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Continuous water quality monitoring for the hard clam industry in Florida, USA

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Abstract In 2000, Florida's fast-growing hard clam aquaculture industry became eligible for federal agricultural crop insurance through the US Department of Agriculture, but the responsibility for identifying the cause of mortality remained with the grower. Here we describe the continuous water quality monitoring system used to monitor hard clam aquaculture areas in Florida and show examples of the data collected with the system. Systems recording temperature, salinity, dissolved oxygen, water depth, turbidity and chlorophyll at 30 min intervals were installed at 10 aquaculture lease areas along Florida's Gulf and Atlantic coasts. Six of these systems sent data in real-time to a public website, and all 10 systems provided data for web-accessible archives. The systems documented environmental conditions that could negatively impact clam survival and productivity and identified biologically relevant water quality differences among clam aquaculture areas. Both the real-time and archived data were used widely by clam growers and nursery managers to make management decisions and in filing crop loss insurance claims. While the systems were labor and time intensive, we recommend adjustments that could reduce costs and staff time requirements.

Keywords Aquaculture · Environmental quality · Real-time monitoring · Internet · Precision agriculture · Remote sensing

Introduction

The culture of northern quahog (hard clam), *Mercenaria mercenaria*, represents a significant segment of the state of Florida's $75 million aquaculture industry; between 1989 and 1999 revenue from farm-raised hard clams increased fifteen-fold (USDA 2000a, 2006a, b). Florida farm-raised hard clams are now a recognized commodity on the national market. Florida farms produce over 130 million clams each year, a crop worth $10 million and having an economic impact of about $55 million (USDA 2006a; Philippakos et al. 2001). The phenomenal production of clams in Florida is attributed to the high natural productivity of subtropical waters that allow for almost year-round growth.

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Clam farming is a relatively new agricultural industry in Florida. Beginning in 1991, state-owned submerged lands were identified, surveyed and marked for aquacultural activities. These shellfish aquaculture lease areas (variously called Aquaculture Use Zones, Aquaculture Use Areas or High-Density Lease Areas, but for the purposes here collectively referred to as "lease areas") are administered by the Florida Department of Agriculture and Consumer Services (FDACS), Division of Aquaculture, Bureau of Aquaculture Development. Today, about 425 active shellfish growers farm approximately 593 ha off 10 coastal Florida counties.

Hard clam production has three culture stages; production of small seed in a hatchery, growth of larger seed in a land-based nursery (1–2 mm in size) and/or field nursery (5–6 mm in size), and growout to marketable size on an open-water lease area. A crop of clams (25 mm shell width) can be grown in 12–18 months. In both the land-based nursery stages and the open-water growout phase, clams are exposed to vagaries of the environment.

In 2000, selected clam growers became the first aquaculturists in the USA eligible to purchase federally subsidized crop insurance under a pilot program developed by the US Department of Agriculture (USDA) Risk Management Agency. The pilot Cultivated Clam Crop Insurance Program covers losses due to "unavoidable damage" including hurricanes, tidal waves, surge, excess wind, disease, oxygen depletion, salinity decreases, and freezing (USDA 2000b). To date, approximately 95% of the clam growers in the four eligible counties in Florida have purchased crop insurance.

Water quality and local weather condition information is desired by hatcheries, clam growers and processors to make informed decisions concerning such activities as planting and harvesting. In addition, under the provisions of the Cultivated Clam Crop Insurance policy, the responsibility for identifying the cause of crop loss lies with the grower. While events such as hurricanes and storm surges are easily identified, losses caused by water quality variations, such as oxygen depletion and salinity changes, are much more difficult to quantify. Therefore, we developed and tested a monitoring process to provide real-time and archival water quality and weather information to hard clam growers.

Here we describe the continuous water quality monitoring system installed at hard clam aquaculture areas on both the Atlantic and Gulf coasts of Florida and show examples of the data collected with the system. The system is generally similar to those being used for other monitoring programs such as the National Estuarine Research Reserve's System-Wide Monitoring Program (NERR SWMP; Trueblood and Krantz 1998; Wenner and Geist 2001) and the Monitoring Your Sound project (Tedesco et al. 2003). The goals of this system were to 1) provide real-time water quality data to aquaculture producers and 2) construct a database for use in filing and processing insurance claims and in research to improve aquaculture practices.

Materials and methods

Monitoring sites

Between January and November 2002, water quality monitoring platforms were installed at 10 lease areas in four different geographic regions of Florida: the Panhandle region, the southern Big Bend, southwest Florida, and the Indian River Lagoon on the east central coast (Fig. 1). The lease areas were chosen to represent a range of environmental conditions while also providing environmental quality information on the largest and potentially most economically important aquaculture areas (Table 1). The single lease area in the Panhandle region, Alligator Harbor (46 individual lease parcels and covering 28 ha), was monitored. The lease areas monitored in the southern Big Bend region lie off the coast of Levy and Dixie counties. This area included nine different lease areas containing a total of 470 individual lease parcels and covering a total of 381 ha. Four lease areas were monitored in this region: Gulf Jackson, Horseshoe Beach, Pine Island and Dog Island. The lease areas in southwest Florida lie in and around Charlotte Harbor and include three lease areas containing 106 individual lease parcels and covering 212 ha. Two lease areas in this area were monitored: Sandfly Key and Pine Island Sound. The Indian River lagoon contains four lease areas containing a total of 62 individual lease parcels and covering 171 ha. Three lease areas were monitored in this region: North Indian River, Body A and Body F. Selection of monitoring sites represented a cooperative effort between personnel of the University of Florida (UF) Department of Fisheries and Aquatic

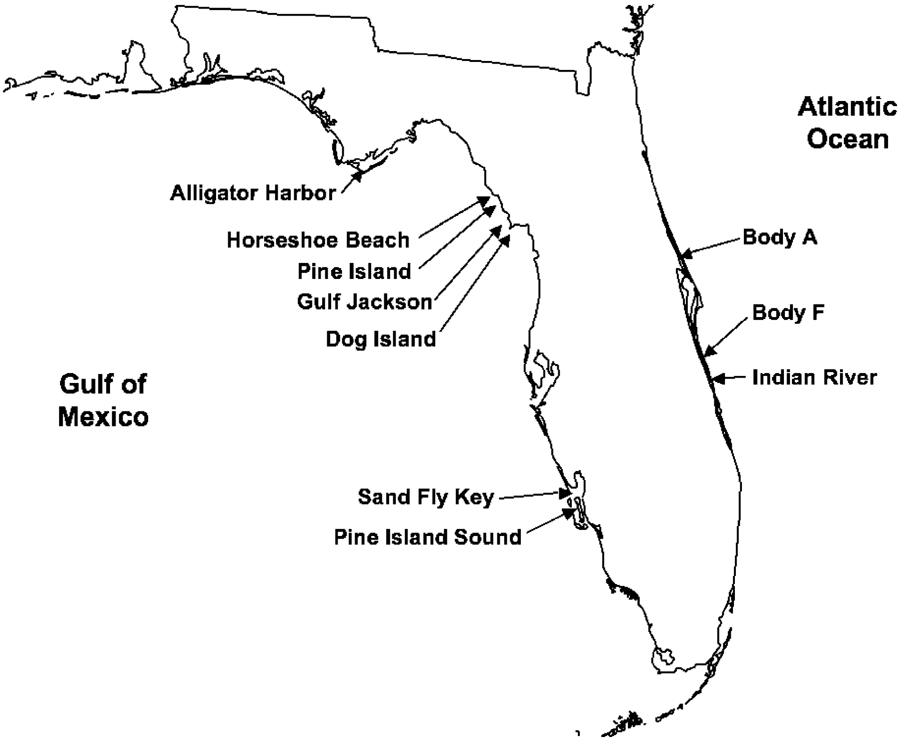


Fig. 1 Locations of 10 lease areas in Florida equipped with continuous water quality monitoring systems

Sciences, UF Shellfish Aquaculture Extension Program, and FDACS, Division of Aquaculture.

Hardware components

One of two hardware configurations was used to monitor water quality at each location. The first configuration, henceforth referred to as the real-time system, was deployed at the Alligator Harbor, Gulf Jackson, Horseshoe Beach, North Indian River, Sandfly Key and Pine Island Sound lease areas and was intended to provide data for both historical archives and real-time applications (Fig. 2). This real-time system consisted of a YSI 6600 multi-parameter system with a pressure sensor, sensors to record temperature and conductivity (YSI 6560), turbidity (YSI 6062, with automated wiper), chlorophyll (YSI 6025, with automated wiper) and a dissolved oxygen rapid pulse Clark cell electrode (YSI 6562). Using internal algorithms, the system provided the following final parameters: depth (m),

Table 1 Lease areas equipped with continuous water quality monitoring equipment

Region	County	Lease area monitored	Monitor type	Hectares	Number of parcels
Panhandle	Franklin	Alligator Harbor	Real-time	31	46
Big Bend	Dixie	Horseshoe Beach	Real-time	58	64
		Pine Island	Archive	87	96
	Levy	Gulf Jackson	Real-time	100	110
		Dog Island	Archive	28	27
Southwest	Charlotte	Sandfly Key	Real-time	46	51
	Lee	Pine Island Sound	Real-time	36	40
East Central	Brevard	Body A	Archive	6	3
		Body F	Archive	24	12
	Indian River	Indian River	Real-time	53	47

Included are the configuration used (real-time or archival), the number of hectares, and the number of individual lease parcels in each lease area

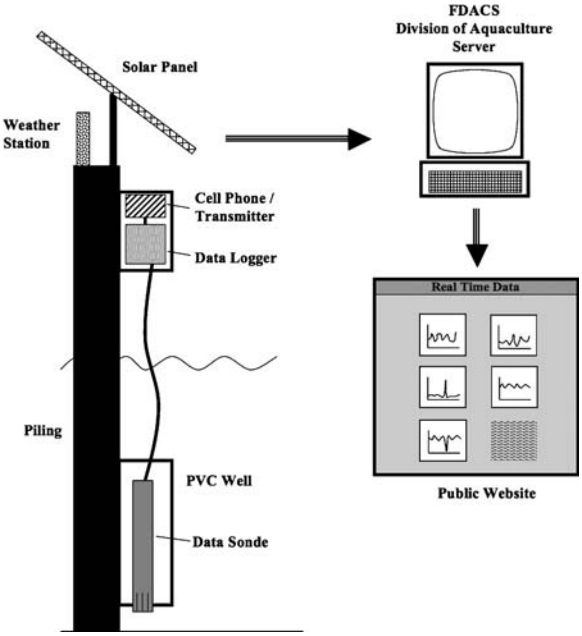


Fig. 2 Configuration of the real-time remote sensing hardware

temperature (°C), salinity (ppt), dissolved oxygen saturation (%) and dissolved oxygen concentration (mg l^{-1}), turbidity (NTU) and chlorophyll (μg l^{-1}). Data from this system were recorded by a Campbell data logger (CR510 with 128 KB of memory) at 30 min intervals and transmitted to a central computing facility (FDACS, Division of Aquaculture) via satellite phone (COM 200 CSI telephone modem and COM 100 CSI cellular telephone pack with transceiver and switching relay; in 2004 changed to Airlink CDPD modems). Power for data logging and transmission was provided by solar panels (Solarex 20 W) attached to a rechargeable sealed cell battery (12 V, 12 AH). Un-manipulated raw data were posted to the world-wide web (CSI PC 208 and CSI Real Time Data Monitor software) and updated every 2h. Starting in early 2003, back-up data logs were recorded internally within the data sonde. Both transmitted data and back-up data logs were later used to construct historical water quality archives for each lease area. Product names are provided for the reader's information and are not meant to imply superiority to other products.

The second configuration, henceforth referred to as the archive system, was deployed at the Dog Island, Pine Island, Body A, and Body F lease areas and was intended to provide data for water quality archives. This configuration consisted of a YSI 6600 multiparameter system with sensors to record all of the same parameters recorded by the real-time system at 30 min intervals. The system provided the following final parameters: temperature (°C and °F), salinity (ppt), dissolved oxygen (% saturation and mg l^{-1}), depth (m), turbidity (NTU) and chlorophyll (μg l^{-1}). The Body F sonde lacked sensors to record depth, turbidity and chlorophyll. Hardware was selected and installed cooperatively by FDACS and UF personnel.

For both the real-time and archive systems, each sonde was suspended by a stainless steel cable approximately 20 cm from the bottom within a PVC well (20 cm in diameter) attached to a piling (Fig. 2). Sondes were retrieved and new sondes deployed at each site as often as every 7 days, but typically every 10–14 days. Pre-deployment procedures included calibrating sensors using standard solutions, and subjecting the sonde and sensors to a routine maintenance procedure as described by the YSI 6600 instruction manual. Post-deployment procedures included testing sensors in standard solutions and checking and recording information on sonde and sensor condition using modifications on protocols developed by the NERR SWMP (most recent version: Small 2005). Sondes were maintained primarily by FDACS personnel.

Data transmission and storage

Data transmitted in real-time to the central server was simultaneously posted to the public website (http://www.floridaaquaculture.com) and added to an archival raw dataset. Graphs of the raw values for temperature (°F), salinity (ppt), dissolved oxygen (mg/l and % air saturation), turbidity (NTU) and water depth (ft) were posted in real-time to the public website and updated every 2 h. The server and website were maintained by FDACS personnel.

Data recorded internally by the sondes were downloaded to a computer by field staff immediately following deployment. These downloaded files were sent to the University of Florida where they were imported into a spreadsheet program (Excel 2000, Microsoft Corp). Information from pre- and post-deployment procedures was used in a strict quality control/quality-assurance process before the data was made available in on-line archives. This process was based on that used for the NERR SWMP (Small 2005), but with modifications for the type and condition of data obtained in the environments monitored here

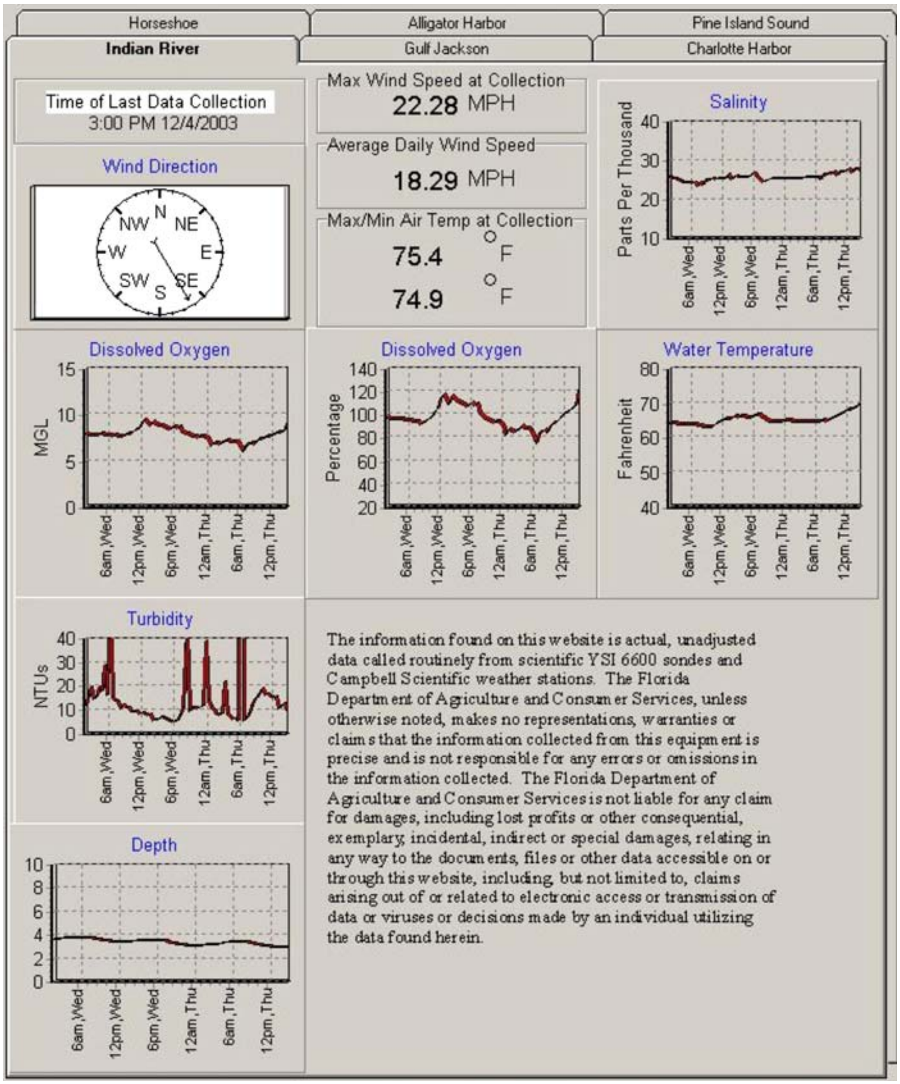
(DCB, unpublished data). The archives consisted of month-long and year-long records in both tabular and graphic formats. The quality control/quality-assurance process was conducted by UF personnel.

Results

The real-time systems provided around-the-clock, web-accessible water quality data for six lease areas in Florida's nearshore coastal zone (Fig. 3). When functioning properly, the previous 36 h of raw data were updated every 2 h. This primarily allowed real-time adjustment of management decisions by clam farmers as environmental conditions fluctuated.

Archived datasets consisted of quality-controlled data at longer time scales of 1 month and 1 year. This allowed the interpretation of environmental trends at individual lease areas as well as comparisons amongst lease areas. Using the archived data collected at the Gulf Jackson lease area during 2003 as an example, these trends become apparent. Water temperatures exceeded 30°C during summer, and generally did not fall far below 10°C in winter. Salinity was highly variable between 15 and 30 ppt but with several striking drops to less than 10 ppt; salinity fell to almost zero in April 2003. Oxygen, while also highly variable, generally remained well above hypoxic levels (2 mg l^{-1}) at this lease area, but reached its lowest levels during the warmer summer months.

Fig. 3 Web-accessible view of real-time water-quality data



Time of Last Data Collection
3:00 PM 12/4/2003

Max Wind Speed at Collection
22.28 MPH

Average Daily Wind Speed
18.29 MPH

Max/Min Air Temp at Collection
75.4 °F
74.9 °F

The information found on this website is actual, unadjusted data called routinely from scientific YSI 6600 sondes and Campbell Scientific weather stations. The Florida Department of Agriculture and Consumer Services, unless otherwise noted, makes no representations, warranties or claims that the information collected from this equipment is precise and is not responsible for any errors or omissions in the information collected. The Florida Department of Agriculture and Consumer Services is not liable for any claim for damages, including lost profits or other consequential, exemplary, incidental, indirect or special damages, relating in any way to the documents, files or other data accessible on or through this website, including, but not limited to, claims arising out of or related to electronic access or transmission of data or viruses or decisions made by an individual utilizing the data found herein.

Turbidity and chlorophyll both had a fluctuating baseline value and commonly increased to near the sensor detection limits. Turbidity generally remained below 50 NTU but commonly rose above 200 NTU with many spikes exceeding the 1,000 NTU detection limit of the sensor. Such spikes were most common in the late summer when temperatures were highest. Chlorophyll rose from around 10 μg l^{-1} during the winter to a high in May and June then decreased again in July.

The short interval of consecutive measurements (30 min) allowed the examination of environmental trends at several temporal scales. For example, the year-long record for Gulf Jackson in 2003 showed that salinity was typically in the range 20–25 ppt, with the most obvious example of a departure from typical conditions being in April (Fig. 4b). The monthly record for April showed salinity fluctuating with tides, as would be expected in an estuary, but with a precipitous drop during which tides had little influence (Fig. 5a). Salinity then rose slowly over the course of several days, during which salinity fluctuated widely with flood and ebb tides. Even closer examination of the 36-h record (such as might be posted on the website by the real-time systems)

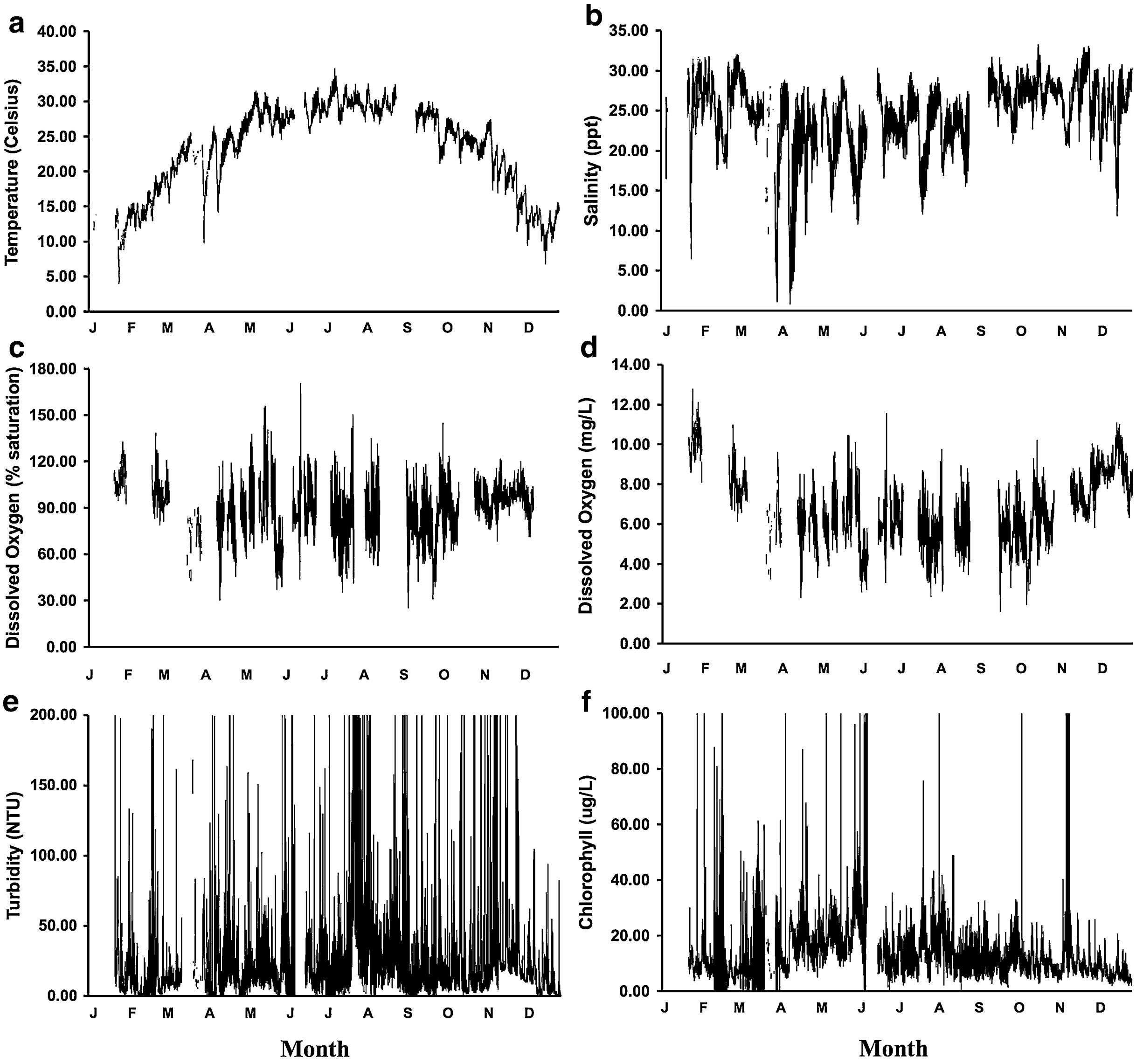


Fig. 4 Data for **a** temperature, **b** salinity, **c** dissolved oxygen saturation, **d** dissolved oxygen concentration, **e** turbidity, and **f** chlorophyll measured at the Gulf Jackson lease area during 2003

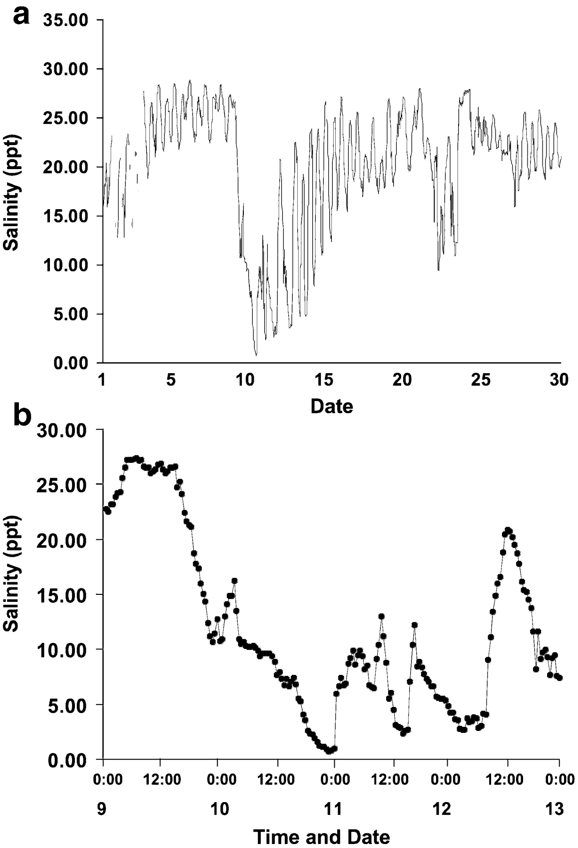


Fig. 5 Detailed view of the salinity drop at the Gulf Jackson lease area during **a** the full month of April 2003 and **b** 96 h around the drop

showed that salinity decreased from approximately 27 to 10 ppt in a period of just 8h, then dropped to near zero over the subsequent 24 h.

Salinity records for 2003 at four lease areas show the range of variability among different aquaculture areas (Fig. 6). Horseshoe Beach, Pine Island and Gulf Jackson are located in the Suwannee River estuary and during this period were all highly variable. Horseshoe Beach and Pine Island were located within 3.2 km of each other and showed very similar salinity trends on multiple time scales. A strong seasonal cycle appeared at both of these sites, with salinities being highest in the winter (25–30 ppt) and decreasing to a low during the summer (12–18 ppt). Substantial short-term (days) salinity drops in April, May and August and a large salinity increase in May also occurred at both of these sites. Gulf Jackson, located approximately 16 km south of Pine Island, while having a highly variable salinity, showed little similarity to Horseshoe Beach and Pine Island. The seasonal cycle was much less apparent at Gulf Jackson, as salinities tended to remain above 18–20 ppt except for short periods of time. Except for sharing an episodic decrease in April, the shorter-term behavior of salinity at Gulf Jackson was dissimilar to the other two sites in the Suwannee River estuary.

The salinity at the Indian River site, located in a lagoon on the Atlantic coast of Florida, behaved very differently than those on the Gulf coast. Salinity at this lease area was generally higher (>25 ppt) and less variable, and the seasonal cycle was opposite, with salinity being lower in the winter and higher during the summer, than that seen at the Gulf coast sites. The tendency of salinity to sharply increase or decrease over the course of hours to days was lacking at the Indian River lagoon site.

Discussion

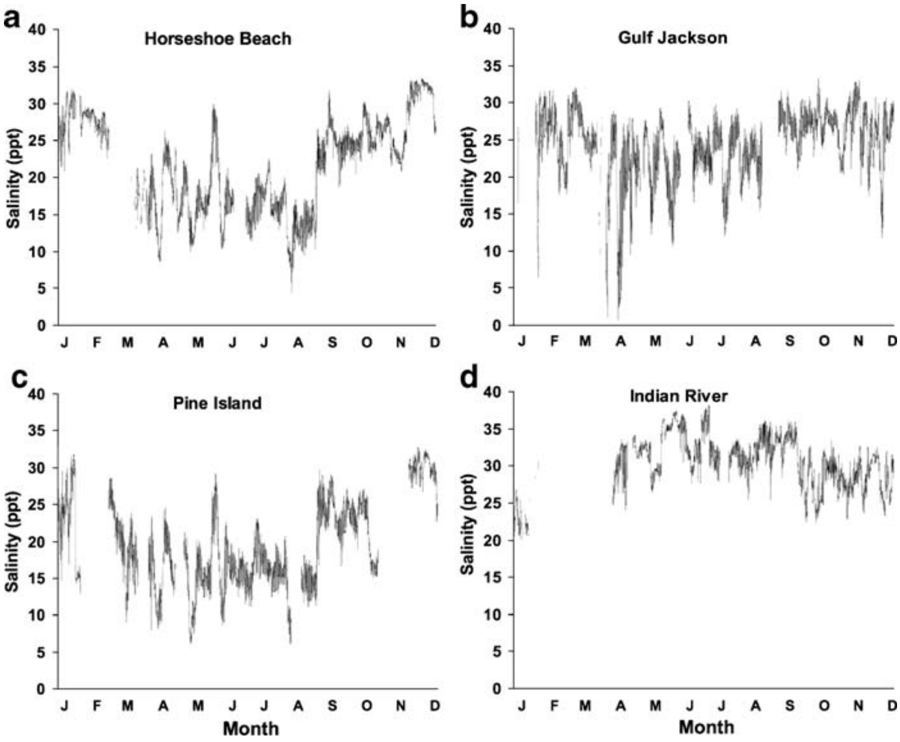
Use of systems by clam farming industry

The remote sensing network described here provided web-accessible water quality data in real-time for six clam aquaculture areas along the Florida coastline. Surveys of aquaculturists indicated that approximately 25% of clam growers and 80% of nursery managers accessed the real-time data and incorporated it into their decision-making processes. For example, growers accessed real-time data prior to purchasing or moving clam seed to ensure that conditions were compatible. Likewise, hatchery managers accessed real-time data prior to transferring clam seed from land-based raceways to open-water leases. As a result, growers experienced reduced clam mortality and increased crop profitability (LNS, unpublished data). Archived data collected by this monitoring system were critical to detecting and documenting natural sources of mortality and successfully filing insurance claims. During 2003–2005, the archived data were used to document qualifying perils, particularly oxygen depletion and salinity (USDA Risk Management Agency, unpublished data).

Water quality trends

The monitoring array was capable of providing water quality data relevant to hard clam growth and mortality. As an example, water quality data collected at the Gulf Jackson lease area illustrates that con-

Fig. 6 Salinity at the **a** Horseshoe Beach, **b** Gulf Jackson, **c** Pine Island, and **d** Indian River lease areas during 2003



ditions were generally well within the range tolerated by hard clams; however, the conditions seasonally and episodically deviated from the range expected to support optimum productivity. Temperatures never reached levels known to cause mortality in *M. mercenaria*, but in winter they fell well below and in summer climbed well above levels that support optimal growth (15–25°C; Arnold et al. 1991). Salinity generally remained well within the range tolerated by hard clams, but salinities below 27 ppt and 17–20 ppt have been shown to affect growth rates in juveniles and adults, respectively (Chanley 1958; Castagna and Kraeuter 1981; Castagna and Chanley 1973). Dissolved oxygen levels never fell to hypoxic levels during 2003, but they did reach their lowest levels during the warmest months when clam metabolic rates and respiratory demands would be highest. While hard clams are extremely tolerant of hypoxia and anoxia, they have been shown to reduce feeding rates at oxygen concentrations less than 5.0 mg l^{-1} (Hamwi 1969), a factor certain to influence growth rate. Dissolved oxygen was also supersaturated (>100% air saturation) throughout much of the year at Gulf Jackson, conditions that have also been shown to reduce growth rates (Bisker and Castagna 1985). Therefore, very high oxygen concentrations could be as important, if not more important, than low oxygen availability in at least this lease area. Turbidity also tended to increase more often during warmer months, and an overabundance of suspended material (reflected in high turbidity) could reduce hard clam feeding efficiency (Murphy 1985; Bayne 1993). While clams grown here likely face multiple simultaneous environmental stressors, it is critical to note that Gulf Jackson is widely known within the industry as a highly successful and productive lease area. This likely reflects that 1) the conditions supporting fast growth rates at this site far outweigh the rather short-lived periods of sub-optimal conditions and 2) most of our information on the physiological response of *M. mercenaria* to environmental stressors comes from studies on populations occurring in much colder waters off the mid-Atlantic and northeast coast of the USA. This only further highlights the need to better understand the responses of the hard clam to the multiple simultaneous environmental gradients common to the warmer and more productive subtropical waters of Florida.

The presence of several rapid salinity changes at Gulf Jackson, Horseshoe Beach and Pine Island during 2003 indicated this is perhaps the most important stressor affecting hard clams planted in many of Florida's lease areas. Hard clams have been shown to be fairly resilient to the 10–15 ppt salinity fluctuations that were common at these sites (Baker et al. 2005). However, Baker et al. (2005) demonstrated that, in a laboratory setting, salinity drops of up to 24 ppt over 24 h can result in very high mortality in juvenile hard clams, particularly those that have been recently planted. Several drops of greater than 15 ppt occurred at the Big Bend lease areas, but most notable is an approximately 27 ppt decrease over a period of 36 h at Gulf Jackson in April 2003. Following this drop, salinity increased and decreased wildly (±15–20 ppt) with ebb and flood tides for almost a week. Although month-specific indemnity information is unavailable, personal communications with individual clam growers suggest that recently planted seed clams suffered high mortality during this time and that growers used archived data to document salinity as the cause of loss and successfully file insurance claims.

Salinity trends at four different lease areas also illustrate the kind of spatial variability seen amongst lease areas. Horseshoe Beach and Pine Island are both located just north of the mouth of the Suwannee River and they have very similar salinity patterns. Interestingly, Gulf Jackson is located just south of the Suwannee River mouth, but this site's salinity, aside from being highly variable, is not very similar to the other two lease areas within the same estuary. The Suwannee River estuary is shallow and unenclosed, thus freshwater discharges directly into the ocean where currents and winds cause the plume to fluctuate north and south along the coastline (Phlips and Bledsoe 2002). The fluctuating plume probably accounts for the very strong similarity between the lease areas located north of the Suwannee River and their dissimilarity to the lease area located to the south. Salinity at the Indian River lease area, by contrast, varied little and remained above 30 ppt (the general upper bound of salinities in which hard clams are found naturally) for much of the year. Little is known of the physiological response of hard clams to salinities greater than 30 ppt, but certainly the relatively high and constant salinities of the Indian River lease area do not provide the type of predator and parasite refugia typically afforded by the low and variable salinities of other estuaries (Shumway 1996). The constancy of salinity at this lease area relative to that of the Big Bend lease areas likely reflects that the Indian River Lagoon is a tidally dominated lagoon with no large direct source of freshwater. The result is that lease areas in this region are not likely to be greatly influenced by upland storm events, while those located in the estuary of the unimpeded Suwannee River face drastic fluctuations in salinity.

Challenges and recommendations

The real-time system provided a useful reference for short-term management decisions by real-time users, clam farmers and nursery managers, but because data were posted in raw form, problems experienced by the system (malfunctions, sensor failure, fouling, etc) also appeared on the public website. The most obvious technical problem in the real-time system was an apparent inability of the sonde to communicate consistently with the data logger. During 2002, the first year of the program, this problem resulted in the loss of 6,938 of 41,919 total data points across three stations. Gulf Jackson lost 19.4%, Horseshoe Beach lost 14.3% and Indian River lost 15.0% of all data points during 2002. This both complicated short-term interpretations by real-time users and compromised the archived datasets. Only vigilance by the field staff (regularly checking the website) could minimize the impact for real-time users. To reduce the impact on the archival dataset, the real-time sondes were reprogrammed in 2003 to send readings through the data-logger to the website and then minutes later record data to the sonde's internal memory. From that point forward, all archived datasets were created using data from the sonde's internal memory, when possible, and using the real-time web data as a back-up in case of a problem with the internal memory data.

The data obtained for the different parameters varied substantially in quality, reliability and cost of handling. This variation arose from several expensive standard solutions (particularly non-zero conductivity and turbidity standards), calibration difficulties (dissolved oxygen, turbidity, chlorophyll and occasionally conductivity) and the effects of biofouling organisms on the sensors (dissolved oxygen, turbidity and chlorophyll). Additionally, the quality control process was relatively simple for several parameters (temp, salinity, depth) but complex, time-consuming and often subjective for oxygen, turbidity, chlorophyll (DCB, unpublished data). Reducing the number of parameters to some critical subset known to impact hard clam mortality and productivity (for example, temperature, salinity and dissolved oxygen) could significantly reduce the time and cost involved in maintaining the systems and quality-controlling the data.

Maintaining the systems in the field was labor intensive. Pre-deployment cleaning, maintenance, and calibration of each sonde required between 2 and 3 h of dedicated staff time to complete; post-deployment checks required between 30 and 60 min to complete. Deploying and retrieving a sonde required up to a full day, although multiple sondes could be retrieved and/or deployed in a day if the lease areas were in close proximity. Biofouling organisms often interfered with the accurate recording of several parameters (oxygen, turbidity and chlorophyll and sometimes salinity) within as little as 5–7 days of deployment, thus necessitating frequent deployments to minimize loss of data. The monitoring program did not have the funds to hire full time staff to maintain the water quality monitoring systems in the field, and the time-consuming nature of maintenance precluded the participation of industry personnel. Instead, the program relied upon existing FDACS staff. Existing duties placed severe time constraints on the staffs' ability to maintain the water-quality monitoring systems described here (Table 2). As a result, a significant portion of deployments exceeded 2 weeks, particularly during the busy summer months (Table 2). Future efforts should involve field staff with more time dedicated specifically to sonde maintenance and deployment.

Biofouling represented the single greatest challenge to maintaining the remote sensing network. In the generally warm waters of Florida, barnacles, oysters and algae rapidly and extensively colonized the sonde body and attached probes. The most serious problem that resulted from sensor fouling was the impairment of data quality for several parameters, particularly oxygen, turbidity and chlorophyll. Overgrowth of the membrane on the oxygen electrode resulted in an often rapid decrease of measured oxygen concentrations, in the worst cases causing the sensor to read less that 10% in air when it should be reading 100%. Fouling by hard-shelled organisms sometimes also resulted in the rupture of the membrane and the complete failure of the electrode. The turbidity and chlorophyll probes were equipped with automated wipers to keep the optical surface of the probe clean, but under the heavy fouling of these environments, the wipers often could not keep the sensor clean or were actually prevented from moving at all. As fouling progressed, these sensors mistakenly measured the fouling organisms as suspended material and measurements increased well above the detection limits of the sensors. The effects of fouling organisms not only compromised the quality of the data reported in real-time, but also necessitated more subjective and time-consuming quality control protocols for the archived data (DCB, unpublished data). Heavy fouling also resulted in several other problems that increased cost and staff time commitments. Although the sondes were gently rinsed before taking post-deployment readings in the standard solutions, debris inevitably fell into the solutions, reducing their utility in future calibrations and post-deployment checks. Even a moderate amount of fouling required time-consuming cleaning procedures. Anti-fouling paint proved of limited usefulness, but wrapping the sonde body (except for the area around the sensors) in plastic wrap made organism removal somewhat easier.

Table 2 Demands upon field staff time and the lengths of sonde deployment between April 2003 and August 2004

	Field office	
	A	B
Lease Areas	12	6
Shellfish area closure days	937	448
Total excursions to field	302	129
Number of personnel	3	2
Number of sondes handled	3	4
Total sonde deployments	106	101
% Deployment periods >14 days	22	31
Average deployment length (days)	12.4	13.7

Summary

The continuous water quality network described here was used in real-time by clam growers and nursery managers to make management decisions, and the resulting archived data sets were used in crop loss insurance claims. The systems detected environmental conditions in field-based clam aquaculture areas that could result in reduced clam growth (productivity) as well as increased mortality. The environmental conditions at the various aquaculture areas differed substantially, suggesting each possessed a different set of conditions capable of influencing high-productivity clam farming. The systems were labor and time intensive, but focusing on a reduced set of physiologically critical parameters known to reach stress conditions in the clam aquaculture areas could greatly reduce costs and staff time requirements. A decrease in the time commitment required to maintain the systems would allow clam growers to play a greater role in a program that has proven crucial to their industry.

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References

Arnold, W. S., Marelli, D. C., Bert, T. M., Jones, D. S., & Quitmeyer, I. R. (1991). Habitat-specific growth of hard clams *Mercenaria mercenaria* (L.) from the Indian River, Florida. *Journal of Experimental Marine Biology and Ecology*, *147*, 245–265.

Baker, S. M., Baker, P., Heuberger, D., & Sturmer, L. (2005). Short-term effects of rapid salinity reduction on seed clams (*Mercenaria mercenaria*). *Journal of Shellfish Research*, *24*, 29–33.

Bayne, B. L. (1993). Feeding physiology of bivalves: time-dependence and compensation for changes in food availability. In R. F. Dame (Ed.) *Bivalve filter feeders in estuarine and coastal ecosystem processes* (pp. 1–23). New York: Springer.

Bisker, R., & Castagna, M. (1985). The effect of various levels of air-supersaturated seawater on *Mercenaria mercenaria* (Linné), *Mulina lateralis* (Say), and *Mya arenaria* Linné, with reference to gas bubble disease. *Journal of Shellfish Research*, *5*, 97–102.

Castagna, M., & Chanley, P. (1973). Salinity tolerance of some marine bivalves from inshore and estuarine environments in Virginia waters on the western mid-Atlantic coast. *Malacologia*, *12*, 47–96.

Castagna, M., & Kraeuter, J. N. (1981). Manual for growing the hard clam *Mercenaria*. Special report in: Applied Marine Science and Ocean Engineering No 249.

Chanley, P. E. (1958). Survival of some juvenile bivalves in water of low salinity. *Proceedings of the National Shellfisheries Association*, *48*, 52–65.

Hamwi, A. (1969). Oxygen consumption and pumping rate of the hard clam *Mercenaria mercenaria* L. Dissertation, Rutgers University, New Brunswick, New Jersey.

Murphy, R. C. (1985). Factors affecting the distribution of the introduced bivalve, *Mercenaria mercenaria* in a California lagoon – the importance of bioturbation. *Journal of Marine Research*, *43*, 673–692.

Philippakos, E., Adams, C., Hodges, A., Mulky, D., Comer, D. & Sturmer, L. (2001). Economic Impact of the Florida Cultured Hard Clam Industry. Technical Paper SGR 123, Florida Sea Grant College Program, Gainesville, FL, 23 pp.

Phlips, E. J., & Bledsoe E. L. (2002). The consequences of Suwannee River eutrophication on the dynamics of algae in the river and associated estuary. Report to Suwannee River Water Management District, Live Oak, Florida.

Shumway, S. E. (1996). Natural environmental factors. In V. S. Kennedy, R. I. E. Newell, & A. F. Eble (Eds.) *The eastern oyster*, *crassostrea virginica* (pp. 467–513). College Park, Maryland: Maryland Sea Grant College.

Small, T. A. (2005). CDMO NERR SWMP Data Management Manual, Version 5.2. Prepared for the NERR System-wide Monitoring Program.

Tedesco, M., Bolen, W. F., Howard-Strobel, M. M., Cohen, D. R., & Tebeau, P. A. (2003). The MYSound Project: building and estuary-wide monitoring network for Long Island Sound. U.S.A. *Environmental Monitoring and Assessment*, *81*, 35–42.

Trueblood, D. D., & Kranz, R. (1998). Ecological monitoring in the National EstuarineResearch Reserve System. US Dep. Commerce, NOAA, NOS, OCRM. Silver Spring, MD.

Wenner, E. L., & Geist, M. (2001). The National Estuarine Research Reserves Program to monitor and preserve estuarine waters. *Coastal Management*, *29*, 1–17.

USDA (United States Department of Agriculture). (1990). ‘Aquaculture: Florida Aquaculture Sales Total $51 Million in 1989. National Agricultural Statistics Service, Florida Field Office.

USDA (United States Department of Agriculture). (2000a). Aquaculture: Florida Aquaculture Sales Total $86 Million in 1999. National Agricultural Statistics Service, Florida Field Office.

USDA (United States Department of Agriculture). (2000b). Cultivated Clam Pilot Crop Insurance Underwriting Guide. Federal Crop Insurance Corporation, Product Development Division: FCIC-24100.

USDA (United States Department of Agriculture). (2006a). 2002 Census of Agriculture, Census of Aquaculture (2005). National Agricultural Statistics Service:, Volume 3, Special Studies Part 2, AC-02-SP-2.

USDA (United States Department of Agriculture). (2006b). Aquaculture: Florida Aquaculture Sales Total $75 Million in 2005. National Agricultural Statistics Service, Florida Field Office.