCX85DD). The battery packs are located on the outside pie sections to allow easy exchange without removing the instruments.

An electrically independent flashing light and tracking device was built by combining a solar powered marine light (Sealite, SL60) and GPS (Global Positioning System)/GSM cell phone tracking device (Trimble Trimtrac). The solar collector and battery within the light provides enough power for the light (night time only) and to text-message GPS fixes every 8 h. The Trimtrac is configured to periodically send SMS (Short Message Service) text messages that include the unit's ID number, date, time, and location. The messages are received by a shore-side GSM MODEM (Sony Ericsson) paired with a terminal server (Lantronix) that directs the incoming GPS data stream to a custom UNIX server application for processing and plotting. This optional add-on system is simply clamped onto the mast of the mooring, and gives users a confirmation of

proper location, any anchor dragging, and the size and position of the actual watch circle.

Shallow mooring design—The mooring described above extends about 1.5 m below the surface and can be deployed in waters as shallow as about 3 m. Many important processes, however, occur in the extended reaches of estuaries where waters are much shallower. Thus, a second design, using many of the same features, was developed for deployment in areas with depths as shallow as 0.5 m (Fig. 2).

The shallow mooring uses the same sensors, instrument pie sections, controller and network radio, but the pie sections are oriented horizontally within the upper 20 cm of the water column. Up to 180° of pie sections fit in the horizontal instrument area located under a half-cylinder of flotation.

The bow of the mooring is attached to a mooring cable similar to that used for the vertical mooring. Since the horizontal design has a lower drag and currents are usually not as strong in these areas, a lighter anchor can generally be used which also permits deployment from smaller boats. For areas with up to 1 m s⁻¹ currents (2 kt), a low-profile steel plate anchor with a central swiveling connection allows connecting bottom sensors mounted on the swivel (e.g., pressure sensor). A chain and claw (Danforth style) anchor is attached to one corner of the anchor plate to further reduce the needed weight of the anchor by resisting drag. The secondary anchor also eases recovery whereby grappling the chain can dislodge the plate anchor that may have settled into a muddy bottom over time. Minimizing anchor weight is important for deployments and recoveries made by hand from smaller boats.

Mooring controller and network radio—Each mooring is managed by a custom controller designed for this project (Fig. 3). The controller consists of an Onset Computer Co. Model TT8V2 datalogger augmented with a Persistor Instruments Model CF8V2 Compact FLASH adapter and a custom interface board that supports eight separate relay-isolated RS232/RS485 channels, a USB interface adapter, five switched power channels, and support circuitry. The TT8V2 datalogger was chosen for its low power performance (0.6-750 mW), small size, and its general reliability in existing oceanographic applications. A second circuit board supports the interface of the network radio (Cirronet WIT2410) to the controller and provides isolated power, RS232 and I2C communications. Isolation of the power and digital communication lines between the controller and the network radio, ~3 m apart, minimizes sensitivity loss in the radio due to conducted emissions. The network radio also includes a 2.4 GHz RF antenna that is connected to a custom 1/2 wave 1.5 mm thick copper ground plane. All components of the radio assembly, including the antenna, are housed within a 15 cm dia, 30 cm tall PVC housing with a wall thickness of ~6 mm. By locating the antenna inside the PVC radome, performance degradation and damage due to exposure are eliminated, and no appreciable loss in signal strength was observed. The network radio housing has external connection ports for both RS-232 and high-speed USB communications to

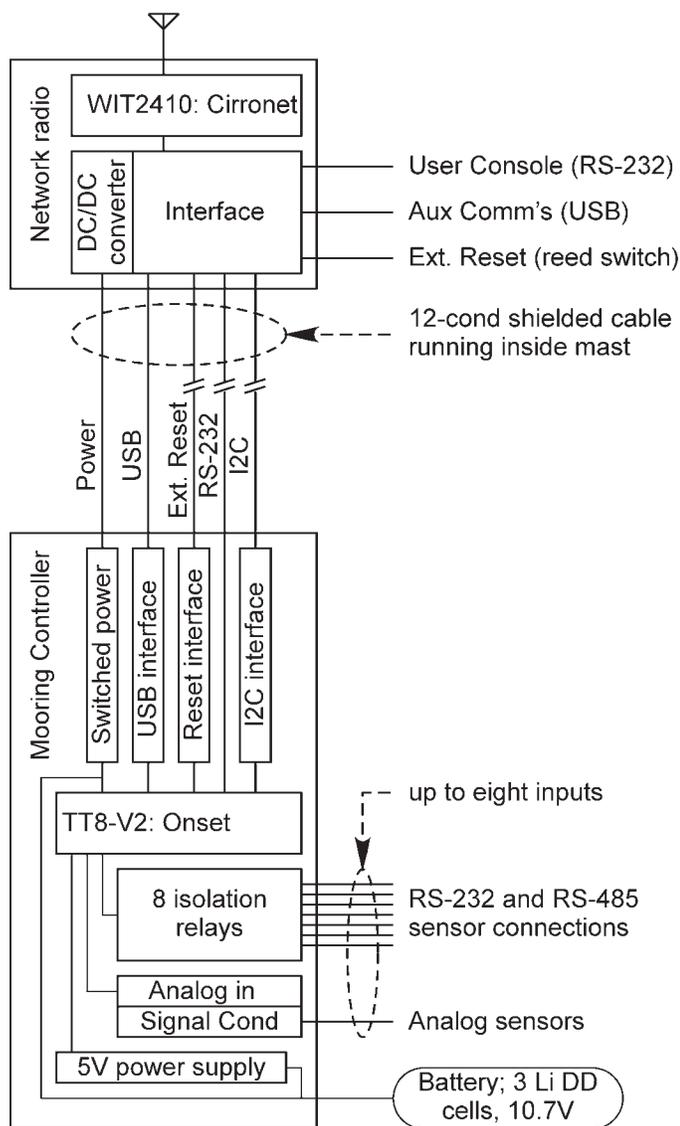


Fig. 3. Schematic of LOBO mooring controller and wireless network radio assembly.

the datalogger and a reed switch that can be magnetically activated to reset the controller in the event of a system malfunction. All data acquisition and control code was written in ANSI C (Manx C, v 5.2d) and native 68000 assembly language. An embedded implementation of the ZMODEM binary transfer protocol (Industrial ZMODEM) was licensed from Omen Technologies and was ported to run on the Onset TT8V2 datalogger. The total power consumption for the controller and network radio averages ~30 mW throughout a deployment. The controller can acquire, log, and telemeter the serial data streams from up to eight instruments for up to 6 mo on a single universal battery pack and has proven to be extremely reliable.

Telemetry system—The LOBO monitoring network uses a wireless Local Area Network (LAN) topology employing

Frequency Hopping Spread Spectrum (FHSS) radios within the 2.4 GHz ISM band to telemeter data from multiple moorings to shore. Wireless LAN employing Direct Sequence Spread Spectrum (DSSS) radios, such as the ubiquitous 802.11b, was not considered since its high bandwidth is unnecessary, and the inherent bandwidth loading would limit network capacity and reliability. The FHSS radios include low power operation (typically 200 mW), data transmission at relatively high speed (0.5 Mbaud over-the-air), multi-path and jamming immunity, and seamless network socket connection of remote radios to shore-side computers.

Each mooring controller acquires instrument data and transmits it to a shore-side UNIX server over a bridged wireless LAN link (Fig. 4). Controllers are programmed to transmit hourly. When powered, the mooring’s network radio (Cirronet WIT2410) and antenna (Antenex TRA24003P), located about 1.5 m above the water, establishes a connection with the access point (Cirronet SNAP2410) in one of the land-based Wireless Network Stations (WNSs) managing a particular coverage zone. Each coverage zone has a unique frequency hopping pattern and band to minimize interference. Upon receiving an incoming radio connection, the access point establishes a network socket connection over a wireless ethernet link to a UNIX server located at MBARI. Co-located ethernet bridges (Cirronet SEM 2410) provide the WNSs with ethernet access. The access point socket connection to the remote server is managed by a custom server application running out of the UNIX Internet daemon (INETD). The INETD server application decodes the incoming connection to identify its source and then performs a series of services that include updating the controller’s real-time clock, determining data transmission rates, and other system management functions. Finally, the controller transfers the logged instrument data to the server using the ZMODEM binary file transfer protocol that ensures absolute end-to-end integrity between the local and remote file systems. Data transmission reliability is ensured by the network radios’ built-in ARQ (automatic repeat-request) mode, which provides error correction at the link layer, and by the ZMODEM protocol, which provides application-level error correction. ZMODEM also features “crash recovery” that restarts an interrupted file transmission at the point at which transmission was dropped. Thus, if a file transmission is interrupted for any reason, the transmission will resume during the next download session. Onboard FLASH memory can store all logged instrument data for a full year.

Each WNS has a maximum 20-mile line-of-sight range, but the geographic layout, terrain, and distribution of moorings deployed in Elkhorn Slough required two WNSs and the base station at MBARI to provide adequate coverage to the entire network except L05 (Fig. 5). The radios for the two land-based WNSs are located within waterproof housings connected to antennas atop a 5-m retractable tower next to Elkhorn Slough and on the roof of a commercial building in the harbor. The WNSs are powered by standard line voltage which makes the units virtually maintenance-free.

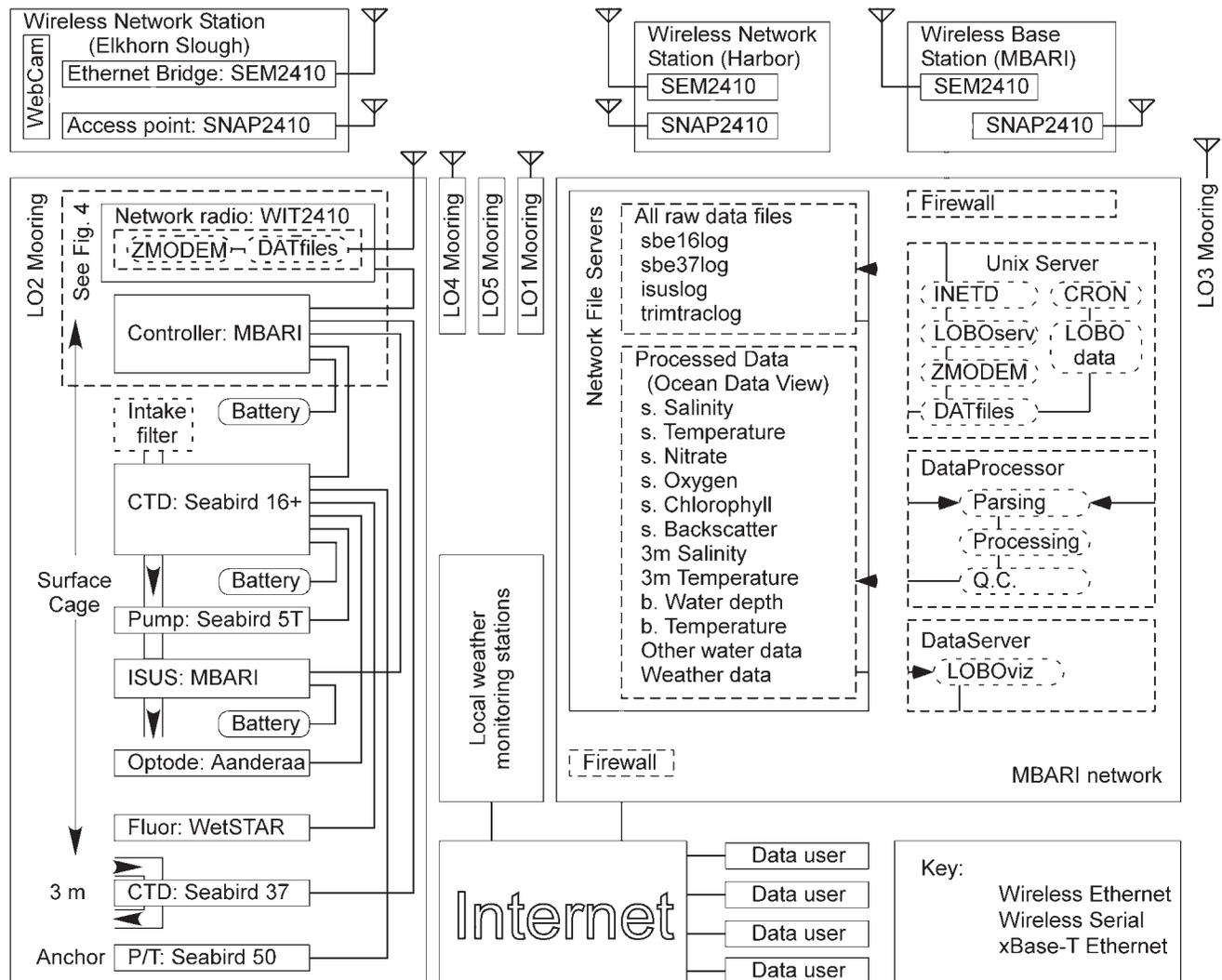


Fig. 4. Schematic of LOBO integrated monitoring system depicting the data streams from the sensor to the end user. The solid, dashed, and dotted lines represent hardwiring, wireless serial (to each mooring) and wireless Ethernet (backbone), respectively. Data files proceeded with an s or b indicates that the originating sensors were surface or benthic.

The wireless ethernet bridges form a seamless extension to the MBARI shore-side network and provide ethernet access to the field deployed access points, which in turn manage the mooring radios. Extending the MBARI network with wireless ethernet bridges also provides access to other ethernet-based equipment. Remote access to both a weather station and webcam are current examples. Rogue connectivity is eliminated since the LOBO wireless network is not peer-to-peer. Further network security is achieved using a multi-level authentication protocol between the Cirronet ethernet bridges and unique frequency hopping and ISM band settings.

Data processing and distribution—A data processing application, running on a UNIX server as a scheduled CRON task, parses the incoming mooring files and logs the data records into separate data files for each mooring instrument. Each log

file contains the native data as produced by each instrument with the addition of a pre-appended timestamp that indicates when the record was retrieved by the mooring controller. These files are stored on a network file server that supports multi-protocol file access.

To facilitate data analysis, a set of programs running under the Microsoft Windows operating system then operates once per hour to convert the raw sensor data for each network node to appropriate units. The converted data at each node is then appended to an Ocean Data View (Schlitzer 2000) compatible ASCII data file for that node. These merged files are used for all subsequent data visualization. The program *LOBOViz* (<http://www.mbari.org/lobo/loboviz.htm>) was developed to provide users a simple interface to the merged data files via the World Wide Web. *LOBOViz* is a compiled Visual Basic application

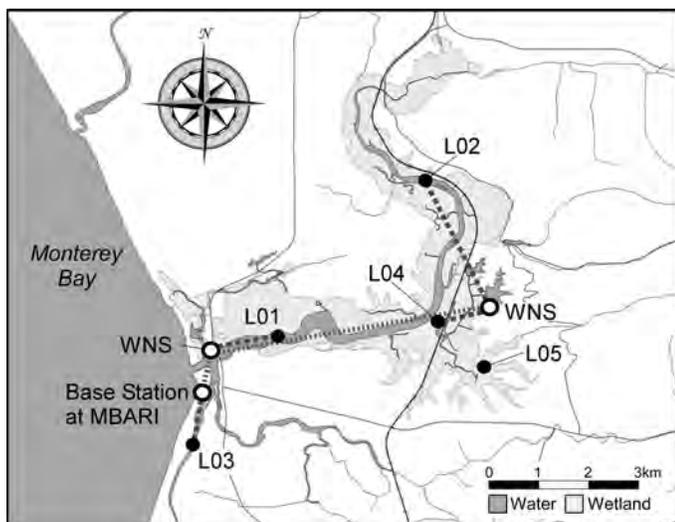


Fig. 5. Map of Elkhorn Slough showing five moorings (L01 to L05) and two wireless network stations (WNS). The dashed and dotted lines represent the wireless serial (to each mooring) and Ethernet (backbone) links, respectively. Data are collected, stored, processed, and distributed at MBARI. Local terrain prevented wireless communication with L05, and data were thus downloaded manually.

that uses the CGI (Common Gateway Interface) protocol to respond to requests made by the user on the *LOBOViz* web page for plots or ASCII text data. The system will typically return plots that may contain data from multiple years and several sensor nodes in approximately 10 s.

Sensors—The mooring array was developed to support physical, chemical, and biological sensors. To date, sensors installed in the subsurface instrument cage include the following:

CTD (modified Seabird16plus). This sensor monitors salinity, temperature, and pressure. Salinity is calculated from conductivity and temperature using the 1978 practical salinity scale equations (Perkin and Lewis 1980). The 16plus was modified by removing the batteries and replacing the stock pressure housing with a shortened Delrin housing with a connector for an external power supply. Power is supplied by one of the universal battery packs, which can be replaced without removing the CTD. Sample is pumped through the conductivity flowcell (Seabird, 5T pump).

ISUS Nitrate Sensor (MBARI/Satlantic). The ISUS sensor determines nitrate concentration by measuring the UV absorption and curve fitting the spectrum of the nitrate ion (Johnson and Coletti 2002). A wide range of nitrate concentrations are seen in Elkhorn Slough (< 1 to > 2000 $\mu\text{M NO}_3^-$), which requires a sensor with a large dynamic range. The lower limit of detection with the ISUS is near 1 μM in turbid waters. The upper limit of detection is greater than 10,000 μM if the spectral range used to determine nitrate is adjusted automatically to use wavelengths where the nitrate absorption is less than 1. At high nutrient concentrations ISUS is generally limited by turbidity (increased baseline and lower light throughput),

but the quality of the nitrate measurements are determined by the residual of the curve-fitting algorithm. Dissolved organic material absorbs over a wider range and to higher wavelengths than nitrate and may thus increase the residual at high concentrations. Generally, in high-turbidity/high-nutrient conditions, the proportion of stray light to signal increases, and ISUS will underestimate nitrate concentrations.

Fluorometer and backscatter (WETlabs, FLNTU). This sensor measures the 470/695 nm fluorescence and 700 nm backscatter to calculate chlorophyll concentrations and turbidity, respectively. The optical window was fitted with a copper shutter that opened prior to measurements.

Oxygen optode (Aanderaa, 3930). Similar to nitrate, oxygen concentrations within estuaries can vary widely (0 to 400 $\mu\text{M O}_2$). We have found the optode to be resistant to fouling as previously suggested (Tengberg et al. 2006) and to be extremely stable. Sensors were calibrated prior to deployment using the factory-suggested, two-point calibration. There was no noticeable drift in instrument accuracy before and after deployment.

Deeper sensors installed on most moorings include the following:

Secondary CTD (Seabird, 37). This self-contained pumped system is attached to the mooring line ~3 m below the surface to monitor stratification, especially during winter rains.

Pressure sensor (Seabird, 50). This sensor is installed directly on the anchor to accurately monitor the tides, and is connected to the surface CTD with an armored cable.

Acoustic Doppler Current Profiler, ADCP (R&D Instruments, Workhorse Sentinel). Currents are monitored near several moorings with a bottom-mounted ADCP. The units are mounted on their own anchoring platform, but are connected to the mooring anchor with a 20 m cable.

Several other instruments were also tested on the mooring, including a solenoid pumped wet-chemistry nitrate analyzer (YSI 9600), and a prototype analyzer for monitoring ammonia (Plant, pers. comm.).

Assessment

A network of five moorings, two remote wireless network stations and a base station were installed around Elkhorn Slough, a tidal estuary at the head of Monterey Bay, California (Fig. 5). Elkhorn Slough has a main channel that extends 11 km from the coast and has a 182 km² watershed (Caffrey et al 2002). The waters of the Slough are part of the Monterey Bay National Marine Sanctuary, and the Elkhorn Slough National Estuarine Research Reserve is located along its eastern boundary. Tidal currents reach most of the slough, and precipitation is usually limited to several months in the winter. Fresh water agricultural runoff may occur throughout the year.

The first mooring, L01, was deployed within the main channel of Elkhorn Slough in October 2003, followed by L02 and L03 in 2004, L04 in 2005, and L05 in 2006 (Fig. 6). L03 is located within the Salinas River Channel to monitor the river's nutrient input to the mouth of the slough. L05 was designed



Fig. 6. A vertical mooring, L02, being deployed with RV Sheila B.

as a portable mooring for short-term deployments to monitor various shallow connecting lagoons. Table 3 lists various mooring parameters. The wireless network began operation in May 2005, with a direct link between L03 and the base station at MBARI. The full installation of the two remote wireless network stations became functional in late 2005. The telemetry system has proven reliable in that all data prepared for relay to shore was successfully transmitted. About 93% of the hourly transmissions generated no error, and thus transmitted all data on the first attempt. All other transmissions were completed by the ZMODEM protocol during the following successful transmission. In many instances, these exceptions were caused by power loss on shore, servicing or other conditions not directly attributable to transmission failures.

The data handling functions were developed in advance of the telemetry system, and the web interface became publicly available in February 2005 using data that was recovered directly from the moorings and loaded manually. All data are available by selecting the "Real time data" menu the LOBO web page, <http://www.mbari.org/lobo>.

All moorings are equipped with CTD, nitrate, oxygen, fluorometer, backscatter, and a bottom-mounted depth sensor. The vertical moorings also have a secondary CTD at approximately 3 m below the surface. Samples are collected on an hourly basis, which permits reasonable battery life (~6 mo from most sensors) while obtaining enough resolution to accurately capture tidal and other temporally variable trends. Higher rates of data collection would be useful for better characterizing short-term events, but would significantly increase power demands. Adaptive or intelligent sampling, where sampling rates are increased only during specific events, would be a logical upgrade to the monitoring network, but has so far not been incorporated. Sensor performance is summarized in Table 4.

By December 2006 over a million scientific data points were recorded and are available within the *LOBOViz* web application. This does not include the many status values returned by all the instruments such as time stamps, battery voltage and current drain, internal housing conditions, and detailed spectral data that allow the continual monitoring of the state and health of the moorings and their sensors.

Mooring preparation and deployment—To significantly reduce biofouling on structural parts of the mooring, the underwater portion of the mooring frame, float and all instrument pies are painted with a peroxide-emitting, nonmetallic, antifouling paint (ePaint, type EP1). Many exposed instrument surfaces are covered with white polyethylene tape before painting to ease cleaning after recovery.

Instrument pies are configured for proper sensor orientation and sampling depth. The ISUS nitrate sensor, for example, prefers to be positioned horizontally to avoid collecting bubbles and sediment particles in the optical path. Routinely deployed sensors are sometimes combined into a single pie section to simplify connections or maintenance and to minimize space in the instrument section. The vertical moorings, for example, use a single 135° pie section that includes the mooring controller, CTD, pump, and ISUS. Clamps on the

Table 3. LOBO moorings deployed in Elkhorn Slough, CA

	L01	L02	L03	L04	L05	Units
Mooring style	Vertical	Vertical	Horizontal	Vertical	Horizontal	
Initially deployed	28 Oct 2003	15 Oct 2004	17 Sep 2004	30 Apr 2005	22 Aug 2006	
Location:						
Latitude	36°N + 48'45"	50'27"	47'32"	48'56"	48'27"	
Longitude	121°W + 46'29"	44'52"	47'22"	44'43"	44'17"	
Water depth*	9	4	3	5	3	m
Cable length	12	6	4	8	4	m
Expected max. current	1.5	1.0	1.0	1.5	0.5	ms ⁻¹
Anchor weight†	320	200	35	320	10	kg
Secondary CTD‡	at 3 m	at 1 m	None	at 2 m	None	

*Depth at mean high water (MHW). The tidal range at the mouth of Elkhorn Slough is approximately 2 m.

†The horizontal moorings also have a 4 m chain and 5 kg claw anchor (Danforth).

‡CTD clamped on mooring cable or lower frame (depth below surface at slack water).

Table 4. Sensor performance

Sensor	Depths [*]	Battery life [†]	Main limiting mode	Duration before cleaning [‡]	Overall duration [§]
Conductivity	s, 3m	6 m	Deplatinization of electrodes	12 m	12 m
Temperature	s, 3m, b	— [†]	none	—	12 m
Depth	s, 3m, b	— [†]	none	—	12 m
ISUS (NO ₃)	s	6 m	Biofilm on optics	3-8 w	12 m
Optode (O ₂)	s	— [†]	Biofouling on sensing film	2-8 w	12 m
Fluorometer (Chl)	s	— [†]	Biofilm on optics	4+ w	6 m
DigiScan (NO ₃)	s	1 m	Reagents, Cd column	—	1 m
DigiScan (NH ₄)	testing	3 m	Reagents	—	2 m
DigiScan (PO ₄)	testing	1 m	Reagents	-	1 m

^{*}Regularly mounted depths; s = surface cage, b = bottom anchor mounted.

[†]Using the universal battery pack described. A single battery pack powers the surface CTD, which also supplies power to the surface pump, optode, fluorometer, the 3-m pumped CTD and the bottom pressure/temperature sensor.

[‡]Sensor endurance between manual cleaning from boats (m = months, w = weeks).

[§]Sensor endurance between overhauls and recalibrations.

exterior section of pies hold the universal batteries for easy exchange without the need to remove the entire pie section.

In the often turbid waters of Elkhorn Slough, we have found that sensor endurance is significantly increased by integrating the ISUS and optode sensors into the CTD's pumped flow stream. We generally use heavy-walled Tygon tubing (~1 cm inside diameter) to connect (a) the intake, a coarse copper filter with ~1 mm holes to avoid sediment accumulation to (b) the CTD's conductivity cell to (c) the pump to (d) the PEEK™ flow-cell encasing the ISUS optical sensor to (e) the outflow positioned ~1 cm from the copper screen protecting the sensing surface in the optode. During each sampling period, the pump is on for 30 s at ~20 mL s⁻¹. This pumped sampling scheme significantly improves ISUS and optode endurance and response times and also ensures that all measurements are from the same depth. It is important, however, that the pumped flow path be as vertical as possible to avoid entrapment of sediment or bubbles.

The WETStar fluorometer and backscatter sensor is fitted with a modified copper shutter or "biowiper" and a 1-cm copper mesh shield. Shutters are 3-mm thick copper discs connected to the fluorometer wiper shaft either eccentrically, or concentrically with a single window on one side. Thus, the sequential 180 rotations of the wiper shaft expose the fluorometer window during readings, and keep it covered otherwise. Fouling is further reduced by the addition of a fixed copper plate that covers the remainder of the fluorometer's face. These modifications significantly increase the Cu coverage over the wiper supplied by WET Labs and are extensions of work by Chavez et al (2000) and Manov et al. (2004). The copper mesh shield prevents drifting fauna from collecting under, and jamming, the shutter. The 3-m CTD is fitted with two semicircular (~120°) copper tubes on the intake and outflow to prevent sediment from settling into the conductivity cell between readings.

Prior to deployment, all moorings are tested to ensure that all sensors, cabling, and telemetry are fully functional. The vertical moorings with railroad wheel anchors are deployed using the 10-m RV *Sheila B.* that is operated by Moss Landing Marine Laboratories. The *Sheila B.* is fitted with a bow-mounted A-frame and capstan capable of lifting a 300 kg anchor assembly (Fig. 6). The moorings are generally deployed before the anchor is lowered with a secondary line looped through a pear link on the anchor. Moorings are usually deployed at slack low tide to ease operations and navigation.

The horizontal moorings are towed to the site and deployed from shallow-bottomed boats. The anchors, either a steel plate or small mushroom anchor, are lowered by hand and set before the chain and claw anchor are stretched out and deployed in the upcurrent direction of the maximum expected flow.

Maintenance—Periodic maintenance is carried out using stable 5-m, shallow-bottomed boats (Boston Whaler). To access the instrument cage on vertical moorings, a mooring is tied off and tilted onto its side next to the boat. The mooring is then rotated as needed and fastened by securing a line around one of the feet on the mooring frame. The horizontal moorings are simply rolled over to access the instruments. A line is generally tied around the mast, routed under the mooring, pulled up and fastened, so that one side at a time is accessible.

Instruments mounted on the mooring cable, such as the secondary CTD, are also accessible during low slack tides. In the rare occasion that a bottom sensor failed, the instruments were serviced by divers.

Routine cleaning is carried out based on need (See Table 4, column 5). The standard cleaning procedure requires about 30 min per mooring plus travel time. At each mooring, (a) the pumped flow stream is soaked for ~1 min with ~50 mL of 10% HCl; (b) the optode is rinsed with 10% HCl; and (c) all optical surfaces on ISUS and the fluorometer are wiped and rinsed

with methanol, which is followed by (d) all sensors being rinsed with ample distilled water. Within Elkhorn Slough, this procedure is required on average every 3 weeks, although this interval can vary widely among the various locations and throughout the year.

The moorings are completely overhauled about once every 12 to 18 mo. An overhaul includes a complete cleaning of the system, including pressure washing; a complete disassembly and further cleaning of all pie sections and components; a complete check of all components for wear, corrosion (repairs if needed); in-lab calibration and operational checks of all sensors (CTDs are generally factory recalibrated); checking or replacing zinc anodes; repainting mooring, float, instrument pie sections, and sensors (antifouling paint); and reconfiguring pumped system with fresh copper fittings.

If the anchor, mooring cable and any bottom-mounted sensors are functioning well, the surface mooring can be exchanged without needing to raise the anchor. When a total recovery of a vertical mooring is necessary, a diver connects a line (or pulley system) to the second shackle or pear ring on the anchor, which is then raised by the A-frame and capstan onto the deck.

The horizontal moorings, generally deployed with light-weight anchors, are simply pulled up by the mooring cable. Moorings using plate anchors that have settled into the mud can be extricated by using a grapple to snag the chain going to the claw anchor, and pulling up on the chain to dislodge the plate.

Reliability and fouling—Maintaining system reliability involves continually monitoring the data streams and servicing the moorings as needed. The mooring hardware has proven to be sturdy and reliable. The flotation has shown to be sufficient, as the mooring has been observed in currents up to 1.2 m s^{-1} where over a third of the foam float remained above water. The anchors (see Table 3) have also not been observed to drag in these currents.

Corrosion is kept to a minimum by electrically isolating different metals and using a Zn anode on the bottom of the mooring frame. The stainless steel cotter pins in the galvanized shackles are isolated with heat shrink tubing. For most instruments, the universal battery packs are easily accessed and replaced without removing the instrument pies. The exception are the relatively high-power wet-chemical analyzers that are generally power- and reagent-limited to about a month with hourly sampling intervals.

Most of the maintenance effort goes toward resolving geo- and bio-fouling issues, where sensors need to be cleaned or replaced with periodic service trips. Over the past years, several procedures, such as the pumped sample stream, have minimized fouling and significantly reduced the service requirements.

Biofouling by algae and other organisms growing on the mooring can interfere with sensor performance. Seabird supplies the CTDs with two tri-butyl-tin soaked sleeves at each end of the conductivity cell, which supply satisfactory protection to the CTD between replacements with annual factory recalibrations. Fouling of the ISUS nitrate and optode oxygen

sensors has been significantly reduced by adding these sensors to the pumped flow stream. We found that adding Cu tubing to the flow stream can interfere with the ISUS spectra, however using the copper intake screen ~50 cm before ISUS, yields good data. At all moorings except L03, the ISUS light throughput degrades about 1% per day. This light reduction is lower at L03, which directly samples irrigation runoff. The irrigation channels are regularly treated with herbicides to keep the channels clear, which may be responsible for the reduced fouling.

During the hourly sampling, the pump is turned on long enough to completely flush all the sensors (~30 s). Although the CTD measures conductivity while the pump is on, more stable nitrate and oxygen measurements are observed immediately after flushing. The fluorometer has not been added to the flow stream because the volume of the required sample cell would be difficult to flush completely.

Fouling by larger drifting flora (e.g., *Ulva*) that becomes entangled with the mooring frame and instruments can inhibit mechanical operation of pumps and shutters due to physical blockage. This problem has been eliminated by installing copper-mesh shields around moving parts and ensuring that sample intakes cannot easily snag drifting seaweed. The rotating shutter on the WETstar fluorometer, for example, is protected by a 5-cm diameter mesh cylinder. Both the shutter and mesh cylinder are made of copper to reduce biofouling around the sampling volume.

Geofouling occurs when sediment suspended by tidal currents collects in sensors or the pumped flow stream. This problem is especially acute in estuaries with sediment-rich tidal flats and during heavy rains when fresh sediment is washed into the watershed. If not appropriately configured, these sediments can clog pumped systems, jam mechanical systems, and interfere with sensor readings. The fluorometer/backscatter sensor and protective tube are oriented downwards to avoid collecting debris on the optical window, whereas the source/receiver window and mirror in the cell on ISUS are oriented vertically for the same reason. The two semi-circular copper tubes on the 3-m CTD also prevent sediment from settling within the conductivity cell.

Copper has proven to be an excellent material to avoid biofouling within estuaries; however it needs to be kept electrically isolated from other metals and confined spaces near the ISUS probe. Copper sheets or tubes, drilled as needed, are more resistant to corrosion than screens due to the lower surface to volume ratio. For year-long deployments, a minimum dimension of about 3 mm is sufficient.

Overall, maintenance involves (a) overhauling moorings yearly, (b) replacing batteries every 6 mo, (c) cleaning optics approximately monthly, and (d) making occasional trips to correct other problems. All five moorings are currently visited with an average of one boat trip every 10 to 14 d, which includes work for testing experimental sensors.

Data handling—All data streams are monitored for quality on a regular basis. One of three quality control factors are

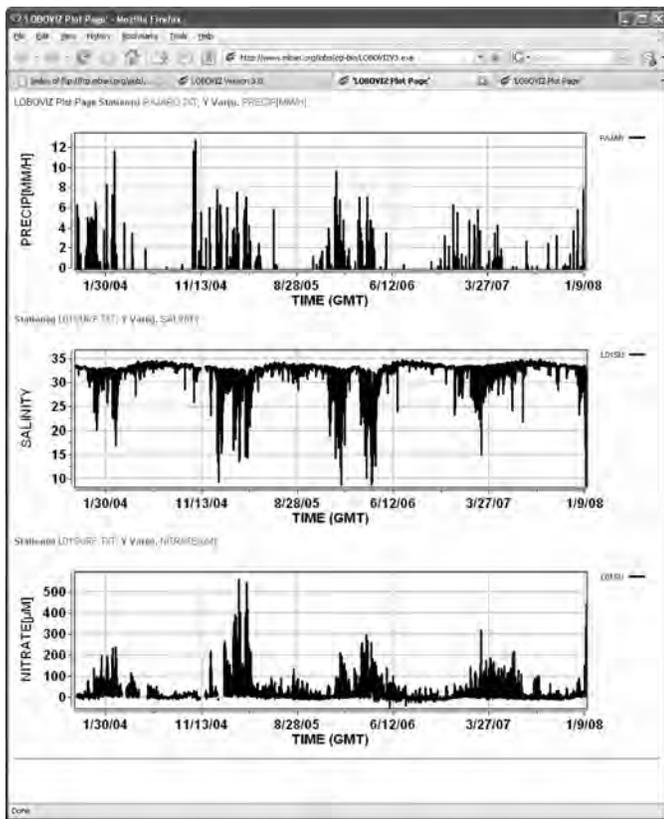


Fig. 7. The effects of rain on salinity and nitrate concentrations as observed over 4 y at the mooring in the main channel (L01). LOBOviz automatically incorporates precipitation data collected at a weather station nearby (Pajaro).

assigned to each data point based on the system used by Ocean Data View: 0 = “good,” 4 = “questionable,” and 8 = “bad.” The qualities of nitrate values are determined from the calculation of the RMS residual fit; where absorbance values of < 0.001, < 0.01, and > 0.01 determine which of the three factors are assigned. Physical observations are generally reliable enough to earn a “good,” whereas more difficult to analyze data from optical sensors are assigned “questionable.” The data are manually checked on a periodic basis, and obviously erroneous values, such as during mooring servicing and severe fouling, are downgraded to “bad.”

Since 2003, the availability of quality data has significantly increased. During the first year of deployment at L01, for example, there were several extended gaps in the nitrate data, but with the improved pumping system and telemetry, the data are now almost continuous. During 2004, 2005, and 2006, we observed an increase of “good” nitrate data from 85% to 95% to 97%.

Example data from Elkhorn Slough—Critical tests of the system include demonstration of the ability to monitor both long-term variations in coupled biogeochemical cycles and to demonstrate the capability to observe the flow of material through the environment at relatively high frequency. The

long-term records of salinity and nitrate values collected at L01 from Nov 2003 through Jan 2008 are shown in Fig. 7 along with the rate of rainfall at a nearby weather station in the CIMIS (California Irrigation Management Information System) network, whose data are also assimilated into LOBOviz. This data set clearly shows the coupling between the hydrological cycle and the nitrogen cycle. As shown in Fig. 7, the salinity record reflects the annual winter rain events in the resulting surface freshening. Associated with these rain events, the nitrate record shows significant nutrient input.

The data reveals events and processes that can only be observed with high temporal resolution data from a networked monitoring system. As an example, Fig. 8 shows nitrate, salinity, and tide data as monitored by three moorings along the main channel of Elkhorn Slough over a 3-d period in August 2005. This graphic was created by using the capabilities

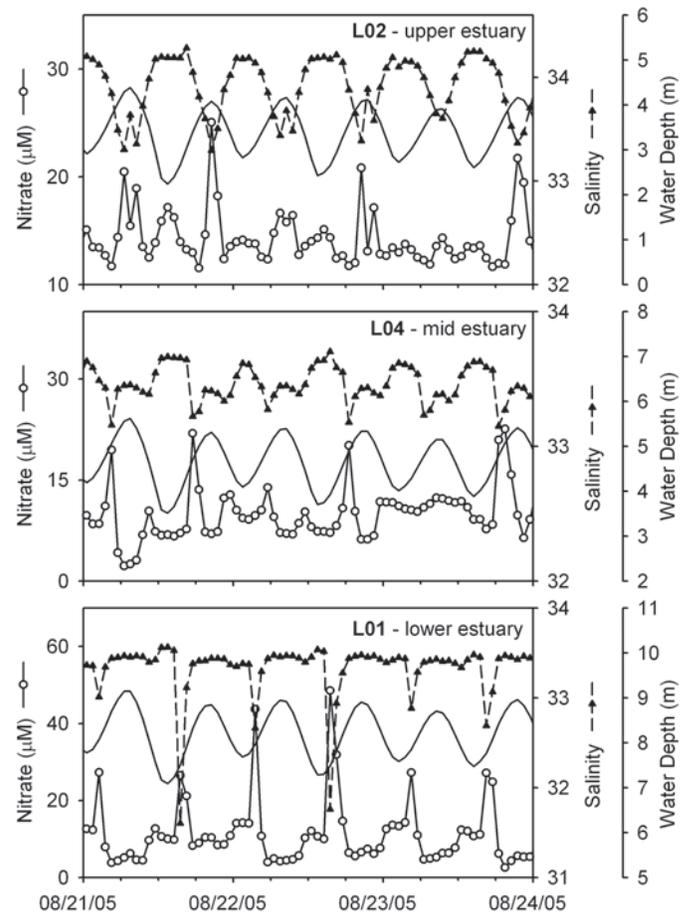


Fig. 8. High-resolution salinity, nitrate, and tide data collected at three moorings along the main channel. The data highlight the progression of trapped high-nitrate water parcels from the Salinas River being transported up the slough on rising tides past all three moorings along the main channel (L01, L04, and L02). The tides and chemical pulses travel up the slough at different speeds because they are carried by the pressure wave and water current, respectively. The tide data are derived from anchor-mounted pressure sensors.

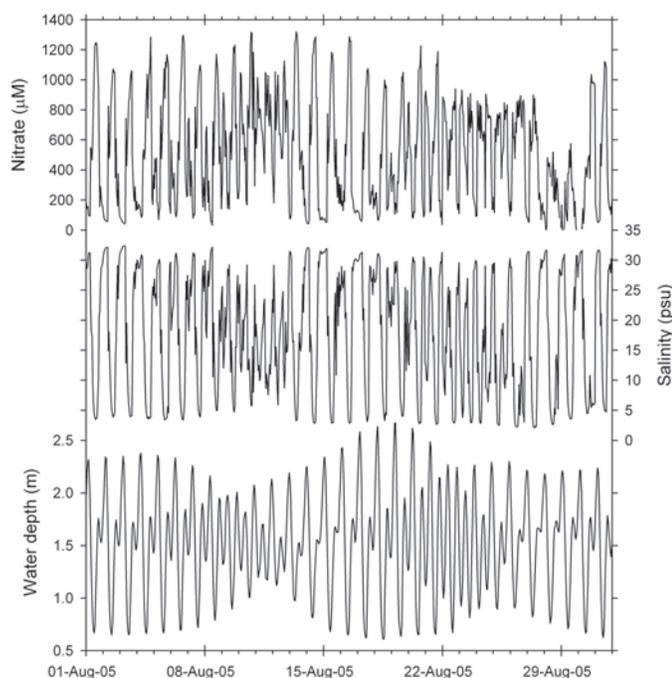


Fig. 9. Nitrate, salinity, and water depth observed at the L03 mooring during August 2005.

of *LOBOViz* to export numeric values to scientific graphics software for more detailed analysis. The data show that nitrate spikes and salinity drops seen in the lower estuary (L01) appear at the beginning of the rising tide. The nitrate values in these events are often higher than would be present in natural seawater, which has at most $45 \mu\text{M}$ nitrate. The high concentrations most likely come from the ebbing waters from the Salinas River Channel, which carries water with nitrate concentrations greater than $1000 \mu\text{M}$. These waters appear at the L03 mooring regularly at low tide as a low salinity, very high nitrate signal (Fig. 9). The salinity regularly approaches a value of 5 on each low tide, and this freshwater must represent irrigation water from farms in the lower Salinas Valley, as the summer months from May through September have no significant rainfall. This water reaches the mouth of the Harbor at low tide, and some of the fresh nitrate-rich river water is then entrained into the tidal flow that enters the slough as the tide rises. It is seen in both nitrate and salinity at the L01 mooring. *LOBOViz* was designed to allow properties to be compared at different locations in the network. The value of this feature can be seen by creating a plot of nitrate versus salinity at the L01 and L03 moorings (Fig. 10). The trend in the data at L03 is clearly seen at L01, although the amplitude is much lower. This parcel of water can be seen to bring nutrients all the way up the slough, passing L02 and L04, in about 4 h. Although a more complete discussion and interpretation of these data and associated processes is left to other papers (Chapin et al. 2004; Johnson et al. 2007; Needoba et al. 2007),

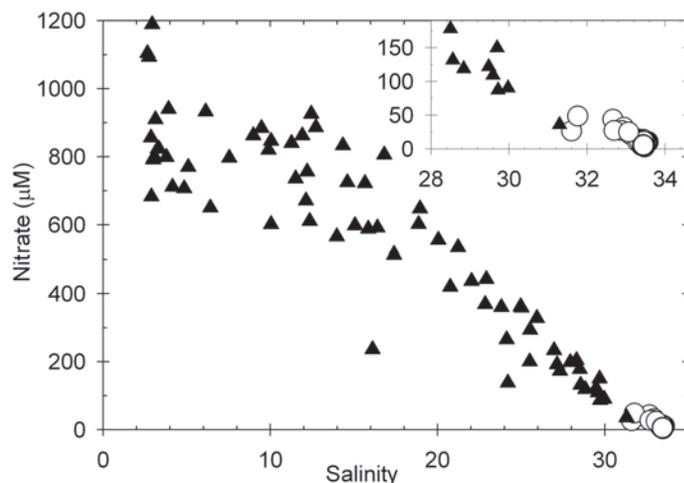


Fig. 10. Nitrate plotted versus salinity for the L01 (○) and L03 (▲) moorings from August 21 to 24, 2005. The inset shows the same data in the high-salinity low-nitrate region.

the above example demonstrates the need for such high-resolution monitoring networks to study and understand complex biogeochemical processes within coastal environments.

Discussion

The main goals of the LOBO monitoring program were to build and implement an estuarine and protected coastal ocean monitoring system, test and develop new in situ sensors, and demonstrate the improvements that a networked observatory provides for studies of important biogeochemical processes and complex ecosystems in these environments. In Elkhorn Slough, these include identifying nutrient concentrations and fluxes, and observing changes that may result from management practices within the watershed and climate variability.

The LOBO monitoring system described here has proven to be a robust, reliable, and flexible sensor network for continuously observing physical and biogeochemical processes within estuarine and protected coastal ocean during the 4 y it has been deployed in Elkhorn Slough. The moorings are designed to be readily customized, cost-effective, and operated with a minimum of maintenance. The two mooring designs, for deeper waters and shallow tidal flats, are highly compatible and configured with the same instrument pie sections and connections. A reliable telemetry system autonomously downloads data to shore where data are processed (calibrated and quality controlled), and made available to users via a simple web interface. Although the system was developed for use in Elkhorn Slough, its simple design and modular configurability allow it to be readily adapted to other sensors and locations, or used as a testbed mooring for new sensors.

The system has allowed us to identify processes that were unrecognized, despite a monthly nutrient monitoring program that has operated for nearly 20 y in Elkhorn Slough. For example, it is apparent that the main direction of nitrate flux

along the Elkhorn Slough channel is inland and the Slough acts primarily as a nitrate sink (Fig. 8). The Old Salinas River Channel, which intersects the Slough in Moss Landing Harbor, is the source of the nitrate transported into the Slough (Fig. 9 and 10). This transport occurs on each rising tide.

In September 2006, the LOBO technology was licensed, and it is now available through Satlantic Inc. in Halifax, Nova Scotia. Satlantic has implemented several modifications to the system described here for the commercial system. These include the addition of an anti-biofouling system for the pumped flow stream to further extend sensor service intervals, and an optional cell phone-based telemetry system. Several LOBO systems produced by Satlantic are currently being deployed (e.g., Comeau et al. 2007).

One of the advantages of a standardized mooring system such as LOBO is a commonality in data systems. This allows data to be exchanged between systems with little difficulty. As a result of the facile exchange of data, our *LOBOViz* server now distributes realtime data from Satlantic LOBO systems in Halifax, Nova Scotia, and Yaquina Bay, Oregon, as well as the original Elkhorn Slough system (<http://www.mbari.org/lobo/loboviz.htm>). This allows a direct comparison of biogeochemical processes in different regions. Such easy data exchange would make it feasible to link individual moorings into an integrated, continental-scale estuarine observing system as additional systems come on line. As coastal populations and their impact on the watershed increase over time, such cost-effective, large-scale aquatic monitoring networks will be essential for scientists, educators, and policymakers to understand and intelligently regulate the use of coastal waters (Johnson et al. 2007).

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