Briefing for OMSAP workshop on ambient monitoring revisions June 18-19, 2003

Massachusetts Water Resources Authority

Environmental Quality Department
Report 2003-ms-085

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Information Briefing to Outfall Monitoring
Science Advisory Panel

To: Dr. Andrew Solow, Chair OMSAP
From: Dr. Andrea Rex, Director, Environmental Quality, MWRA
Cc: OMSAP, IAAC, PIAC
Date: June 13, 2003
Subject: Briefing materials for review of effluent and water column monitoring

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MWRA is in the process of reviewing its outfall monitoring program, using the process described in its NPDES discharge permit. As the Outfall Monitoring Science Advisory Panel requested, a two-day workshop has been scheduled for June 18 and 19, 2003 to review the Outfall Ambient Monitoring Plan. The monitoring areas for review include effluent and water column. The attached briefing materials include:

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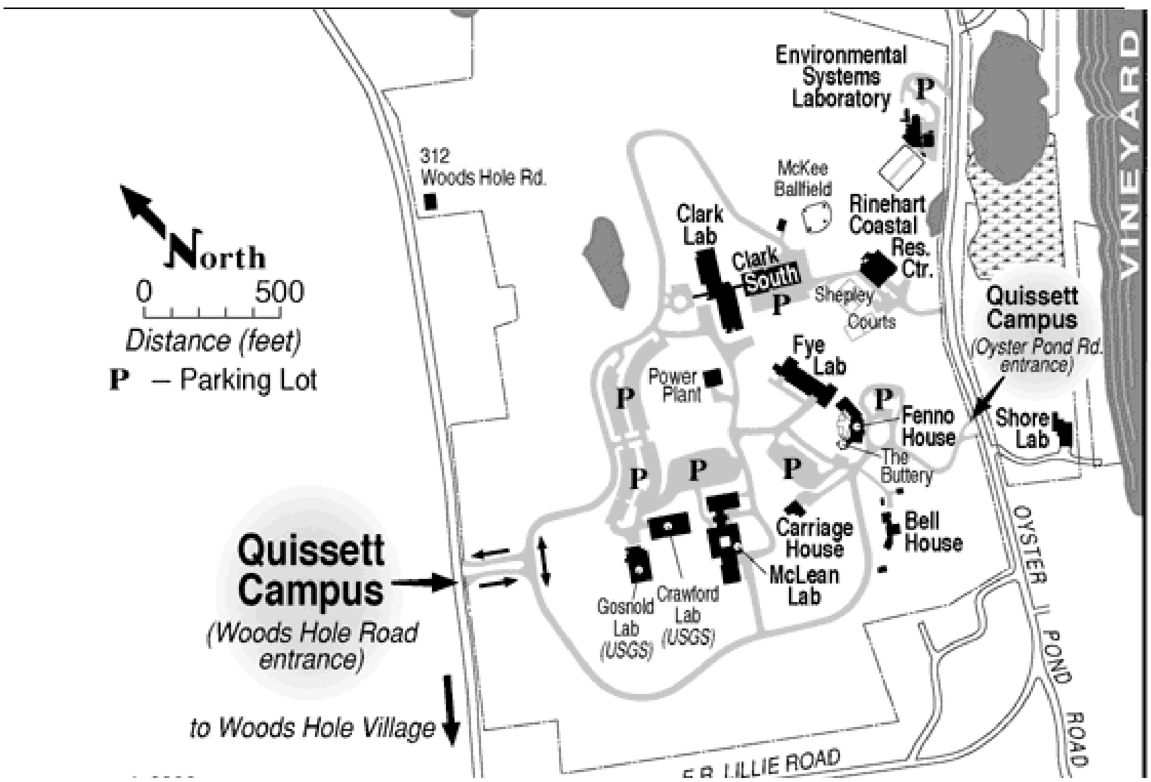
June 18, 2003 Wednesday (day 1of 2)
10:00 AM - 5:00 PM. WHOI, Quissett Campus, Clark 507.
http://www.epa.gov/region01/omsap/upcoming.html
Briefing materials can be found at: http://www.mwra.state.ma.us/harbor/html/omsap_briefing_june03.htm

10:00	5'	Welcome and review of action items from last workshop	Andy Solow
10:05	10'	Introduction to the review	Andrea Rex
10:15	10'	Annual sediment contaminant sampling design (from workshop #1)	Ken Keay
	5'	Discussion and OMSAP recommendation	
10:30	10'	Effluent	Andrea Rex
10:40	10'	Environmental concerns and design of ambient monitoring plan	Mike Mickelson
10:50	30'	Physical oceanography and larger oceanographic paradigms	Rocky Geyer
	10'	Discussion	
11:30	60'	Lunch (on your own)	
12:30	5'	Bacteria and floatables	Andrea Rex
12:35	45'	Nutrients, chlorophyll, DO, and productivity	Scott Libby and Candace Oviatt
	10'	Discussion	
1:30	15'	Satellite chlorophyll	Ajit Subramaniam
1:45	45'	Phytoplankton and zooplankton	Jeff Turner and Carlton Hunt
	15'	Discussion	
2:45	15'	Break	
3:00	20'	Summary	Carlton Hunt
	10'	Discussion	
3:30	90'	Discussion of results	Carlton Hunt
5:00		end of day 1 (meet again tomorrow at 10 AM)	

June 19, 2003 Thursday (day 2)
10:00 AM - 5:00 PM. same room

10:00	10'	Monitoring redesign	Carlton Hunt
10:10	45'	Statistical model	Steve Rust
	30'	Discussion	
11:10	20'	Number of nearfield stations per survey	Suh Yuen Liang
11:30	60'	Lunch (on your own)	
12:30	15'	Discussion	
12:45	45'	Number of surveys per year	Mike Mickelson
	30'	Discussion	
2:00	15'	Break	
2:15		General Discussion, OMSAP recommendations	
5:00		Close	



1. INTRODUCTION

Since 1985, MWRA has worked to minimize the effects of wastewater discharge on the marine environment by ending the discharge of sludge and inadequately treated effluent into Boston Harbor, reducing pollutants at their source, improving wastewater treatment to modern standards, and providing increased dilution. Concerns about potential effects of moving the effluent outfall from the harbor to Massachusetts Bay have been recognized by MWRA and by the joint permit for the outfall issued by the U.S. Environmental Protection Agency (EPA) and the Massachusetts Department of Environmental Protection (MADEP).

MWRA is committed to ensuring good treatment and conducting monitoring necessary to ensure that environmental impact of the discharge is minimal. This commitment is formalized in MWRA's discharge permit, which requires MWRA to monitor the effluent and the ambient receiving waters for compliance with permit limits and in accordance with the monitoring plan (MWRA 1991, 1997a). EPA and MADEP have established an independent panel of scientists, the Outfall Monitoring Science Advisory Panel (OMSAP), to review monitoring data and provide advice on key scientific issues related to the permit. The monitoring plan can be modified, under OMSAP's guidance, to incorporate new scientific information and improved understanding resulting from the monitoring.

In the current fiscal year, MWRA will spend over $5 million on effluent monitoring and environmental studies of Massachusetts Bay. Since 1990, MWRA has invested approximately $35,000,000 in environmental monitoring and modeling. The water column monitoring is the largest part of this program.

Table 1-1 Breakdown of July 2002-June 2003 permit-required monitoring costs by project area

Project area	MWRA cost	Cost-share
Effluent	$330,000	$79,000
Outfall	$3,702,000	$895,000
water column	1,835,000	595,000
benthos	1,155,000	300,000
fish/shellfish	368,000	
pathogens	344,000	
Model	$136,000	$52,000
Permit reporting and management	$900,000	
Total	$5,068,000	$1,026,000

There are now more than two years of post-discharge monitoring to compare with baseline conditions; monitoring results to date document minimal environmental effect. In addition, the nearly nine years of baseline monitoring provide abundant data to use in evaluating the effectiveness and efficiency of the sampling design. Thus it is appropriate to revisit the monitoring program, as recommended by the National Research Council (NRC, 1990), and refocus it on the potential for long-term chronic effects. Ongoing effluent monitoring will remain at the core of the monitoring program.

The June 18-19, 2003 OMSAP workshop addresses effluent and water column monitoring. This briefing package includes a brief summary of the monitoring approach, a description of key results, statistical analysis and rationale for changes in sampling design, and MWRA recommendations for monitoring plan modifications. No changes to the effluent monitoring are being proposed at this time. Proposed revisions to the water column monitoring are in the sampling design of the nearfield, specifically, the number of stations sampled and the number of surveys carried out annually. The intensive monitoring of the nearfield has generated a large database, enabling a detailed statistical evaluation of alternative sampling designs. MWRA does not propose to change any of the parameters being measured; our analysis and recommendations are limited to the spatio-temporal characteristics of the sampling design. There are no changes to the farfield monitoring water column monitoring proposed during this workshop; MWRA anticipates possibly returning to OMSAP next year with a further evaluation of farfield study design when another year of monitoring data is available.

A workshop held in March-April 2003 reviewed the fish and shellfish and sediment contaminant monitoring designs (MWRA 2003). A workshop to be held in July, 2003 will review the benthic community and nutrient flux monitoring designs.

References

MWRA. 1991. **Massachusetts Water Resources Authority effluent outfall monitoring plan: Phase I baseline studies**. Boston: Massachusetts Water Resources Authority. Report ENQUAD ms-02. 95p.

MWRA. 1997a. **Massachusetts Water Resources Authority effluent outfall monitoring plan: Phase II post discharge monitoring**. Boston: Massachusetts Water Resources Authority. Report ENQUAD ms-44. 61p.

MWRA. 2003. **Briefing for the OMSAP workshop on ambient monitoring revisions: March 31-April 1, 2003**. Boston: Massachusetts Water Resources Authority. Report ENQUAD ms-083. 91p.

NRC. 1990. **Managing Troubled Waters**: The Role of Marine Monitoring. National Research Council. National Academy Press, Washington, DC. 125pp.

2. MWRA EFFLUENT MONITORING

Andrea Rex, David Wu, Steve Rhode, Michael Delaney, Maury Hall, Suh Yuen Liang, Grace Vitale, David Duest, David Taylor

Much of this section is the same as the effluent report in the "Briefing for OMSAP on ambient monitoring revisions March 31-April 1, 2003;" the discussion at that workshop focused on toxic contaminants. The effluent discussion for this workshop about water column monitoring will focus on other components of the effluent, including nutrients (pages 2-17, 2-19 and 2-29 to 2-33), indicator bacteria and pathogens (pages 2-27 to 2-30), and floatables (pages 2-19 to 2-20). The floatables part of this section has been revised to include more recent monitoring data, and the nutrients discussion has been expanded to include analyses of phosphorus as well as nitrogen.

2.1 Ensuring Effluent Quality: Pollution Prevention and Wastewater Treatment

The most important part of protecting Massachusetts Bay from pollution is ensuring that the final treated effluent is as clean as possible. MWRA accomplishes this through a vigorous pretreatment program and pollution prevention initiatives that minimize toxic contaminants entering the waste stream, and by maintaining and operating the treatment plant well. The MWRA toxic reduction and control program sets and enforces limits on the types and amounts of pollutants that industries can discharge into the sewer system. This has the important effect of minimizing contaminants in effluent and in the sludge that is removed during secondary treatment, enabling beneficial re-use of treated sludge.

Secondary treatment further reduces the concentrations of contaminants of concern (except nutrients) that are in the effluent that is ultimately discharged to Massachusetts Bay.

To prevent accidental discharge of pollutants to the system, MWRA has implemented best management practice plans for the Deer Island plant, its headworks facilities, the combined sewer overflow facilities, and the sludge pelletizing plant. Best management practices include daily visual inspections and immediate corrective response. Effectiveness of BMP measures are assessed by non-facility staff.

The extensive monitoring required in MWRA's stringent discharge permit, and the additional monitoring required in the Ambient Monitoring Plan and the Contingency Plan demonstrate how well the flow is treated.

MWRA is not proposing modifications to the effluent requirements in the Ambient Monitoring Plan at this time. Effluent monitoring data are presented here in detail because these results show that the plant is performing as well or better than anticipated in initial environmental impact studies during the treatment plant's design phase, and because the quality of the effluent provides a foundation for changes that MWRA will propose in the fish and shellfish and sediment contamination monitoring.

Pollution prevention

Details of MWRA's pollution prevention program are in the "*Massachusetts Water Resources Authority Industrial Waste Report, No. 18 October 2002*" on the web at http://www.mwra.com/sewer/html/trac_indust02.pdf. In addition to regulation of industrial discharges, MWRA's recent initiatives include programs for source reduction of mercury from dental facilities and household hazardous waste education programs. The report shows that in FY02 (ending June, 2002) there was no evidence of interference with treatment by toxic contaminants at the Deer Island Treatment Plant (DITP); sludge pellets met EPA Type 1 sludge criteria and met Massachusetts DEP criteria for Type 1 sludge except for molybdenum. In August, 2002 however, a high-sulfate industrial discharge to DITP did cause an upset of the secondary treatment process, discussed further below in section 2-3.

Table 2-1 Levels of influent organic and metal contaminants to the Deer Island Treatment Plant, which have remained at low levels since the early 1990's.

Influent contaminant loadings

Constituent	Loading (lbs/day) 2001	Loading (lbs/day) 2002
Arsenic	2.4	2.2
Chromium	15.0	10.0
Copper	188	172
Lead	37.2	25.3
Mercury	0.67	0.48
Nickel	14.4	11.0
Silver	4.9	3.9
Zinc	321	294
VOA	532	485
Pesticides	0.040	0.043
Phthalates[1]	58.9	64.1
Total phenols	104	120
PAHs[2]	28.5	26.5

[1]**Phthalates:**
BIS(2-ETHYLHEXYL)PHTHALATE
BUTYL BENZYL PHTHALATE
DI-N-BUTYLPHTHALATE
DI-N-OCTYLPHTHALATE
DIETHYL PHTHALATE
DIMETHYL PHTHALATE

[2]**PAH's** are estimated based on 9 samples and include
2-METHYLNAPHTHALENE
ACENAPHTHENE
ACENAPHTHYLENE
ANTHRACENE
BENZO(A)ANTHRACENE
BENZO(A)PYRENE
BENZO(B)FLUORANTHENE
BENZO(GHI)PERYLENE
BENZO(K)FLUORANTHENE
CHRYSENE
DIBENZO(A,H)ANTHRACENE
DIBENZOFURAN
FLUORANTHENE
FLUORENE
INDENO(1,2,3-CD)PYRENE
NAPHTHALENE
PHENANTHRENE
PYRENE

Effects of Secondary Treatment

Biological secondary treatment effectively removes contaminants except for nutrients. Figure 2-1 shows how the proportion of flows receiving secondary treatment increased as construction on the DITP progressed; the final battery of secondary treatment was completed in the spring of

2001 (mid FY2001). Figure 2-2 shows how solids discharges from MWRA sources including Deer Island and Nut Island treatment plants and sludge decreased by 80% since the beginning of the Boston Harbor project and Figure 2-3 illustrates how biochemical oxygen-demanding constituents also dramatically declined.

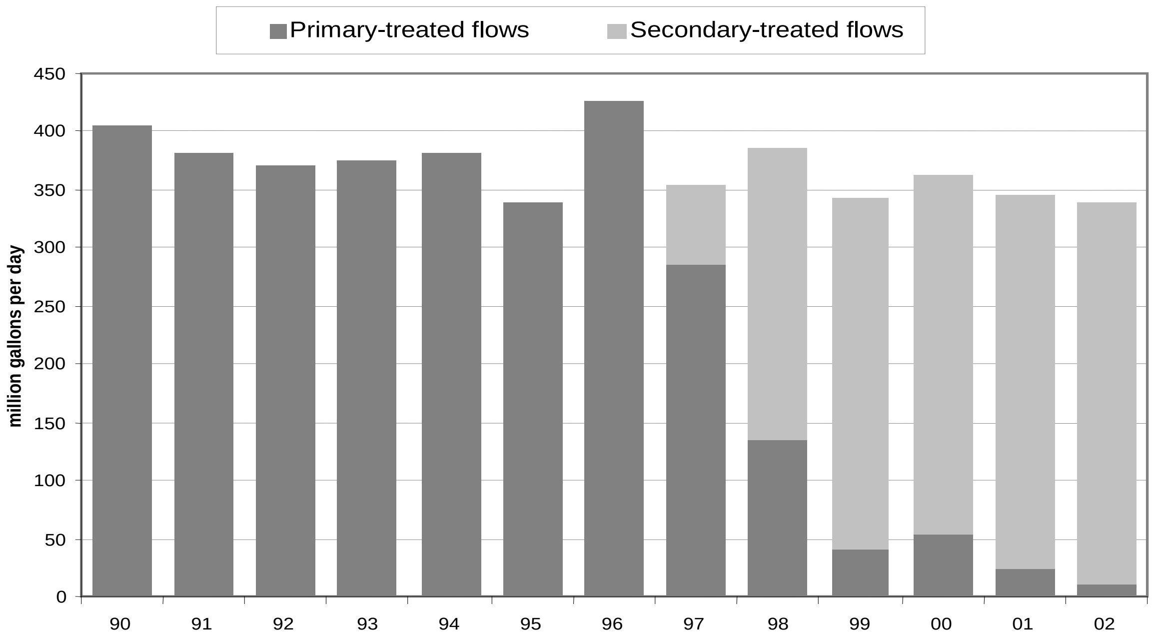


Figure 2-1 MWRA Primary and Secondary Treated Flows, 1990-2002

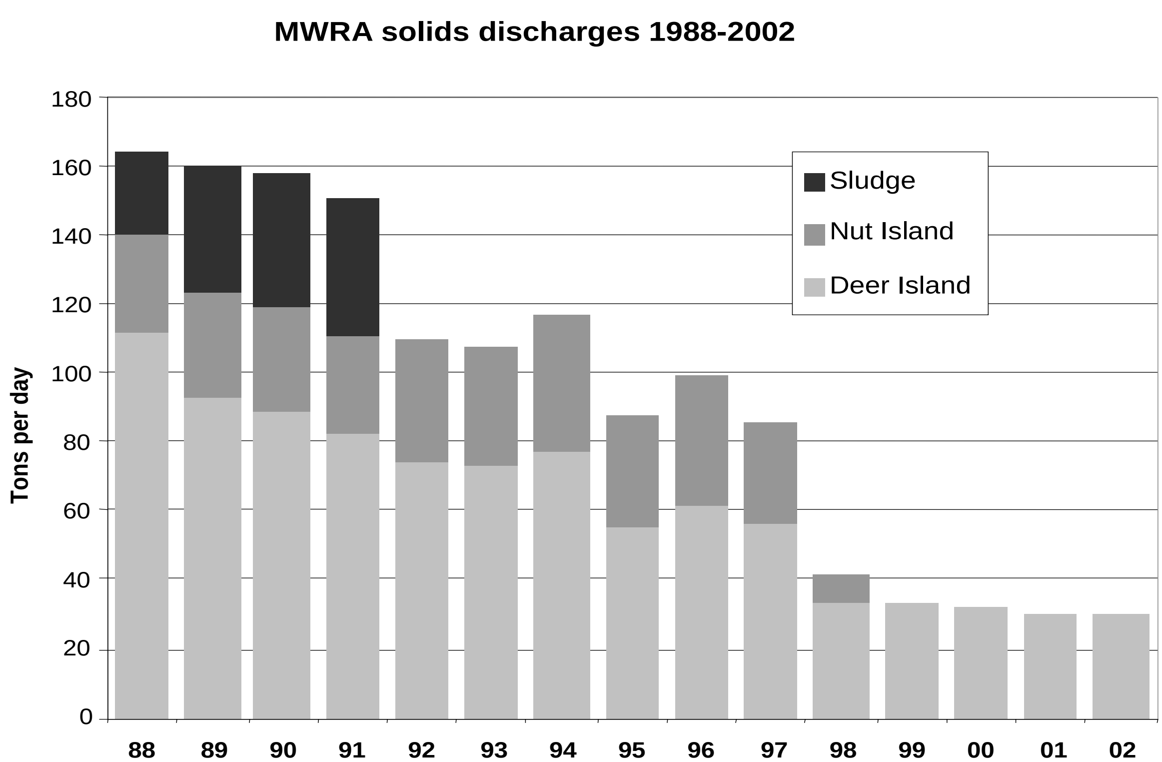


Figure 2-2 MWRA Solids Discharges, 1988-2002

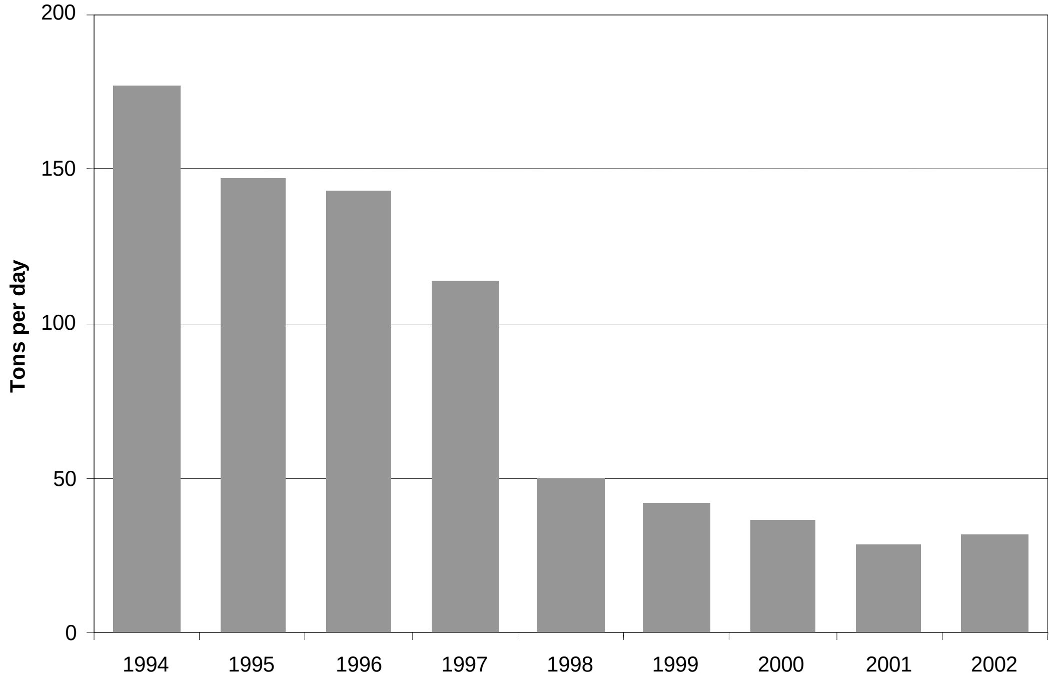


Figure 2-3 Biochemical Oxygen Demand in MWRA Discharges

This table shows that the percent of flow receiving activated sludge secondary treatment since FY1999 has increased. The percent of flow receiving secondary treatment varies with rainfall; the more it rains, the smaller the proportion of flow receiving secondary treatment. Thus, 88% of flow received secondary treatment in FY2001, a wet period, and 98% of flow received secondary treatment in FY2002, a dry period. Note, however that TSS and BOD removal were high in both those years.

Table 2-2 TSS and BOD Removal Efficiencies

MWRA Fiscal Year (July-June)	TSS removal (%)	BOD or cBOD removal (%)	Percent of flow receiving secondary treatment
FY1999	87	80	86
FY 2000	89	83	89
FY 2001	91	89	88
FY2002	92	90	98

Operation and Maintenance Requirements in Permit

MWRA's discharge permit requires that MWRA submit an operation and maintenance plan to regulatory agencies, and report on the results of the implementation of that plan annually. The most recent report is on the web at: http://www.mwra.com/harbor/pdf/omstatus02.pdf

The report summarizes operation and maintenance activities at the treatment plant, conveyance facilities and pipelines, and the sludge pelletizing facilities.

2.2 Tracking effluent quality: Monitoring requirements

MWRA's effluent monitoring requirements are laid out in three different areas of the permit: standard discharge monitoring requirements reported to regulatory agencies monthly in the National Pollutant Discharge Elimination Program (NPDES) Discharge Monitoring Reports (DMRs), additional requirements in the outfall Contingency Plan, and requirements in the Ambient Monitoring Plan.

Monitoring questions

In the Ambient Monitoring Plan (AMP), the monitoring questions on effluent quality address whether MWRA is meeting its permit limits, thus the monitoring to answer these questions will continue. The questions in the AMP are:

1. Do effluent pathogens exceed permit limits?
2. Does acute or chronic toxicity of effluent exceed permit limits?
3. Do effluent contaminant concentrations exceed permit limits?
4. Do conventional pollutants in the effluent exceed permit limits?

Additional effluent monitoring requirements in the Monitoring Plan and the Contingency Plan beyond those in the NPDES DMR monitoring address emerging issues that the Outfall Monitoring Task Force saw as concerns, for example nutrient loading, newer pathogen indicators, and non-standard low-detection methods for measuring contaminants in the effluent. The tables in Section 2-2 list the effluent parameters measured for the different types of permit requirements, and Section 2-3 presents results of effluent monitoring.

Permit discharge monitoring requirements

These requirements, shown in Table 2-3, are typical for wastewater treatment permits, and are not subject to modification under the Ambient Monitoring Plan provisions of the permit. Some of the parameters have limits and some are "report only."

Table 2-3 MWRA Permit-required DMR Monitoring for Deer Island Treatment Plant effluent

Parameter	Sample Type	Frequency	Limit
Flow	Flow meter	Continuous	REPORT ONLY
Flow dry day	Flow meter	Continuous	436 MGD annual average
cBOD	24-hr composite	1/day	40 mg/L weekly 25 mg/L monthly
TSS	24-hr composite	1/day	45 mg/L weekly 30 mg/l monthly
pH	Grab	1/day	not <6 or >9
Fecal coliform bacteria	Grab	3/day	14,000 col/100ml
Total residual chlorine	Grab	3/day	631ug/L daily 456 ug/L monthly
PCB, Aroclors	24-hr composite	1/month	0.045 ng/L
Toxicity LC50	24-hr composite	2/month	50%
Toxicity C-NOEC	24-hr composite	2/month	1.5%
Settleable solids	Grab	1/day	
Chlorides (influent only)	Grab	1/day	
Mercury	24-hr composite	1/month	
Chlordane	24-hr composite	1/month	
4,4' – DDT	24-hr composite	1/month	
Dieldrin	24-hr composite	1/month	
Heptachlor	24-hr composite	1/month	
Ammonia-nitrogen	24-hr composite	1/month	
Total Kjeldahl nitrogen	24-hr composite	1/month	
Total nitrate	24-hr composite	1/month	
Total nitrite	24-hr composite	1/month	
Cyanide, total	Grab	1/month	
Copper, total	24-hr composite	1/month	
Total arsenic	24-hr composite	1/month	
Hexachlorobenzene	24-hr composite	1/month	
Aldrin	24-hr composite	1/month	
Heptachlor epoxide	24-hr composite	1/month	
Total PCBs	24-hr composite	1/month	
Volatile organic compounds	Grab	1/month	Report

Monitoring requirements in the Contingency Plan

All of the DMR effluent monitoring limits have Contingency Plan thresholds; the Warning Level thresholds are the permit limitations. The Contingency Plan specifies additional thresholds for the parameters in Table 2-4.

Table 2-4 Parameters reported as required in the Contingency Plan

Parameter	Sample type	Frequency
Plant performance	not applicable	annual
Annual nitrogen load	composite	annual (based on 5 samples/month)
Floatables (being developed)	7-day composite	1/month
Oil and Grease	grab	weekly

Monitoring requirements in Ambient Monitoring Plan.

The Ambient Monitoring Plan details requirements (Table 2-5) beyond those included in ordinary discharge monitoring. More frequent and additional nutrient measurements are required, and non-standard low-detection limit methods are used to measure toxic contaminants.

Table 2-5 Ambient Monitoring Plan Parameters for Effluent

Parameter	Sample type	Frequency
Nutrients		
Total Kjeldahl nitrogen	composite	weekly
Ammonia	composite	weekly
Nitrate	composite	weekly
Nitrite	composite	weekly
Total phosphorus	composite	weekly
Total phosphate	composite	weekly
Acid base neutrals	composite	bimonthly
Volatile Organic Compounds	grab	bimonthly
Low detection limit analyses		
Cadmium	24-hr composite	weekly
Copper	24-hr composite	weekly
Chromium	24-hr composite	weekly
Mercury	24-hr composite	weekly
Lead	24-hr composite	weekly
Molybdenum	24-hr composite	weekly
Nickel	24-hr composite	weekly
Silver	24-hr composite	weekly
Zinc	24-hr composite	weekly
17 chlorinated pesticides	24-hr composite	weekly
Extended list of PAHs	24-hr composite	weekly
LABs	24-hr composite	weekly
20 PCB congeners	24-hr composite	weekly

Special studies outlined in Ambient Monitoring Plan.

The Ambient Monitoring Plan calls for an evaluation of indicators of human pathogens, but does not explicitly define how MWRA must carry out this evaluation. MWRA has collected data for two projects that address this requirement:

- Anthropogenic viruses and viral indicators in DITP influent and effluent
- *Enterococcus* in DITP influent and effluent

The Ambient Monitoring Plan also calls for an evaluation of effluent tracers. MWRA is co-sponsoring, with Sea Grant, a University of Massachusetts and Tufts University study of endocrine disruptors in Deer Island influent and effluent, in Boston Harbor, and around the new outfall site (these data are not yet available). MWRA's investigators have also measured sulfur and nitrogen isotope patterns in effluent to help determine if nitrogen isotopes may be a useful tracer in evaluating a zone of effect of the effluent. MWRA evaluates proposals to study emerging potential effluent tracers on an ongoing basis as new scientific developments occur. Another special study with the Woods Hole Oceanographic Institution is examining the utility of a gel membrane sensor to detect what proportion of copper in the effluent is bioavailable (data not yet available).

2.3 Effluent Monitoring Results

This section presents results from all the types of effluent monitoring done by MWRA, including the more "routine" effluent monitoring, and more specialized testing required in the Contingency Plan and Ambient Monitoring Plan. Table 2-6 shows how Deer Island effluent quality has changed for "conventional pollutants." (Note that flows from DITP increased in FY99 when the Nut Island Treatment Plant was closed and south system flows transferred to DITP).

Table 2-6 Deer Island Effluent Characterization, FY94-FY02 July 1993-June 2002

Parameter	FY94*	FY95*	FY96*	FY97*	FY98*	FY99	FY00	FY01	FY02
Average flow (MGD)	249	236	250	265.0	296.2	349.7	356	367.3	316.6
Average concentrations									
TSS (mg/L)	73.0	65.0	44.0	41.2	25.4	21.5	17.8	15.4	16.0
cBOD (mg/L)	ND	117.5	82.5	72.7	27.2	22.5	15.0	12.2	13.0
Settleable Solids (ml/L)	0.5	0.4	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Total Kjeldahl Nitrogen (mg/L)	21.7	23.0	22.5	21.9	20.4	23.4	21.8	23.6	25.9
Ammonia Nitrogen (mg/L)	12.6	14.4	14.5	13.1	15.1	18.0	17.6	17.6	21.2
Nitrates (mg/L)	1.04	0.08	0.30	0.34	0.42	0.22	0.69	0.70	0.89
Nitrites (mg/L)	0.10	0.08	0.63	0.11	0.20	0.30	0.95	0.20	0.34
Orthophosphates (mg/L)	2.15	2.22	1.53	1.68	1.71	1.97	1.90	1.90	2.30
Total Phosphorus (mg/L)	2.92	3.35	3.42	2.90	2.77	2.93	3.00	2.80	3.10
Average loading (tons/day)									
TSS	52.1	45.3	27.0	28.7	16.8	14.2	26.5	23.6	21.1
cBOD	ND	114.5	87.1	82.4	32.6	34.0	23.8	19.4	16.9
Settleable Solids	0.4	0.3	0.1	0.1	0.1	0.1	0.1	0.2	0.1
Total Kjeldahl Nitrogen	22.5	22.6	23.4	24.3	25.2	34.2	32.4	36.1	34.2
Ammonia nitrogen	8.97	10.05	8.88	9.12	9.97	11.90	26.16	27.00	28.00
Nitrates	0.74	0.06	0.18	0.23	0.28	0.15	1.03	1.10	1.20
Nitrites	0.07	0.06	0.39	0.08	0.13	0.20	1.41	0.30	0.40
Orthophosphates	2.23	2.18	1.60	1.86	2.11	2.87	2.82	2.91	3.04
Total Phosphorus	3.03	3.30	3.57	3.20	3.42	4.27	4.46	4.29	4.09

*North System only. FY99 and later include South System data.

Permit discharge monitoring results: compliance with regulatory limits

Table 2-7 summarizes the results of effluent monitoring since the permit was effective. Details of monitoring results for individual tests follow.

Table 2-7 Summary of effluent monitoring results for DMR reporting

Parameter	Permit limits	Monitoring Results		
		Sep 6 – Dec 31 2000	2001	2002
Toxicity	Acute: effluent LC50<50% for shrimp and fish Chronic: effluent NOEC for fish survival and growth and sea urchin fertilization <1.5% effluent	No violations	One violation of chronic fish growth and one violation of sea urchin fertilization	No violations
Fecal coliform bacteria	<14,000 fecal coliforms/100 mL (monthly 90th percentile, weekly geometric mean, maximum daily geometric mean, and minimum of 3 consecutive samples)	No violations	One violation of daily geometric mean level	No violations
Total suspended solids	no more than 45 mg/L weekly 30 mg/L monthly	No violations	No violations	Two weekly violations One monthly violation
Carbonaceous biochemical oxygen demand	no more than 40 mg/L weekly, 25 mg/L monthly	No violations	No violations	No violations
Residual chlorine	no more than 631 ug/L daily, 456 ug/L monthly	One daily violation = 900 ug/L; before automated feedback for dechlorination	No violations	No violations
pH	not <6 or >9	One violation = 5.8, sampling artifact	No violations	No violations
PCBs as Aroclor	Aroclor= no more than 0.045 ng/L	No violations	No violations	No violations
Average dry day flow	Flow no more than 436 MGD annual average of dry days	Not applicable	No violations	No violations

Whole effluent toxicity. The MWRA tests effluent toxicity every month at DITP. Effluent toxicity provides an overall view of effluent quality, ensuring that the effluent does not adversely affect the environment. In 1989, the EPA found that the probable cause of most acute toxicity in DITP's waste stream was due to surfactants. Surfactants are most commonly used in household detergents to improve cleansing power. No acute toxicity could be attributed to metals or pesticides.

The MWRA permit requires four tests for effluent toxicity testing. 48-hr acute static toxicity tests using the mysid shrimp (*Americamysis bahia*) and the inland silverside fish (*Menidia beryllina*) measure the short-term lethal effects caused by the effluent. A chronic survival and growth test using *Menidia* and a chronic fertilization test using the sea urchin (*Arbacia punctulata*) both measure subtle toxic impacts over a longer period of time. The results of these tests for 2001 and 2002 are in Table 2-8.

Table 2-8 Toxicity test results for Deer Island Treatment Plant effluent

Month-year	Acute toxicity LC50 (%)	Permit limit minimum = 50%	Chronic toxicity NOEC (%)	Permit limit minimum = 1.5%
	Menidia *(Inland silverside)*	***Americamysis*** *(Mysid shrimp)*	***Menidia*** *(Inland silverside) growth*	***Arbacia*** *(Sea urchin) fertilization*
January-01	100	100	50	1 (failure)
February-01	79.1	100	12.5	25
March-01	100	100	100	50
April-01	100	100	1 (failure)	100
May-01	100	100	50	25
June-01	76.3	100	50	50
July-01	75.2	100	50	25
August-01	87	100	25	6.25
September-01	82.4	100	25	100
October-01	69.5	100	6.25	50
November-01	63.1	100	25	100
December-01	68.3	70.7	50	*
January-02	97.7	95.6	50	25
February-02	100	100	50	100
March-02	100	100	25	100
April-02	100	100	100	25
May-02	100	100	50	50
June-02	72.2	100	50	100
July-02	68.3	100	50	100
August-02	68.3	100	50	50
September-02	100	100	50	50
October-02	100	100	50	100
November-02	64.9	100	50	100
December-02	100	100	50	100

*Not able to perform test due to lack of viable *Arbacia* gametes

The LC50 (Lethal Concentration 50%) is the concentration of effluent in a sample that causes mortality to 50% of the test population during the duration of the test. The NOEC (No Observed Effect Concentration) is the concentration of effluent in a sample to which organisms are exposed in a life cycle or partial life cycle test that has no adverse effects. An NOEC limit of 1.5% means that 1.5% of the sample is effluent, and the remainder dilution water. Any acute LC50 below 50% or chronic NOEC below 1.5% would violate the NPDES limit.

There have been two toxicity test failures since the outfall began operating. In January 2001, the chronic sea urchin fertilization test failed, likely because the test organisms were in sub-optimal condition. This test result is discussed in detail in the notification to EPA and DEP in MWRA's repository libraries and on the web at: http://www.mwra.com/harbor/pdf/px022301.pdf.

In April 2001, the inland silverside fish chronic growth test failed, but this result is likely to have been due to variability in the fish rather than to toxicity of the effluent. Detailed descriptions of these test results are discussed in detail in the notification to EPA and DEP in MWRA's repository libraries and on the web at: http://www.mwra.com/harbor/pdf/px051801.pdf.

Fecal coliform. For fecal coliform, the daily geometric mean of three samples per day has a discharge limit of 14,000 colonies/100mL. Figure 2-4 shows average daily fecal coliform since the NPDES permit became effective in September 2001. There has been one permit violation of fecal coliform, on December 18, 2001, when the daily geometric mean for fecal coliform was 15,597 colonies/100mL. The cause of this violation was a brief drop in total chlorine residual in the disinfection basin due to increased plant flow. With less chlorine and greater wastewater volume, the effectiveness of disinfection fell, leaving greater numbers of fecal coliform bacteria in the effluent. Excepting the one permit violation noted above, the results for Deer Island have been well below the limit, for the monthly geometric means and for the additional limits for fecal coliform of not more than three consecutive samples measuring over 14,000 colonies/100mL and no more than 10% of the samples in a month measuring over 14,000 colonies/100 mL. These three limits were not approached.

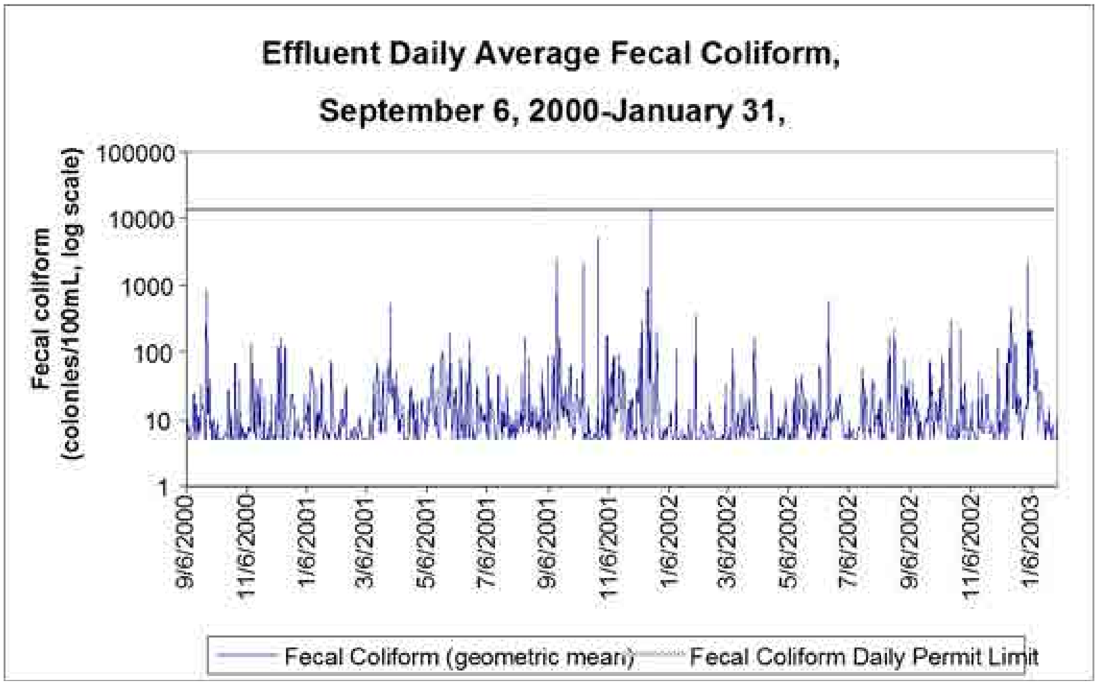


Figure 2-4 Effluent Daily Average Fecal Coliform, Deer Island

Total suspended solids and carbonaceous biochemical oxygen demand. For total suspended solids (TSS) and carbonaceous biochemical oxygen demand (cBOD), the permit limits monthly and weekly average concentrations. Figures 2-5 and 2-6 show that the monthly averages for TSS and cBOD generally were well below the regulatory discharge limits of 25 mg/L for cBOD and 30 mg/L for TSS for monthly average concentration. Both parameters have improved markedly from the historical trends before secondary treatment began in 1997.

In August, 2002, TSS exceeded the permit limitations (and by definition exceeded the Contingency Plan warning level thresholds) for weekly and monthly values. The high TSS in August, 2002 were caused by an “upset” of the secondary treatment plant process: high sulfate industrial waste discharged to the plant during an experiment caused an overgrowth of filamentous bacteria which prevented effective secondary treatment. See http://www.mwra.com/harbor/pdf/200208tpx.pdf for a detailed explanation of this exceedance and how it was handled at the treatment plant to minimize potential impacts. Note that there was no exceedance of BOD during that time period, reflecting the fact that secondary treatment, although compromised, was still removing oxygen-demanding constituents.

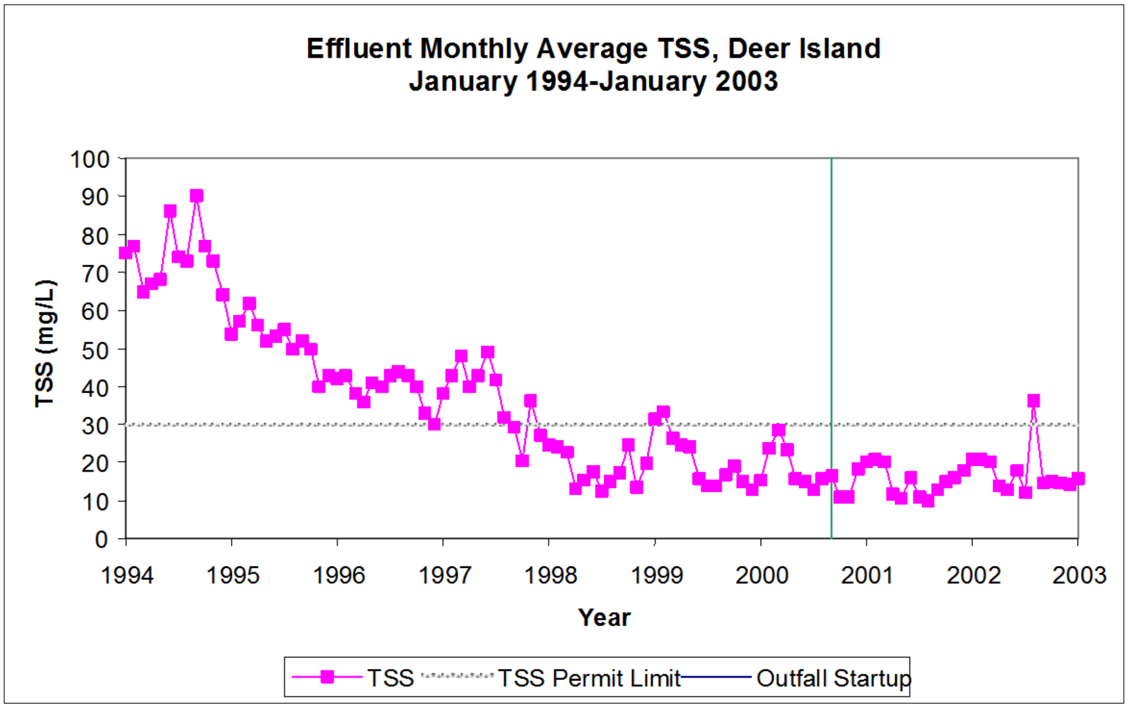


Figure 2-5 Effluent Monthly Average TSS, Deer Island

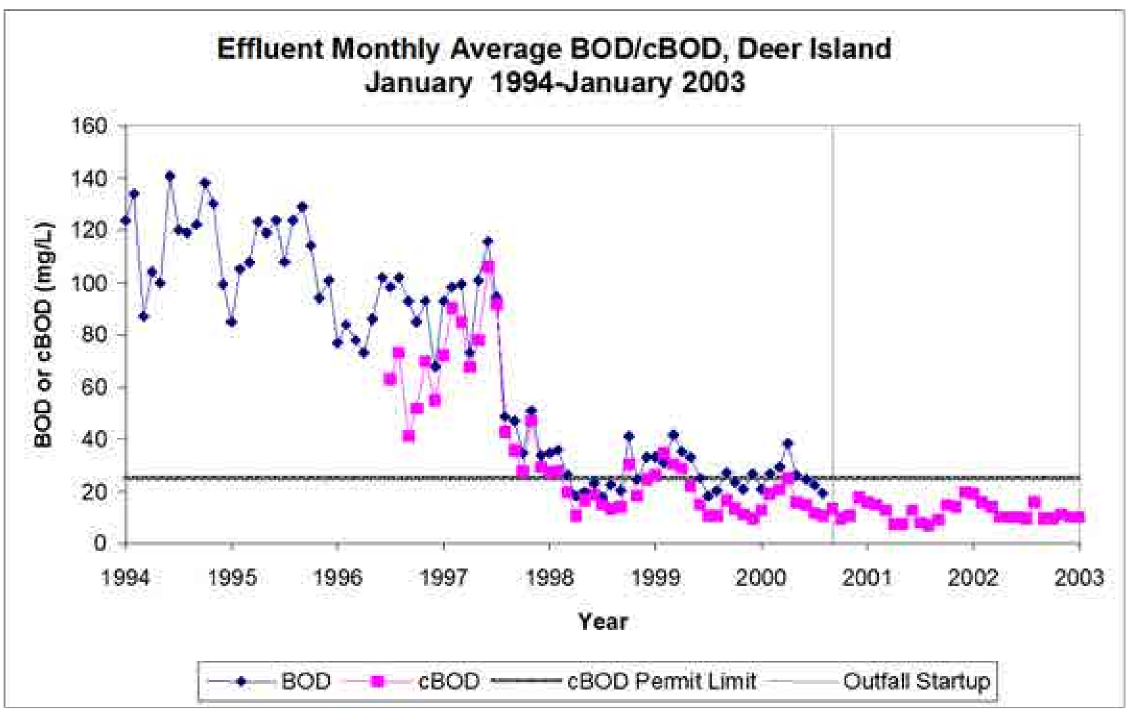


Figure 2-6 Effluent Monthly Average BOD/cBOD, Deer island 1994-2003

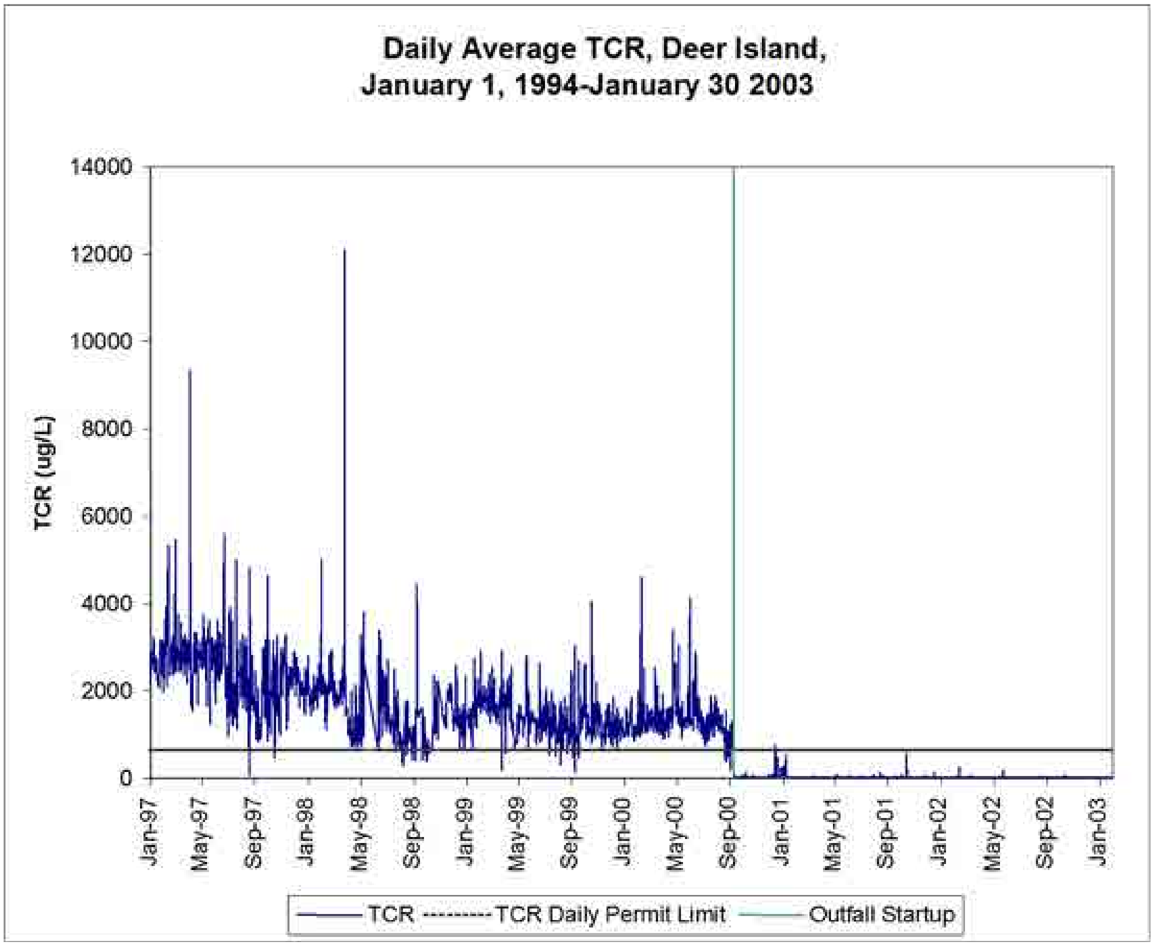


Figure 2-7 Daily Average TCR, Deer Island, 1994-2003

Total chlorine residual. Figure 2-7 shows how the chlorine residual in the effluent discharged from Deer Island has dropped dramatically since 1997. Chlorine is necessary for effective disinfection of the wastewater, but because it can have toxic effects on marine life it is desirable to minimize the amount of chlorine remaining in the final effluent after treatment. As secondary treatment came on line, beginning in mid-1997, the amount of chlorine necessary for effective disinfection decreased. Then, when the new outfall began operating in September 2000, dechlorination also began, greatly reducing the chlorine residual.

pH. DITP effluent tends to be acidic because the pure oxygen used in secondary treatment causes the production of relatively large amounts of CO_2, which when dissolved in the wastewater, increases its acidity. The dissolved CO_2 out-gasses as the effluent tumbles down the shaft from the treatment plant to the outfall tunnel. There was a single pH violation early in the operation of the outfall, because the sampling method was not allowing for a period of out-gassing. Since the sampling method was adjusted, pH measurements have been within permit limits. Figure 2-8 shows the range by month for daily pH for 2002.

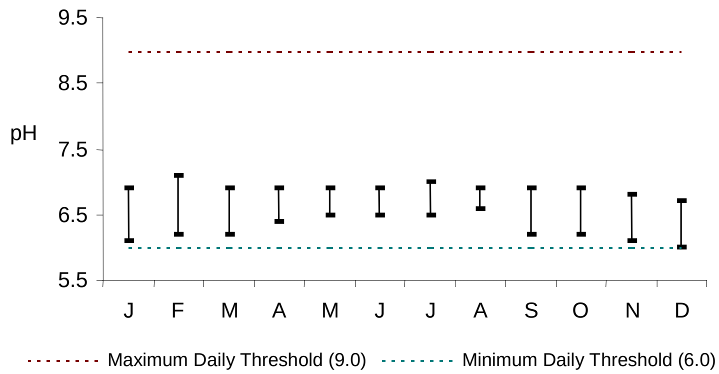


Figure 2-8 pH in Deer Island Effluent, 2002

Aroclors. These PCBs have never been detected in MWRA effluent by EPA standard methods. However, PCBs are detected as part of the Ambient Monitoring Plan sampling, when specialized low-level detection methods are used; see Table 2-11 and further discussion below.

Dry Day Flow. Average dry day flow has been well within permit limits (Figure 2-9).

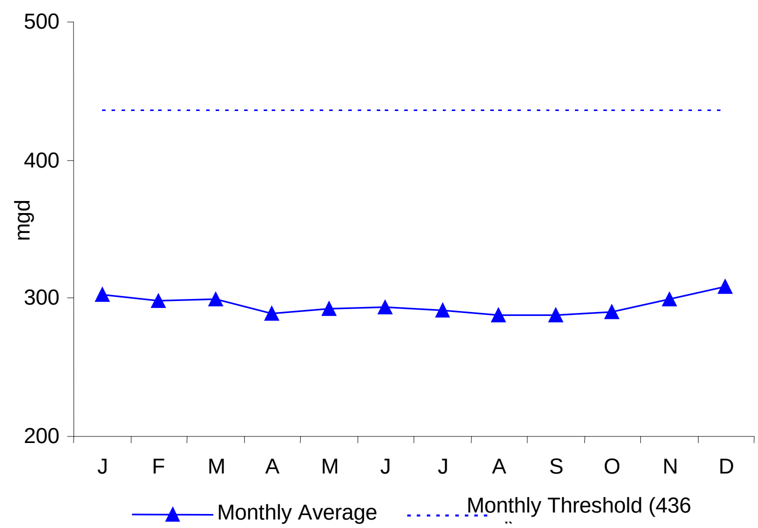


Figure 2-9 Dry Day Flow, Deer Island, 2002

Priority pollutants (metals) in MWRA discharges. MWRA has no numerical limits for most priority pollutants, but must report on test results. Figure 2-10 shows how metals in MWRA effluent have dropped over time. Further discussion of priority pollutant results follows in the discussion of results of the low-detection level sampling required by the Ambient Monitoring Plan.

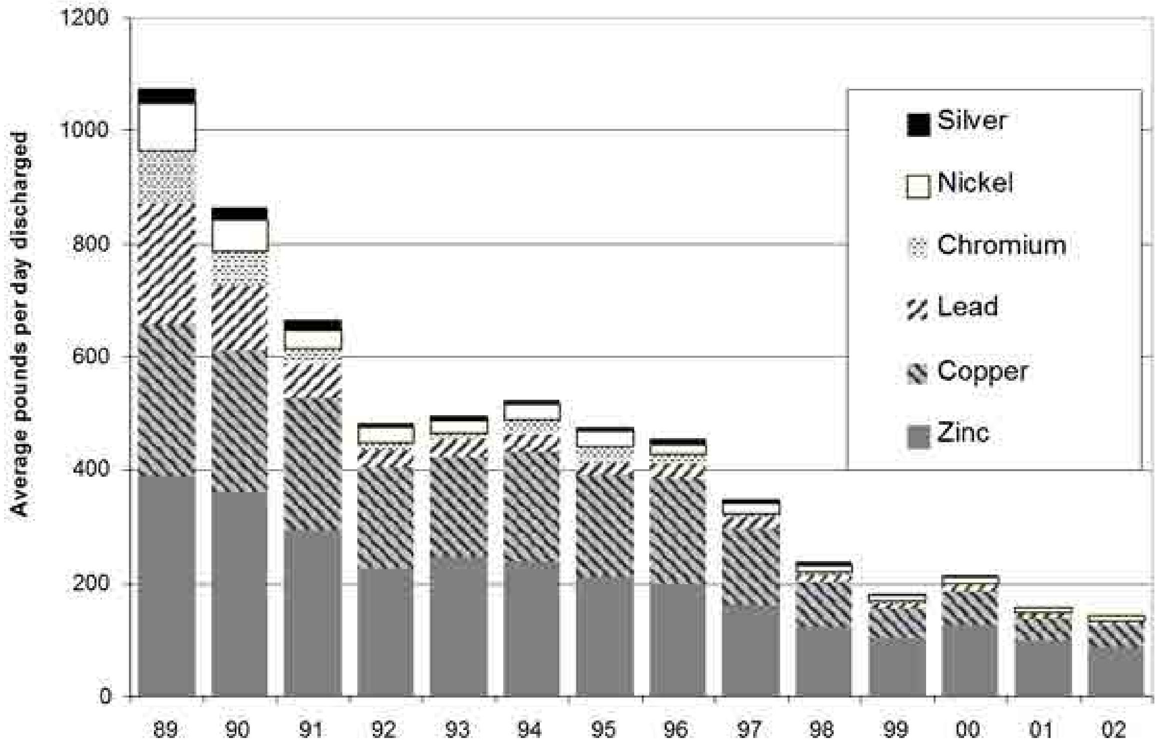


Figure 2-10 Metals in MWRA Treatment Plant Discharges 1989-2002

Contingency Plan Results

Plant performance. This Contingency Plan threshold assesses overall treatment plant performance; the Deer Island Treatment Plant meets the threshold if there are fewer than 5 permit violations in a year, thus qualifying for the American Metropolitan Sewerage Association's "Silver Award." DITP received the Silver Award in 2001, and is applying for the award for 2002, having had fewer than 5 violations.

Total nitrogen load. The total nitrogen load from MWRA treatment facilities has remained stable and below the Contingency Plan Caution Level threshold of 12,500 metric tons/year. (The Warning Level threshold is 14,000 metric tons/year.) Figure 2-11 shows that in 1996, before secondary treatment, total nitrogen would have exceeded the Caution Level threshold. Nitrogen levels have remained below 12,000 metric tons since secondary treatment began in 1997. The amount of dissolved inorganic nitrogen has increased since 1996, as anticipated, because secondary treatment converts organic nitrogen to inorganic nitrogen (ammonia + nitrate/nitrite).

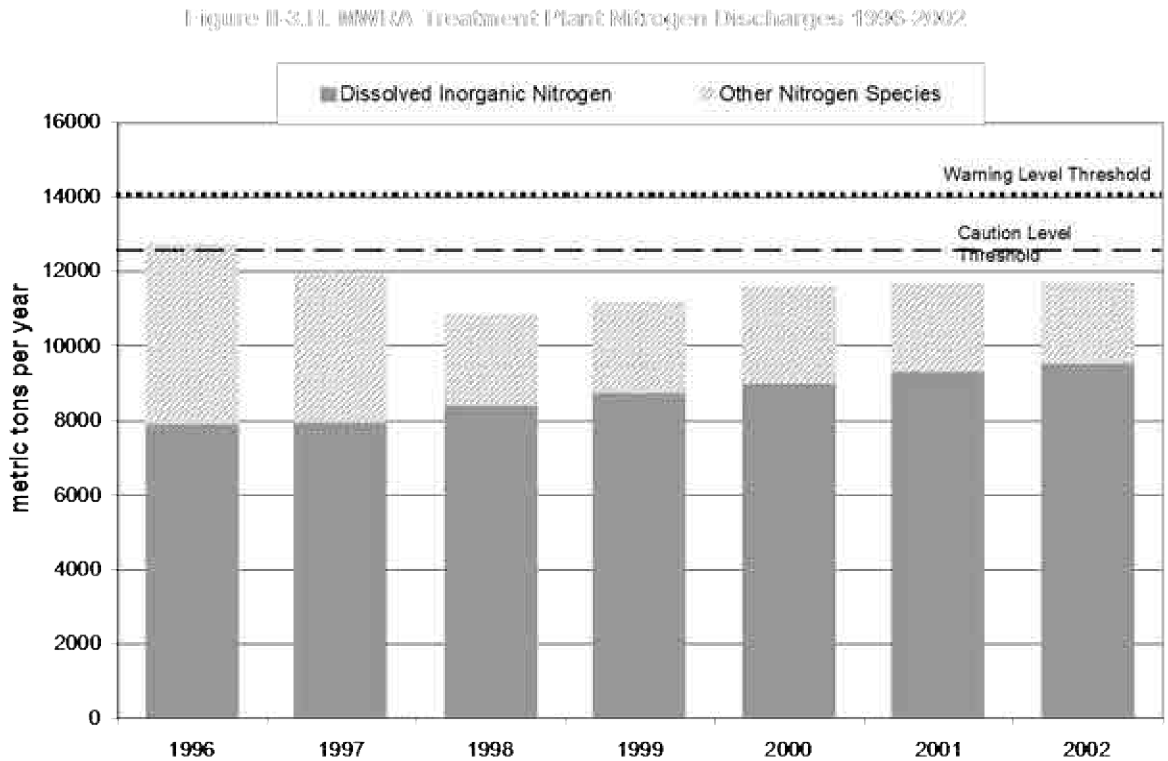


Figure 2-11 MWRA Treatment Plant Nitrogen Discharges 1996-2002

Floatables. MWRA has designed and constructed a floatables sampling device which screens small bits of solid matter from the final effluent. The floatables threshold is still being developed. Data collected indicate that:

- the floatables sampling device is working well, and gives a representative sample of what is discharged in the effluent;
- visual observations confirm that most of the material is broken into small pieces, less than an inch in diameter;
- floatables of special concern (condoms, plastic bags) are very rarely found;
- the average amount of floatables discharged is 11 gallons or 12 kg per 100 mgd;
- approximately 86% of this material (by weight) is degradable, and 14% is non-degradable
- thus, on average, about six gallons of non-degradable floatables are discharged per day;
- volume and weight of total floatables are highly and consistently correlated during normal plant operations; and
- the proportion of floatables in the effluent increases with flow through the treatment plant, and thus rainfall, (Figure 2-12).
- the relationship of floatables to rainfall can be described by a polynomial equation, as shown in. (When DITP reaches its maximum pumping capacity of 1,200 mgd, the amount of flow, and presumably floatables reaches a maximum.)

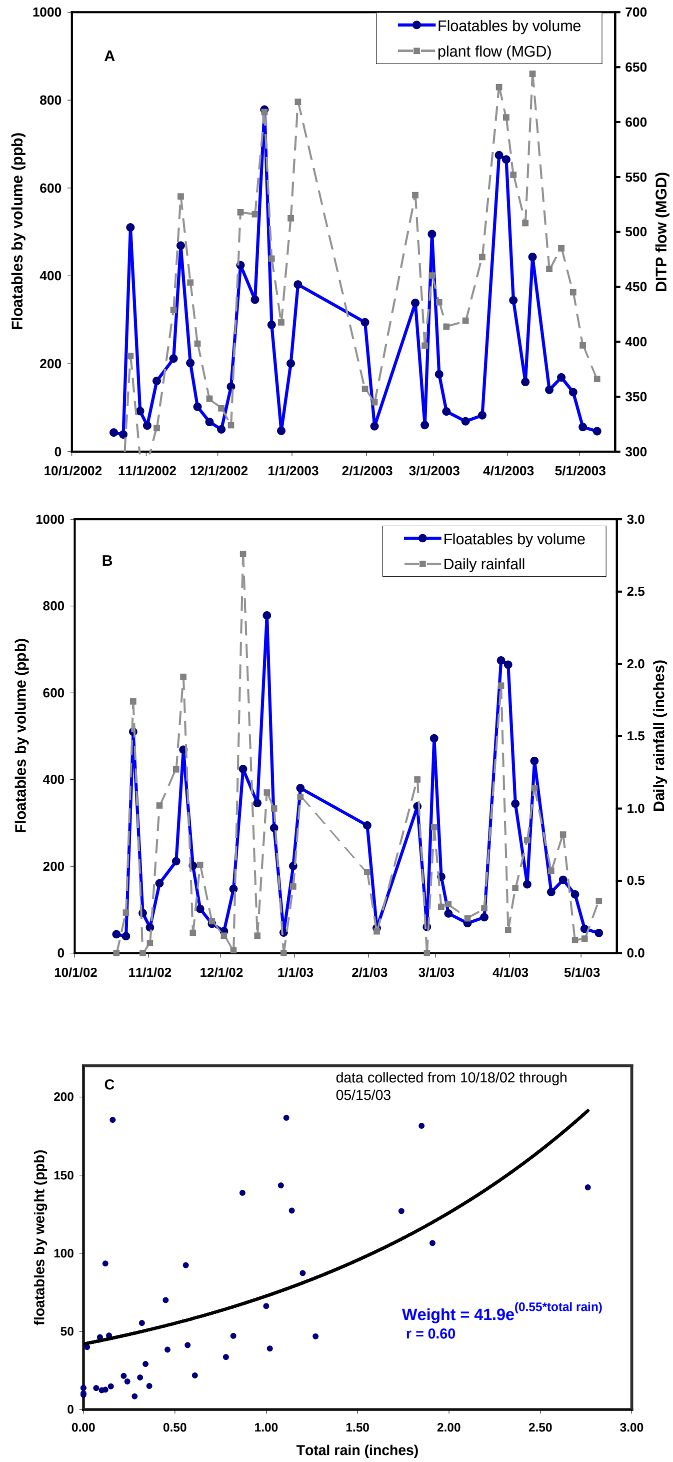


Figure 2-12 Effluent floatables are a function of rain. A. shows time series relationship of floatables with DITP flow, B with rainfall, and C. the regression of floatables on rainfall.

Oil and Grease. A second measure of effluent quality in the Contingency Plan is oil and grease, measured as petroleum hydrocarbons (PHC). As shown in Figure 2-13, and Table 2-9 PHC has averaged less than 0.2 mg/L, well below the 15 mg/L threshold.

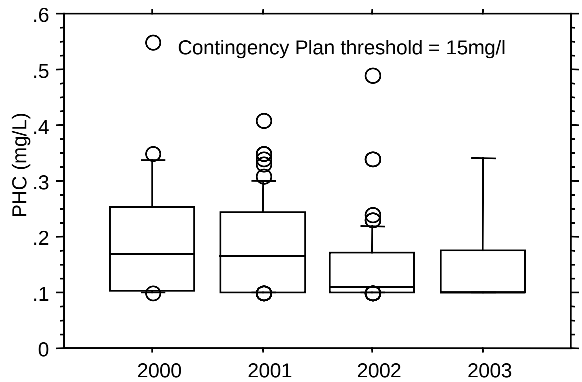


Figure 2-13 Petroleum Hydrocarbons in DITP Effluent

Table 2-9 Petroleum Hydrocarbons in DITP effluent, descriptive statistics (mg/L)

-

	All years	2000	2001	2002	2003
Mean	.167	.201	.181	.144	.152
Std. Dev.	.085	.116	.083	.070	.105
Std. Error	.007	.027	.010	.009	.047
Count	153	19	64	65	5
Minimum	.100	.100	.100	.100	.100
Maximum	.550	.550	.410	.490	.340

Ambient Monitoring Plan Results: Detailed effluent characterization study, using low detection limit methods.

Metals

Low detection limit effluent monitoring for metals is conducting using NPDES approved methods, based on inductively coupled plasma atomic emission spectrometry (ICP) or graphite furnace atomic absorption spectrometry (GFAA).

Priority pollutant concentrations in Deer Island effluent are very low. Table 2-10 compares concentrations of priority pollutant metals in DITP effluent to water quality criteria.

Table 2-10 Comparison of DITP Effluent to Water Quality Criteria for Metals, 2001-2002

ACUTE

	Total Recoverable Maximum (ug/L)	Total Dissolved Maximum (ug/L)	Dilution	Estimated Concentration in ZID	Acute Criteria*** (ug/L)	Times Detected
Arsenic	0.4	0.4	50	0.008	69	0 of 23
Copper	22.2	18.4	50	0.37	4.8	87 of 107
Lead	4.3	4.1	50	0.082	210	5 of 75
Mercury	0.053	0.045	50	0.0009	1.8	74 of 88
Nickel	5.38	5.33	50	0.11	74	76 of 76
Silver	1.06	0.901	50	0.018	1.9	72 of 75
Zinc	51.2	48.4	50	0.97	90	75 of 75

CHRONIC

	Total Recoverable Average (ug/L)	Total Dissolved Average (ug/L)	Dilution	Estimated Concentration in ZID	Chronic Criteria*** (ug/L)	Times Detected
Arsenic	0.4	0.4	70	0.006	36	0 of 23
Copper	12.6	10.5	70	0.15	3.1	87 of 107
Lead	1.38	1.31	70	0.019	8.1	5 of 75
Mercury	0.0181	0.0154	70	0.00023	0.94	74 of 88
Nickel	2.7	2.7	70	0.038	8.2	76 of 76
Silver	0.309	*	70	*	**	72 of 75
Zinc	27.7	26.2	70	0.37	81	75 of 75

ZID: Zone of Initial Dilution
* No applicable conversion factor
** No applicable criteria
*** Criteria from National Recommended Water Quality Criteria for Priority Toxic Pollutants, Federal Register, December 10, 1998
Total Dissolved Max Conc (Col D) = Total Recoverable Max Conc (Col C) * Criteria Maximum Concentration (CMC, see below)
Total Dissolved Avg Conc (Col D) = Total Recoverable Average Conc (Col C) * Criteria Continuous Concentration (CCC, see below)

Conversion factors for "Acute" and "Chronic"

	CMC	CCC
As	1	1
Cu	0.83	0.83
Pb	0.951	0.951
Hg	0.85	0.85
Ni	0.99	0.99
Ag	0.85	*
Zn	0.946	0.946

Federal Register 12/10/98, 98-30272

The majority of priority pollutant parameters were below detection levels. Those that were detected had relatively low concentrations. All of the maximum values measured, except for copper, met acute receiving water quality criteria in effluent *before dilution*. All the average values, except for copper, met the chronic receiving water criteria in the effluent *before dilution*. The water quality criteria apply *after* initial dilution (at the outfall, the acute initial dilution is approximately 50:1, chronic is 70:1). Attachment S in the NPDES permit gives calculation details for estimating the receiving water concentrations based on effluent concentrations.

Organic Contaminants

Low detection limit effluent monitoring for organic contaminants includes pesticides, polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAH), semivolatile organics (ABN), and volatile organics (VOA). The analytical methods for organics are derived from the EPA methods approved for the NPDES program, but modified to achieve increased sensitivity. In particular, selected ion monitoring (SIM) gas chromatography / mass spectrometry (GC/MS) is used to increase the sensitivity of the PAH method.

Twenty-four hour composite samples of Deer Island Treatment Plant effluent are collected at least weekly and tested for most organic parameters. Due to their volatility, VOA samples collected as grab samples in samples twice a month. DITP effluent results for organic parameters for FY02 are summarized in Table 2-11 with all concentrations in parts-per-trillion (ng/L).

Volatile Organic contaminants. (VOA). Six of 43 VOA parameters were detected in 25 grab samples. Detected contaminants were at low parts-per-billion (µg/L) concentrations, and none of these contaminants have water quality criteria for toxicity to marine life. The maximum observed value for tetrachloroethene slightly exceeded the 10^{-6} human health criteria for this compound *before dilution* of the effluent.

Semivolatile Organics (ABN). Only one ABN parameter was detected, in one of 25 samples collected during FY02. Bis(2-ethylhexyl)phthalate (BEHP) was detected in a sample collected 14-Sep-2001 at 14 µg/L. This exceeds the 10^{-6} human health criteria for BEHP (5.9 µg/L) by about a factor of two *before dilution* of the effluent.

Table 2-11 Comparison of Deer Island Treatment Plant effluent to water quality criteria for organic contaminants (parts per trillion)

Component	N of samples Detected	Maximum of samples detected (ng/L)	Mean of samples detected (ng/L)	Acute Criteria ** (ng/L)	Chronic Criteria **	Human Health Criteria** (ng/L)
Acetone	23 of 25	28,000	8,040	B	B	B
Carbon Disulfide	1 of 25	5,610	5,610	B	B	B
Chloroform	24 of 25	8,580	6,170	B	B	470,000
Methylene Chloride	9 of 25	5,890	3,570	B	B	1,600,000
Tetrachloroethene	20 of 25	12,800	5,480	B	B	8,850
Toluene	1 of 25	2,810	2,810	B	B	200,000,000
Bis(2-ethylhexyl)phthalate	1 of 25	14,000	14,000	B	B	5,900
Total NOAA PAH	52 of 52	1,274	285	B	B	B
Chrysene	52 of 52	67.9	17.5	B	B	49
Phenanthrene	52 of 52	226	26.8	B	B	B
Chlordane	48 of 62	58.2	4.67	90	4	2.2
04,4'-DDT	7 of 62	1.49	0.58	30	1	0.59
Lindane	51 of 62	9.7	2.06	160	B	63
Heptachlor	6 of 62	6.27	2.87	90	4	0.21
Total DDT	40 of 62	4.27	1.33	B	B	B
Total PCB	42 of 59	5.72	1.30	B	30	0.17

B - No applicable criteria

** National Recommended Water Quality Criteria for Priority Toxic Pollutants, Federal Register, December 10, 1998

Polycyclic aromatic hydrocarbons (PAH). Certain individual PAHs are routinely detected in DITP effluent samples at sub-parts-per-billion concentrations. These results are summarized in Table 2-11 as "Total NOAA PAH" because this is the grouping used in the Contingency Plan threshold for mussels. The NOAA PAH are 24 individual PAH components. None of these have water quality for toxicity to marine life, but seven of the 24 have been listed as probable human carcinogens and are assigned a value of 49 ng/L as 10^{-6} human health criteria (HHC). The average measured concentrations for all seven of these compounds were below the HHC during FY02, with mean measured concentrations ranging from 10% to 40% of the HHC *before dilution*. Chrysene, which had the highest measured single sample concentration amongst the seven for the year, is listed as an example in Table 2-11. Phenanthrene, which had the highest measured single sample concentration amongst the other 17 PAH, is also listed as an example in Table 2-11.

Pesticides. A few individual pesticides are detected in DITP effluent at parts-per-trillion (ng/L) levels. Chlordane, lindane (gamma-BHC), 4,4'-DDD, and 4,4'-DDE were frequently detected during FY02. The maximum detected concentration of lindane was well below the acute water quality criteria and the average measured concentration was well below the HHC for this compound. The average detected concentration of 4,4'-DDT in seven samples that had detectable levels was slightly below the HHC *before dilution* as well.

Chlordane is measured as the sum of six individual components in MWRA effluent (cis- and trans-chlordane, cis- and trans-nonachlor, heptachlor and heptachlor epoxide). Some or all of these were detected in 48 of 62 effluent samples. The average measured concentration exceeded both the chronic water quality criteria and the 10^{-6} human health criteria before dilution.

Polychlorinated biphenyls (PCBs). The NPDES-approved methods for PCBs are based on detecting and quantifying the Aroclors, which are industrial mixtures of PCBs. There is no NPDES approved method for Total PCB or for individual PCB congeners. There are a total of 209 possible PCB congeners, but only about 140 congeners are found in the virgin industrial mixtures. Due to the multiplicity of possible sources, weathering, and possible biological transformation, detecting Aroclors is not reliable as a measure of the Total PCB content of DITP effluent.

MWRA developed a method for determining 67 individual PCB congeners based on dual-column gas chromatography with electron capture detection (GC/ECD). This method is capable of detecting sub-parts-per-trillion (ng/L) levels of these congeners. Samples are tested using the 67-congener list on a monthly basis, and for a shorter list of congeners that matches those analyzed in the tissue and sediment samples on a weekly basis.

PCBs as Aroclors is the only organic contaminant that has a numeric discharge limit in the DITP NPDES permit. The limit is 0.045 ng/L based on the human health criterion and the expected amount of effluent dilution. Aroclors have not been detected in a DITP effluent sample since the current NPDES permit went into effect. However, the 1998 revised water quality criteria are intended to be compared to a sum of congeners or homologues. The average concentration of PCB congeners detected exceeds the HHC value before dilution of the effluent. Some recent high-resolution gas chromatography/high-resolution mass spectrometry (HRGC/HRMS) data indicates that PCB data for the effluent may be strongly impacted by positive interferences. MWRA will be looking in to this issue further.

Trends in priority pollutants

The low-level detection analyses enable MWRA to detect trends, for example Figures 2-14 and 2-15 show how mercury loadings and PAH loadings in MWRA effluent have decreased, respectively, as the proportion of effluent receiving secondary treatment has increased.

Low-detection level analyses for the pesticide chlordane (Figure 2-16) show that the levels in DITP effluent, although low, increase during the summer, possibly indicating increased use or disposal of this banned chemical during the gardening season.

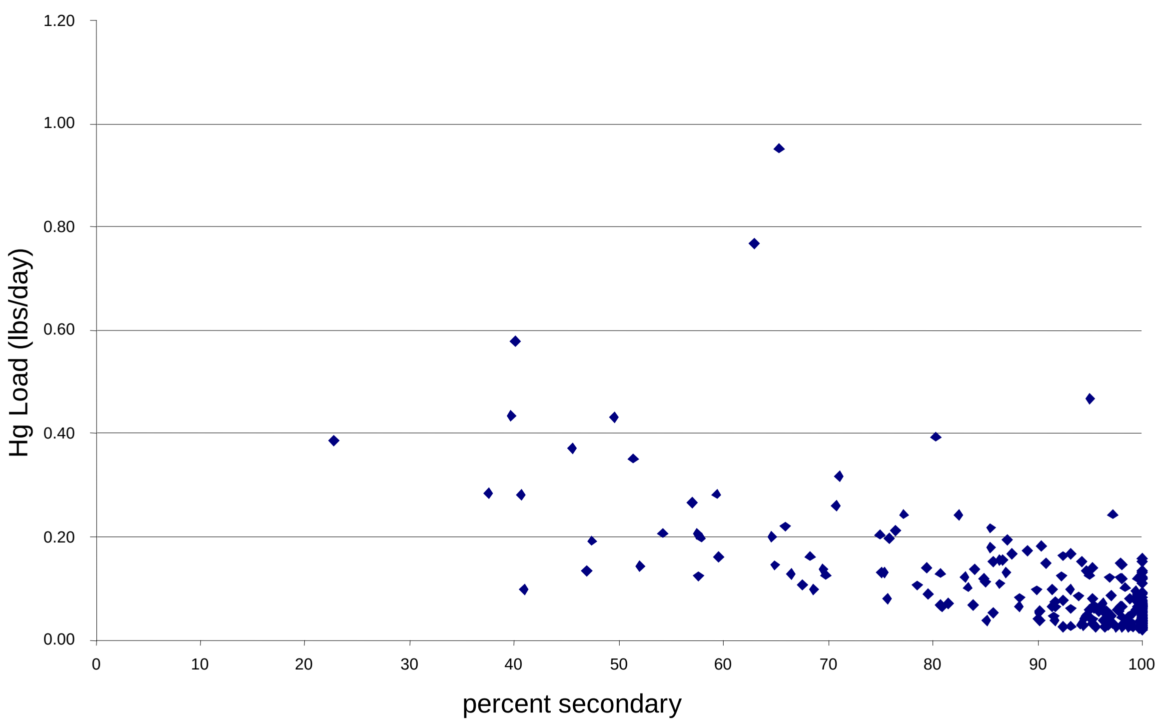


Figure 2-14 Mercury loading in DITP effluent as a function of secondary treatment

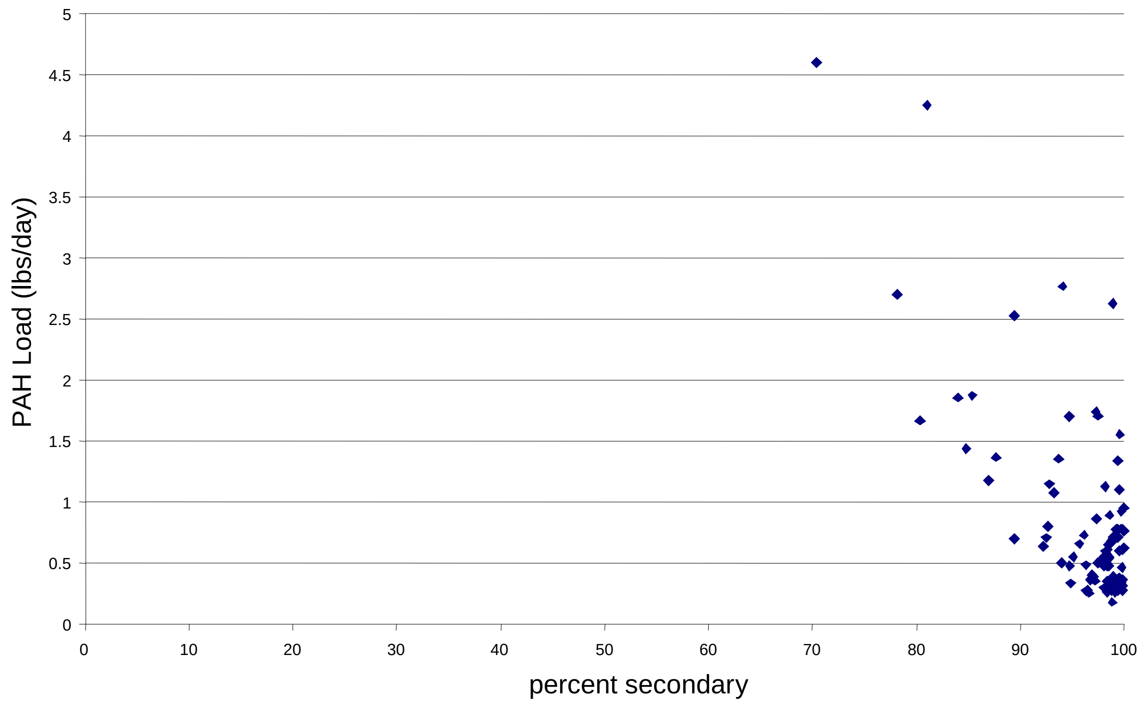


Figure 2-15 PAH loading in DITP effluent as a function of secondary treatment

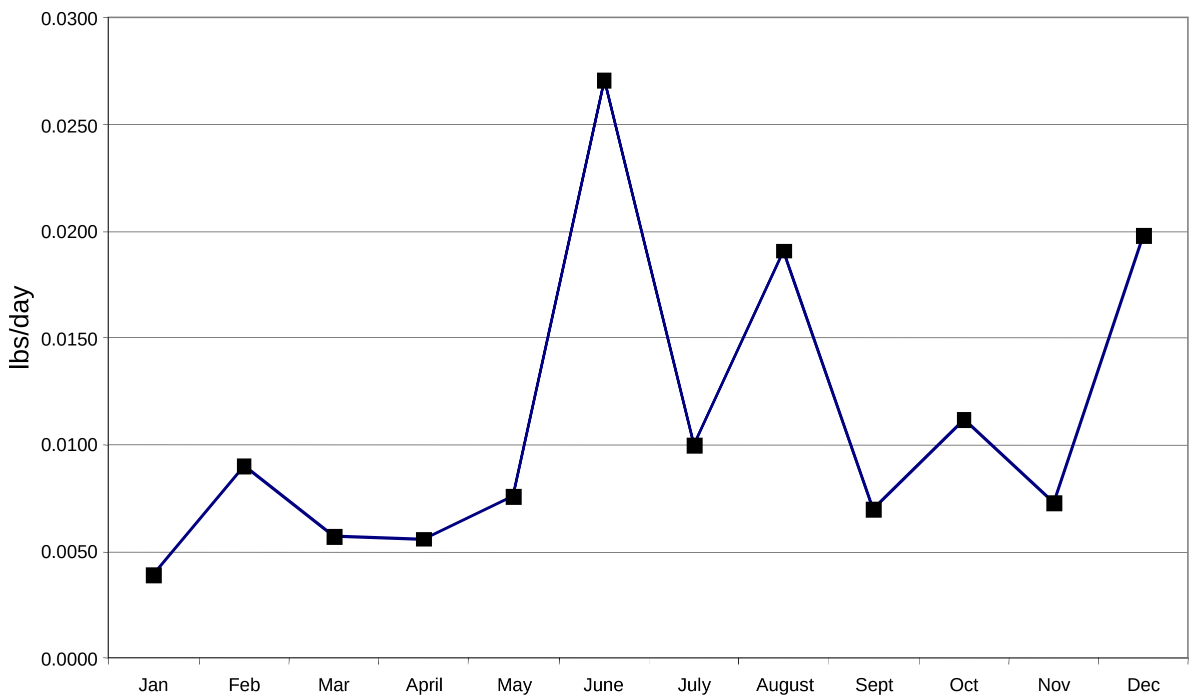


Figure 2-16 Chlordane loadings from DITP, 2002

Ambient Monitoring Plan Special Effluent Studies: Pathogens and their indicators: *Enterococcus*, anthropogenic viruses and bacteriophage

Massachusetts Water Quality Standards use fecal coliform bacteria counts as the indicator of the risk of human pathogens; therefore the Deer Island discharge must meet permit limits for fecal coliform. The Ambient Monitoring Plan calls for an evaluation of other indicators of human pathogens. Together with virologists at the University of New Hampshire, MWRA has conducted studies of the following pathogens: cultivatable enteroviruses including poliovirus, coxsackie virus and echovirus; adenovirus 40/41; rotavirus; and astrovirus. Samples are collected from influent and effluent to assess the presence of human pathogens in raw wastewater and the effectiveness of treatment on pathogen removal. Detailed descriptions of the methods used in this study are on the web at http://www.mwra.com/harbor/enquad/pdf/ms-073.pdf . In addition to the pathogens, MWRA studies four pathogen indicators: male-specific bacteriophage, somatic bacteriophage, and the indicator bacteria *Enterococcus* spp and fecal coliform. (MWRA also monitors the presence of pathogens and indicators in Boston Harbor and Massachusetts Bay, but this discussion is restricted to effluent monitoring.)

Bacteriophage have been suggested by some investigators as indicators that may better mimic the behavior of viral pathogens during treatment and in the environment than do bacterial indicators. Table 2-12 shows the units of measurement for each parameter, and the arithmetic and geometric mean values found in DITP wastewater at each stage of treatment.

Table 2-12 Changes in bacteria and virus counts in Deer Island wastewater through the treatment process

	Geometric Mean Arithmetic Mean			
	Influent	Primary effluent	Secondary effluent	Chlorinated secondary effluent
Enterococcus	457,000	135,000	14,000	9
(Col/100mL)	500,000	205,000	24,300	88
Fecal Coliform	5,130,000	1,410,000	112,000	7
(Col/100mL)	5,550,000	3,350,000	175,000	12
Cultivatable Virus	13.2	6.3	4.9	2.7
(MPN/L)	37.9	54.3	7.3	3.9
Male Phage	246,000	11,500	6,460	10,000
(PFU/L)	408,000	103,000	56,000	75,700
Somatic Phage	60,300	3,390	4,680	2,090
(PFU/L)	82,100	42,800	34,400	14,100

These data are also shown as bar graphs with standard errors indicated in Figure 2-17.

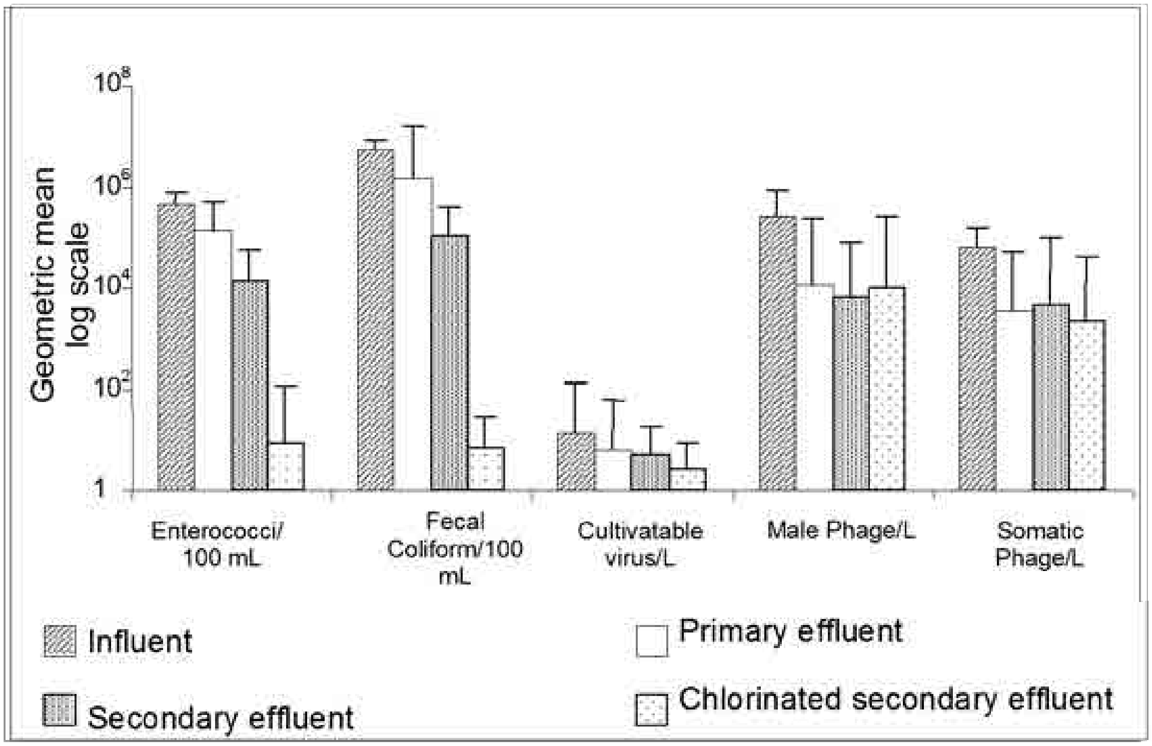


Figure 2-17 Pathogenic viruses and indicator bacteria concentrations at stages of treatment at DITP

These microorganisms differed in their responses to the three phases of treatment. The bacteria indicators fecal coliform and enterococci showed large and significant decreases in counts as treatment progressed: secondary treatment decreased average counts 10-fold, and disinfection of the effluent further decreased average counts 1,000-fold. For pathogenic cultivatable viruses, although the error bars overlap, the biggest difference in counts was after secondary treatment, with a relatively small effect of disinfection. For both the bacteriophages, the biggest change in numbers was after primary treatment, with little effect of either secondary treatment or disinfection. Again, the error bars overlap. These data suggest the indicator bacteria do not respond to treatment the same way the viral pathogens do, but that phages are not a better indicator of the presence of pathogenic viruses than are indicator bacteria.

Figure 2-18 shows results from all the *Enterococcus* samples in Deer Island wastewater collected after the new outfall went on-line. The box plots show frequency distributions of daily geometric means. Although *Enterococcus* are effectively reduced by secondary treatment and disinfection, about 10% of the samples exceed 104 col/100 ml. EPA recommends that Enterococcus be used to indicate the presence of human health risk in marine waters. In the future, Massachusetts may change its standard from fecal coliform to *Enterococcus* for marine waters. (The FDA shellfish program still requires the measurement of fecal coliform in monitoring shellfish-growing waters.) Although it is not possible to predict what a permit limit would be,[1] the box plot shows that at the present level of chlorination (which consistently results in low levels of fecal coliform) it is likely that about 10% of samples would exceed an *Enterococcus* criterion. Thus, future use of the *Enterococcus* indicator may necessitate higher levels of chlorination (and more sodium bisulfite for dechlorination).

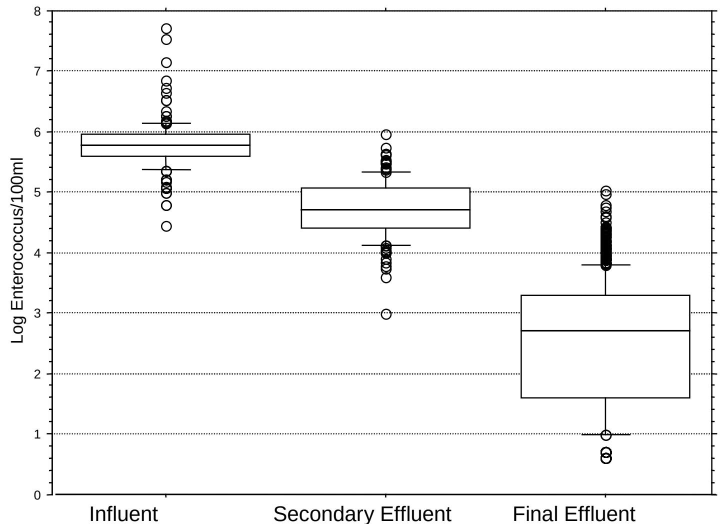


Figure 2-18   Deer Island Treatment Plant Enterococcus counts

[1] If EPA criteria were applied in a manner comparable to the existing fecal coliform limit a criterion of 35 col/100 ml (which applies at a bathing beach), times a dilution factor of 70 would give a hypothetical 2,450 col/100 ml limit in effluent. If the EPA suggested criterion for "infrequent full body contact" of 500 col/100 ml were used, the hypothetical limit could be 35,000 col/100 ml. The existing permit limit for fecal coliform is 14,000 col/100 ml.

Ambient Monitoring Plan Special Effluent Studies: Nitrogen, phosphorus and silica

Annual average loadings of total nitrogen (TN) in effluent have shown no trend for the period 1996 through 2002 (Fig. 2-19); loadings data for the period before 1995 are less reliable. During the same period, average loadings of the dissolved inorganic nitrogen (DIN) fraction, largely as ammonium, have shown a small increase. The increase in DIN is the result of the upgrade to secondary treatment, and not to increased DIN loadings to the treatment plant.

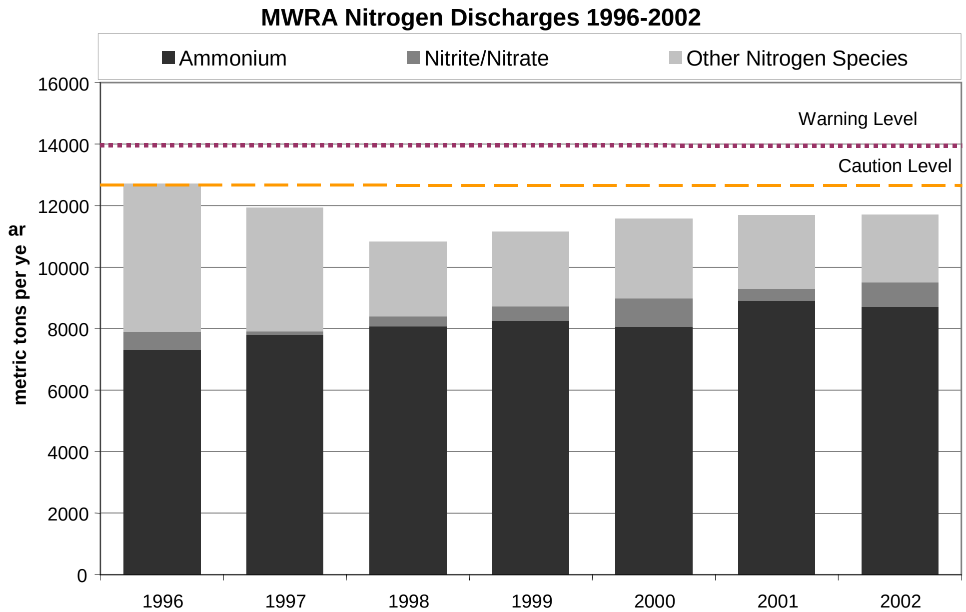


Figure 2-19 Changes in MWRA Effluent Nitrogen Loading

Annual average molar ratios of effluent N:P loadings have also shown no trend since 1996 (Figure 2-20). Thus, there has been no change in the N relative to P loadings over this period. This applied for both TN:TP and DIN:DIP. For both ratios, but especially for the dissolved inorganic fractions, the average ratios exceeded the Redfield ratio of 16:1. This is typical of urban wastewater.

The fact that the ratios were greater than 16:1 suggests that the wastewater discharged to the Bay is slightly enriched with N (and especially with DIN) relative to P, relative to the N:P requirements of phytoplankton. Based on studies of pilot plant effluent, the average DIN:Si ratio of the wastewater discharged from the Deer Island facility is in the order of 4.5:1 (cf. the Redfield ratio of 1:1); this too suggests the wastewater is enriched with N relative to Si.

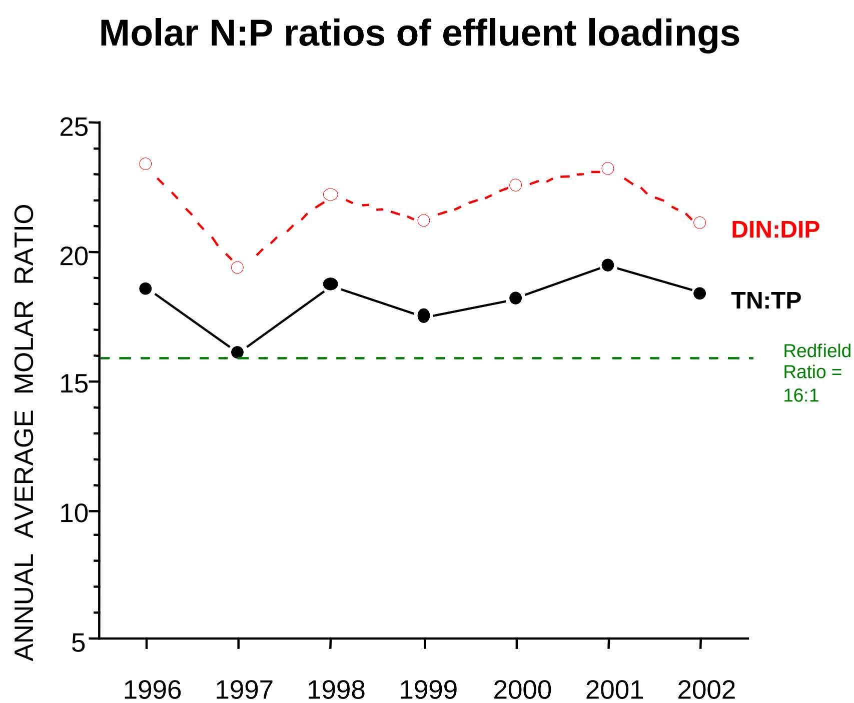


Figure 2-20 Changes in Ratios of Nitrogen to Phosphorus of effluent loadings

Plots of average monthly loadings of total N partitioned into the DIN and non-DIN fractions, show little evidence of a seasonal pattern (Figure 2-21). This is especially true for the DIN fraction (in red), that makes up the bulk of the secondary-treated effluent discharged to the Bay.

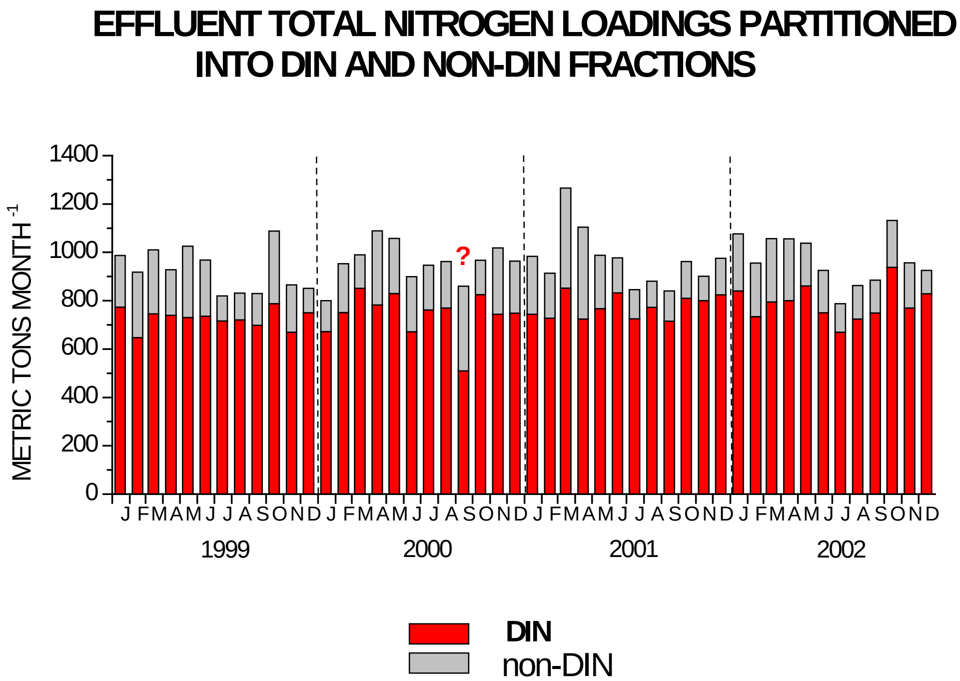


Figure 2-21 Average monthly DIN and non-DIN loadings from Deer Island

Reporting on effluent quality. Results of effluent monitoring required by MWRA's permit and Contingency Plan are reported to regulatory agencies, OMSAP, and the public rapidly and in a variety of communication vehicles. MWRA's routine monthly discharge monitoring reports are placed in repository libraries in Hyannis and at MWRA headquarters, and are published on MWRA's website at:http://www.mwra.com/harbor/html/ditp_performance.htm.

A unique requirement in MWRA's discharge permit is that all treatment plant permit violations are reported within five days to regulatory agencies, OMSAP and the public, and noticed on MWRA's website and in repository libraries. In addition, EPA maintains a listserve which actively notifies those on the list of a permit violation. Quarterly Contingency Plan effluent reports are posted on MWRA's web site at: http://www.mwra.com/harbor/pdf/cpqeff.pdf and are also placed in the repository libraries. Annual summary reports of NPDES compliance, that give detailed effluent quality data are available on MWRA's web site at: http://www.mwra.com/harbor/enquad/. Finally, the annual Outfall Monitoring Overview, published each year, summarizes effluent quality data and effluent Contingency Plan results. The most recent Outfall Monitoring Overview is available at repository libraries and on the web at http://www.mwra.com/harbor/enquad/pdf/2002-18.pdf.

2.4 Conclusions and Recommendations

MWRA's effluent monitoring is intensive and thorough. The "normal" conventional and priority pollutant constituents are measured frequently (for example, most facilities only measure whole effluent toxicity quarterly while DITP carries out these tests monthly). In addition, MWRA is on the "cutting edge" of effluent quality monitoring in several areas:

- low detection-limit measurements of toxic contaminants
- developing a sampling method for quantifying "floatables"
- measuring viral pathogens, bacteriophage and *Enterococcus.*

The results of effluent monitoring show that

1. DITP is operating as designed, and consistently meets permit limits and Contingency Plan thresholds.
2. Discharges of solids and BOD have decreased by 80%, compared to the old treatment plants.
3. Discharges of priority pollutants are well below SEIS predictions, and in most cases meet receiving water quality criteria even before dilution.
4. Low detection level effluent analyses of PAH, pesticides and PCBs help MWRA to define an effluent signature. Changes in the treatment plant performance are detectable over much shorter time scales than can be expected with sediment and tissue monitoring. Characteristic ratios of various PAH components, PCB congeners and pesticide components should also help to separate the MWRA contribution from other sources of these parameters to Massachusetts Bay over time.
5. Total nitrogen discharges have decreased slightly, and the amount of dissolved inorganic nitrogen species has increased about 10% as expected with secondary treatment
6. Pathogenic viruses are detectable in final effluent, but at very low numbers: secondary treatment effectively removes pathogens.

MWRA has found that the ability to detect trace levels of contaminants in its effluent aids in the interpretation of other ambient monitoring data, especially for evaluation of fish and shellfish data and toxicity testing. The pattern of certain organic contaminants can help determine whether MWRA effluent might be a source of contamination found in the environment. The effluent data provide valuable feedback to the treatment plant operators and the pollution prevention team. MWRA is recommending no changes to the Ambient Monitoring Plan Effluent Monitoring projects at this time.

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3. WATER COLUMN CONCERNS AND SAMPLING PROGRAM

3.1 Background

The water column monitoring program focuses on the MWRA wastewater's effect on the water quality of Massachusetts Bay with respect to nutrients, organic material, pathogens, and floatables. The monitoring program looks extensively at possible effects of discharging nutrient-rich effluent into Massachusetts Bay, including eutrophication impacts such as nuisance algal blooms and hypoxia, and ecosystem impacts on planktonic communities.

Deer Island effluent quality has been vastly improved since 1985, as a result of source reduction as well as secondary treatment. As described in Section 2, secondary treatment removes 85% of suspended solids, 85% of oxygen consuming material (BOD), and up to 90% of toxic contaminants from the wastewater stream before discharge. Pathogens are also significantly reduced by secondary treatment and further removed by disinfection. Because toxic contaminants are extensively monitored in the wastewater, and are discharged at very low concentrations, direct water column measurements of toxic contaminants are not done routinely. Sewage indicator bacteria are monitored every month around the outfall according to a Memorandum of Understanding with the Shellfish Sanitation Program of the Massachusetts Division of Marine Fisheries. The assumption that water column concentrations of bacteria and metals are very low was checked during the 2001 dilution (plume tracking) study described in Section 5. MWRA's mussel bioaccumulation study (Lefkovitz *et al*. 2002) also provides information about levels of toxic contaminants in the water near the outfall.

Although secondary sewage treatment effectively removes organic material and reduces the number of pathogens, it removes only about 20% of the nitrogen. Secondary treatment also changes the form of most of the nitrogen in wastewater to ammonium (Section 2), which is more readily taken up by marine algae. Therefore, most of the concern in the water column about the new outfall is focused on the potential for eutrophication and for subtle ecosystem shifts in Massachusetts Bay, due to relocating the nutrient-rich discharge from the shallow, well-mixed, turbid waters of Boston Harbor to the deep, clear waters of Massachusetts Bay. These concerns were translated into specific monitoring questions (MWRA 1991, see Table 3-1.)

Table 3-1 Water Column Monitoring Questions

Monitoring Area	Question
Dilution	Are the model estimates of short-term (less than 1 day) effluent dilution and transport accurate?
	Do levels of contaminants in water outside the mixing zone exceed State Water Quality Standards?
	Are pathogens transported from the outfall toward swimming beaches or shellfishing areas?
Aesthetics	Has the clarity and/or color of water around the outfall changed?
	Has the amount of floatable debris around the outfall changed?
Nearfield	Have nutrient concentrations changed in the water near the outfall?
	Have the concentrations (or percent saturation) of dissolved oxygen in the water changed relative to predischarge baseline or a reference area and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?
	Do the concentrations (or percent saturation) of dissolved oxygen in the water column meet the State Water Quality Standard?
	Has the phytoplankton biomass changed and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?
	Have the phytoplankton production rates changed in the vicinity of the outfall and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations?
	Has the species composition of phytoplankton or zooplankton changed in the vicinity of the outfall and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations?
	Has the abundance of nuisance or noxious phytoplankton species changed?
Farfield	Have water column nutrient concentrations changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are they correlated with changes in the nearfield?
	Have the water column concentrations (or percent saturation) of dissolved oxygen changes at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
	Has the primary production at selected farfield stations in Massachusetts Bay or Cape Cod Bay changed and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
	Do the water column concentrations (or percent saturation) of dissolved oxygen at selected farfield stations meet the State Water Quality Standard?
	Has the phytoplankton biomass changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the near-field or changes in nutrient concentrations in the farfield?
	Has the primary production at selected farfield stations in Massachusetts Bay or Cape Cod Bay changed and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?
	Has the phytoplankton and zooplankton species composition changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the near field or changes in nutrient concentrations in the farfield?

3.2 Monitoring Design

The sampling program is designed primarily to detect outfall-related changes near the outfall in the levels of nutrients, dissolved oxygen, phytoplankton biomass, phytoplankton and zooplankton community composition, zooplankton biomass, or phytoplankton production rates. Changes in nuisance algae are monitored. Sensitive areas of Massachusetts Bay and Cape Cod Bay far from the outfall and reference sites are also monitored for these parameters. Table 3-2 summarized the design of the water-column monitoring.

A dilution study conducted in 2001 quantified the dilution of effluent, and measured contaminant concentrations in water outside the mixing zone for comparison against water quality standards. The dilution study also assessed the aesthetics in the surface water near the outfall.

The monitoring design is based on an understanding that the nearfield *i.e.* the area within several km of the outfall (Figure 3-1), would be most likely to show an effect from outfall relocation. Stations far from the outfall (Figure 3-2) are sampled less frequently, and are included as reference locations and to monitor the spatial extent of any outfall-related change.

The water column monitoring is complemented by a number of special studies. The U.S. Geological Survey special study provides information on water circulation and the fate of pollutants. UMass/Boston is continuing computer modeling of the bays using the Bays Eutrophication Model, a coupled hydrodynamic/water quality model of Massachusetts Bay. Measurements have been added to stations near the boundary to better characterize nutrients and plankton entering Massachusetts Bay from the Gulf of Maine. Additional winter/spring zooplankton collections in Cape Cod Bay provide additional information about the food supply for right whales. The hard-bottom special study looks at deposition of solids near the outfall, and changes in the animal communities living there. The benthic nutrient flux study examines the exchange of nutrients between the water column and benthos; that study will be discussed at the July 2003 workshop. Net tows for sewage-related floatables are carried out, and aesthetic observations made during every survey. Trained observers identify and record the presence of marine mammals on every survey. Sampling for a four-year special study of viruses in the water near the outfall was completed in 2002.

Remotely-sensed ocean color data from the SeaWiFS satellite are reviewed on a regular basis to provide additional spatial and temporal resolution and to place shipboard chlorophyll data in the context of regional changes. Continuously-monitored temperature, salinity, and current data are available from U.S. Geological Survey moorings at the outfall site and off Scituate, and from a Gulf of Maine Ocean Observing System (GoMOOS) mooring off Cape Ann.

Table 3-2 Water column monitoring program summary

Task	Objective	Sampling Locations And Schedule	Analyses
Nearfield surveys	Collect water quality data near outfall location	17 surveys/year 21 stations 5 depths	Temperature Salinity Dissolved oxygen Nutrients
Farfield surveys	Collect water quality data throughout Massachusetts and Cape Cod bays	6 surveys/year 26 STATIONS 5 DEPTHS	Solids Chlorophyll Water clarity Photosynthesis Respiration Plankton Marine mammal observations Floatables Bacterial indicators
Plume-track surveys	Track locations and characteristics of discharge plume, measure dilution of discharge	2 surveys in 2001	Rhodamine dye Salinity Temperature Currents Nutrients Solids Selected metals Bacterial indicators

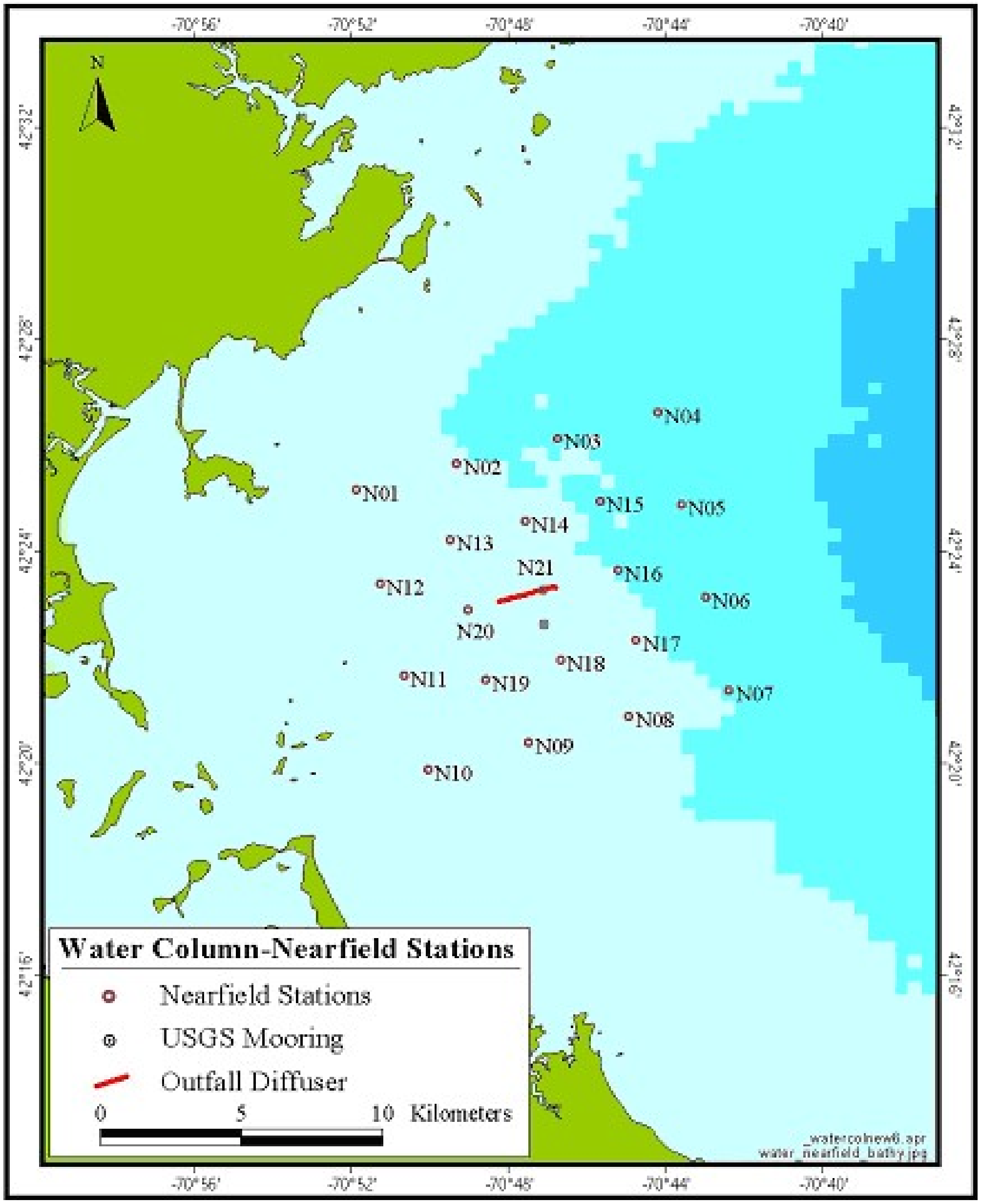

Figure 3-1 There are 21 stations sampled in the outfall nearfield, which are sampled at 5 depths during 17 surveys annually.

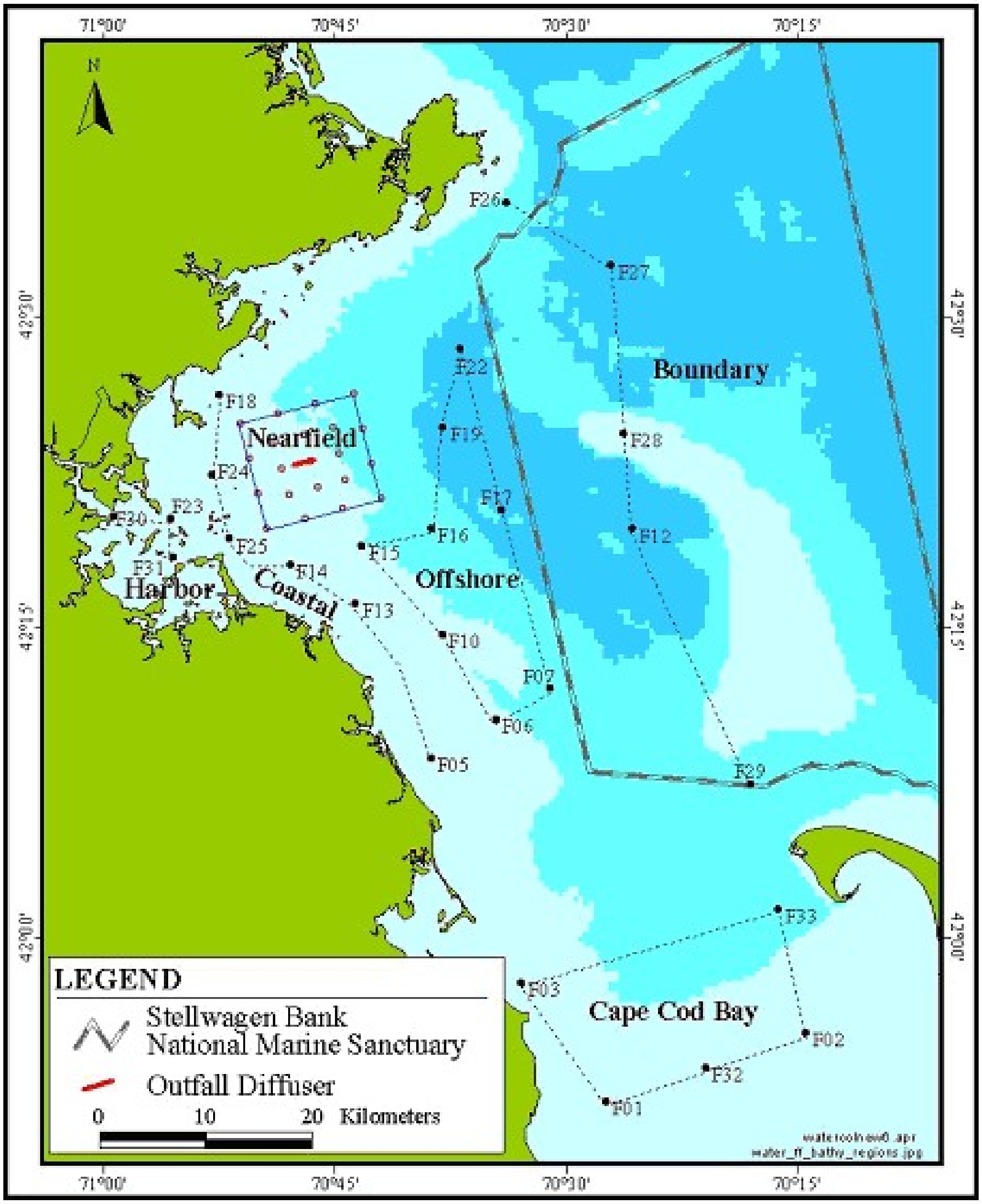

Figure 3-2 **Water column sampling stations, including farfield locations which are sampled six times annually.**

3.3 Contingency Plan Thresholds

Thresholds have been set (MWRA, 2001) for certain environmentally significant components of the marine ecosystem that, if exceeded, indicate a potential for environmental risk. Water column thresholds (Table 3-3) include initial dilution, bottom dissolved oxygen concentration and rate of summertime decline, chlorophyll *a* concentration, and nuisance algal species abundance. Thresholds for zooplankton and for paralytic shellfish poisoning (PSP) are undergoing further development.

3.4 Evolution of Concerns Addressed by Monitoring

When the outfall site was chosen and the outfall monitoring plan originally designed, MWRA expected to discharge primary treated effluent through the outfall for a number of years before full secondary treatment was available. As outfall completion was delayed, it became clear that effluent discharged in Massachusetts Bay would receive more thorough treatment. The primary concerns shifted from effects of high-organic-material discharge on dissolved oxygen levels and on the benthic community, to the effects of a nutrient-rich discharge into the bottom waters of the bay. Although the effluent would be trapped below the pycnocline in summer, would nutrients be available in the euphotic zone? Would spring blooms, which begin before stratification is established, be enhanced, leading to oxygen problems later in the summer? Would the shift in the distribution of nutrients lead to changes in the phytoplankton community, such as an increase in the occurrence of nuisance or noxious algal species? Would this, in turn, affect the zooplankton on which many marine animals, including the endangered right whale depend?

Nearly ten years of baseline monitoring and two years of post-discharge monitoring have provided both a better understanding of the oceanography of the bays, and assurance that the outfall discharge has had only small and localized effects on water quality. No serious acute impacts have been observed. The dye dilution study, and the finely-gridded spatial sampling design around the outfall have well-characterized the location of the discharge plume. It is therefore appropriate to refocus the monitoring program on possible effects of the discharge over the long-term, using our increased knowledge of scales and processes. For example, the intensive spatial and temporal design of the near-field sampling, which has allowed the detailed characterization of the location and behavior of the effluent plume, is no longer necessary.

Table 3-3 Water column thresholds

Parameter type/location	Parameter	Caution Level	Warning Level
water column, zone of initial dilution	initial dilution	-	effluent dilution predicted by EPA as basis for NPDES permit
water column nearfield bottom, Stellwagen bottom	dissolved oxygen (concentration)	6.5 mg/L for any survey during stratification (June-Oct.) unless background conditions are lower	6 mg/L for any survey during stratification (June-Oct.) unless background conditions are lower
water column nearfield bottom, Stellwagen bottom	dissolved oxygen percent saturation	80% saturation for any survey during stratification (June-Oct.) unless background conditions are lower	75% saturation for any survey during stratification (June-Oct.) unless background conditions are lower
water column, nearfield bottom	oxygen depletion rate	1.5 x baseline	2 x baseline
water column, nearfield	chlorophyll	1.5 x baseline annual mean	2 x baseline annual mean
water column, nearfield	chlorophyll	95th percentile of the baseline seasonal distribution	-
water column, nearfield	nuisance algae (except *Alexandrium*)	95th percentile of the baseline seasonal mean	-
water column, nearfield	zooplankton [1]	-	-
water column, nearfield	*Alexandrium tamarense*	100 cells/L	-
water column, farfield	PSP extent [2]	new incidence	-

[1] The MWRA will report annually on appreciable changes to the zooplankton community in its Annual Water Column Report and in the Outfall Monitoring Overview. The MWRA also will report to EPA, MADEP and OMSAP by December 31, 2002 on the results of special zooplankton studies and evaluate whether a scientifically valid zooplankton community threshold can be developed. The MWRA also makes every effort to participate in workshops to investigate food web pathways in Massachusetts and Cape Cod bays sponsored by NOAA Fisheries.

[2] The MWRA is continuing to work on improvements to the calculation of this threshold as proposed in its October 13, 2000 letter to the EPA and MADEP.

Based on our current understanding, key features that we should continue to characterize over the next few years with ongoing monitoring and special studies include the following:

- the winter/spring bloom, including estimate of peaks in chlorophyll, production, and phytoplankton biomass in the nearfield
- early spring *Phaeocystis* blooms and resulting effect on zooplankton
- spatial extent of chlorophyll blooms (SeaWiFS)
- late spring occurrence of Paralytic Shellfish Poisoning (Division of Marine Fisheries monitoring and targeted studies of *Alexandrium*, Anderson *et al.* 2002.)
- stratification, dissolved oxygen, and nutrient levels at the beginning of summer
- summertime levels of chlorophyll and nutrients in the nearfield
- rate of decline of dissolved oxygen over the summer, and fall dissolved oxygen minimum
- summer upwelling or mixing events (USGS moorings and SeaWiFS)
- fall bloom peaks in chlorophyll, carbon, phytoplankton, and production in the nearfield
- phytoplankton and zooplankton community structure through the growing season
- exchange between the Gulf of Maine and Massachusetts Bay (GoMOOS and USGS moorings and boundary stations)

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4. PHYSICAL AND BIOLOGICAL OCEANOGRAPHY OF MASSACHUSETTS BAY

Wendy Leo, Rocky Geyer, Mike Mickelson

4.1 General characteristics

The transport of effluent discharged from the outfall is determined by local mixing and by the general circulation within Massachusetts Bay, which is illustrated by Figure 4-1 (Lermusiaux *et al.* 2001). There are a number of different possible trajectories of the flow, depending on the density distribution in the system and the winds. The residence time of the bay varies with the inflow from the Gulf, and Cape Cod Bay is at times somewhat isolated from Massachusetts Bay.

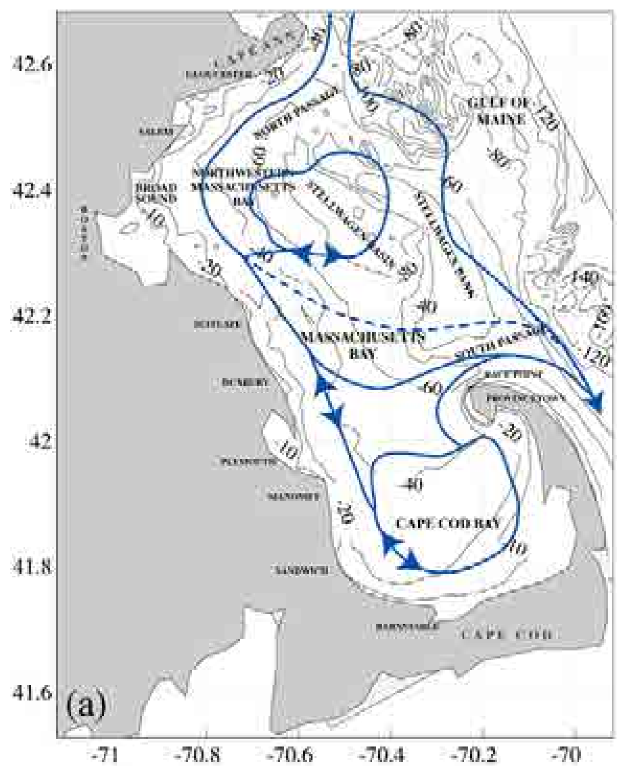

Figure 4-1 Summary of circulation within Massachusetts Bay (Lermusiaux et al. 2001.)

Moorings deployed by the USGS at the outfall site and at Scituate show these different trajectories. For example, in 1999 the residual flow was to the south in March and to the north in May as shown in Figure 4-2 (Butman *et al.* 2002.)

The bay is stratified from about April through October, which leads to trapping of the effluent plume. Density- and wind-driven flow, described in more detail below, determine the near-field transport of effluent.

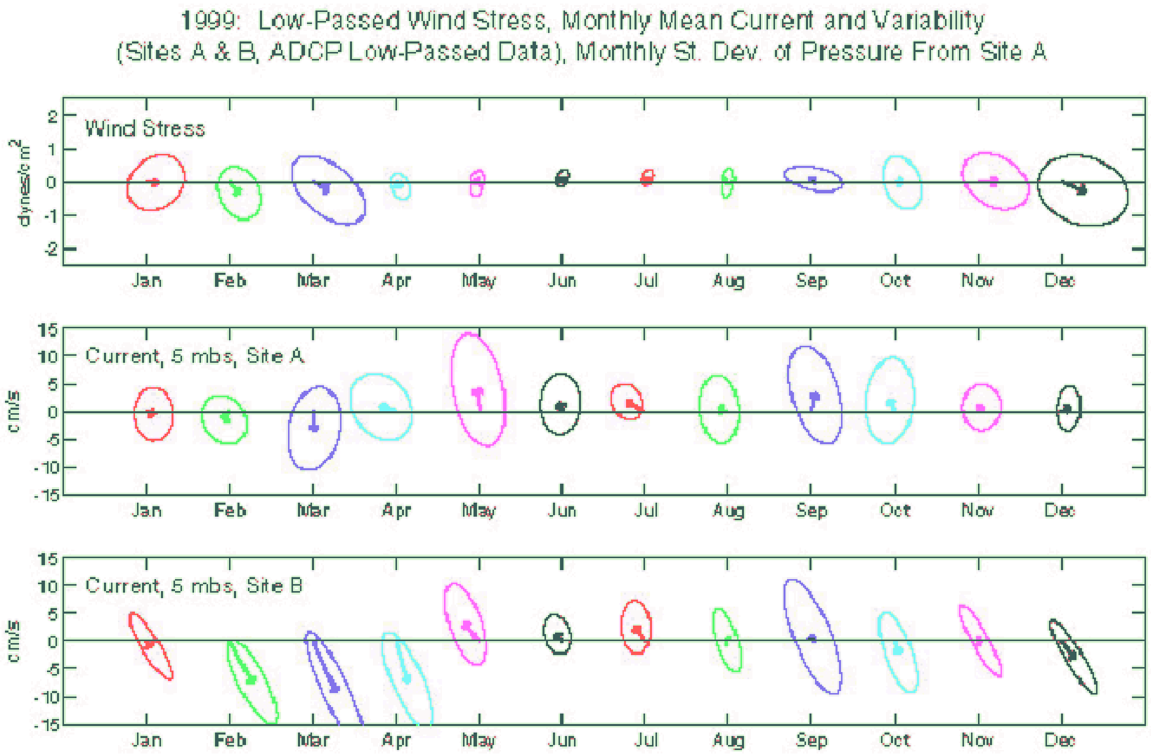

Figure 4-2 Variation in wind and surface currents at two moorings.

Massachusetts Bay wind stress, and currents at 5 meters below the surface (mbs) at outfall site (USGS mooring Site A) and off Scituate (USGS mooring Site B), during 1999 (Butman *et al.* 2002.)

4.2 Influence of the Gulf of Maine

Circulation, water properties, and consequently, the biology of Massachusetts and Cape Cod bays can be affected by the larger pattern of water flow in the Gulf of Maine (Figure 4-3.) The eastern Maine coastal current usually flows southwestward along the coast of Maine and New Hampshire and may enter Massachusetts Bay south of Cape Ann, exiting the Bays north of Race Point at the tip of Cape Cod. During the spring, when fresh water enters from the north and northerly winds are prevalent, the transport often follows the counterclockwise path in Figure, around the perimeter of Massachusetts Bay, into Cape Cod Bay and out around Race Point. In late spring and summer, Cape Cod Bay becomes isolated from this circulation.

The winds strongly influence the direction of circulation and the connectivity between the Gulf of Maine and the Bay. The optimal conditions for input of Gulf of Maine waters are winds from the northeast, combined with significant freshwater inflow from the Gulf. Winds from the south impede the surface water inflow, although they cause upwelling, which allows deep waters to enter from the Gulf.

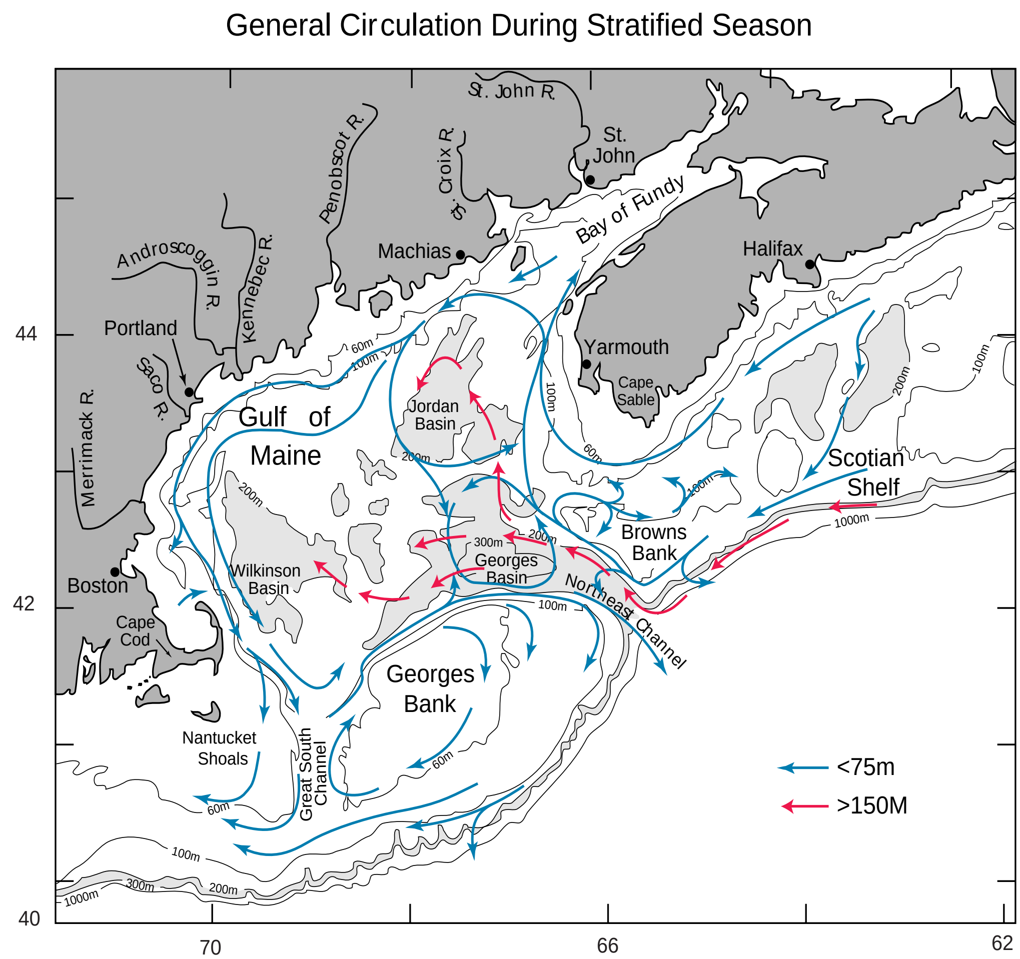

Figure 4-3 **General circulation on Georges Bank and in the Gulf of Maine during the summer, stratified season (from Beardsley et al. 1997.)**

4.3 Vertical structure

The Merrimack River and rivers further north in the Gulf of Maine provide most of the freshwater inflow (Manohar-Maharaj and Beardsley, 1973.) Although they don't empty directly into Massachusetts Bay, their flow is much greater than that of the Charles River and other Massachusetts Bay rivers (Figure 4-4.) The spring freshet results in salinity stratification in early April. Surface warming as the spring progresses enhances the stratification (Geyer *et al.* 1992.) During the summer there is a strong and persistent pycnocline throughout most of Massachusetts and Cape Cod bays, occasionally punctuated by storm mixing events. Stratified conditions continue through October in most years, sometimes later.

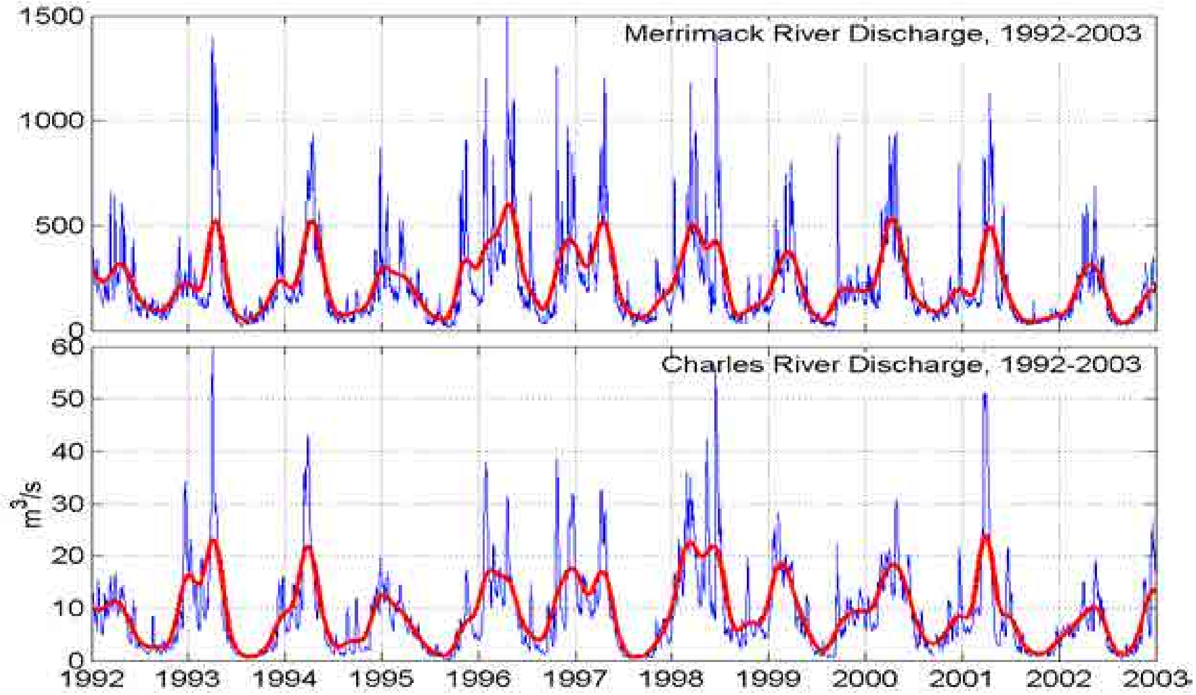

Figure 4-4 Merrimack and Charles River discharge, 1990-2002 (red/thicker line shows 3-month moving average.) Note difference in scale between Merrimack and Charles.

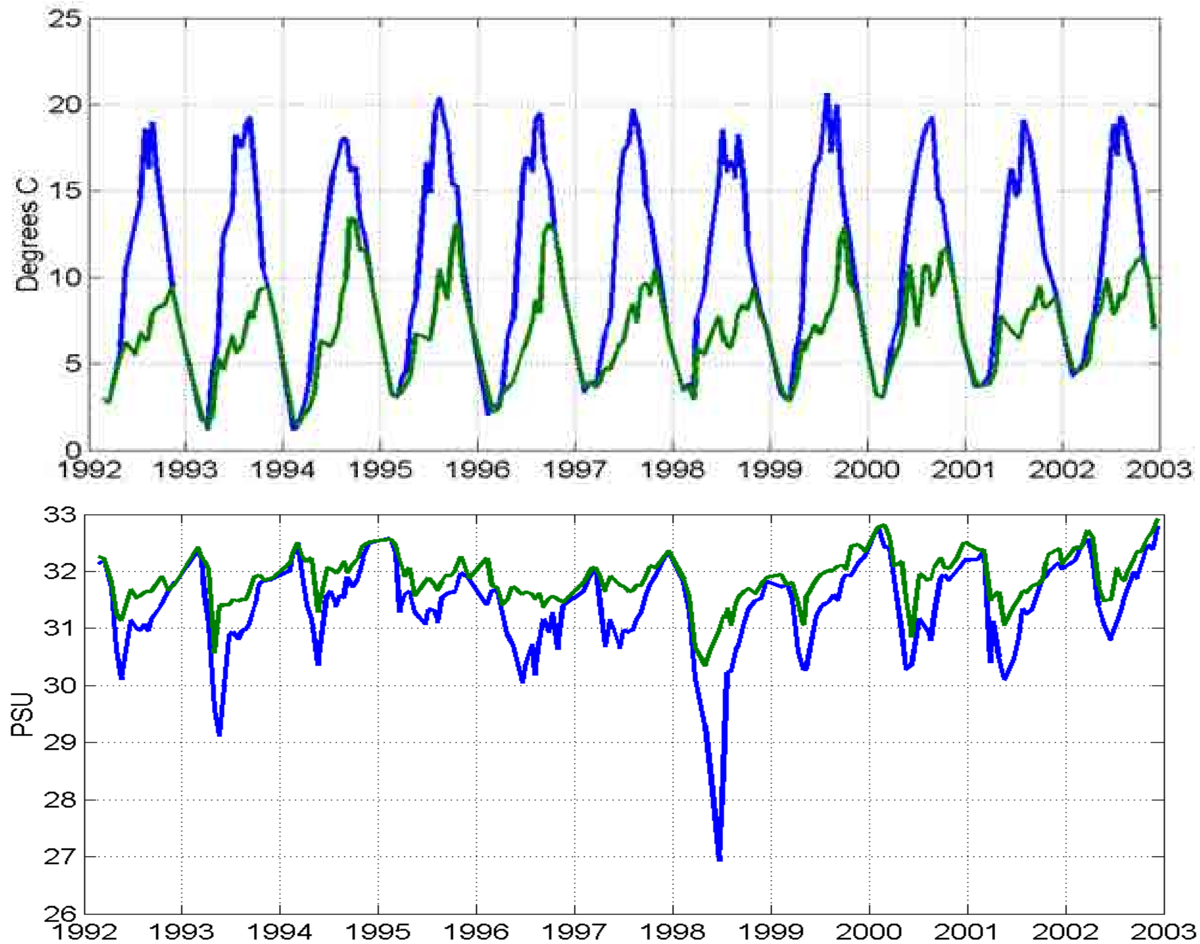

Figure 4-5 Nearfield surface and bottom water temperature (top panel) and salinity (bottom panel), 1992-2002(surface measurements are the upper blue line for temperature and the lower blue line for salinity.)

The waters of Massachusetts Bay become stratified during the spring freshet in April, due to the input of fresh water from the rivers of the Gulf of Maine, and in western Massachusetts Bay from the input of the Charles River. As the surface waters warm up in May and June, temperature stratification dominates over that due to the freshwater input. The waters remain stratified until late October or early November, when surface cooling and wind stress cause the water column to become vertically mixed. Figure 4-6 through 4-8 show the seasonal progression of temperature, salinity and density across northern Massachusetts Bay for the year 2000. The density distribution is determined by both temperature and salinity.

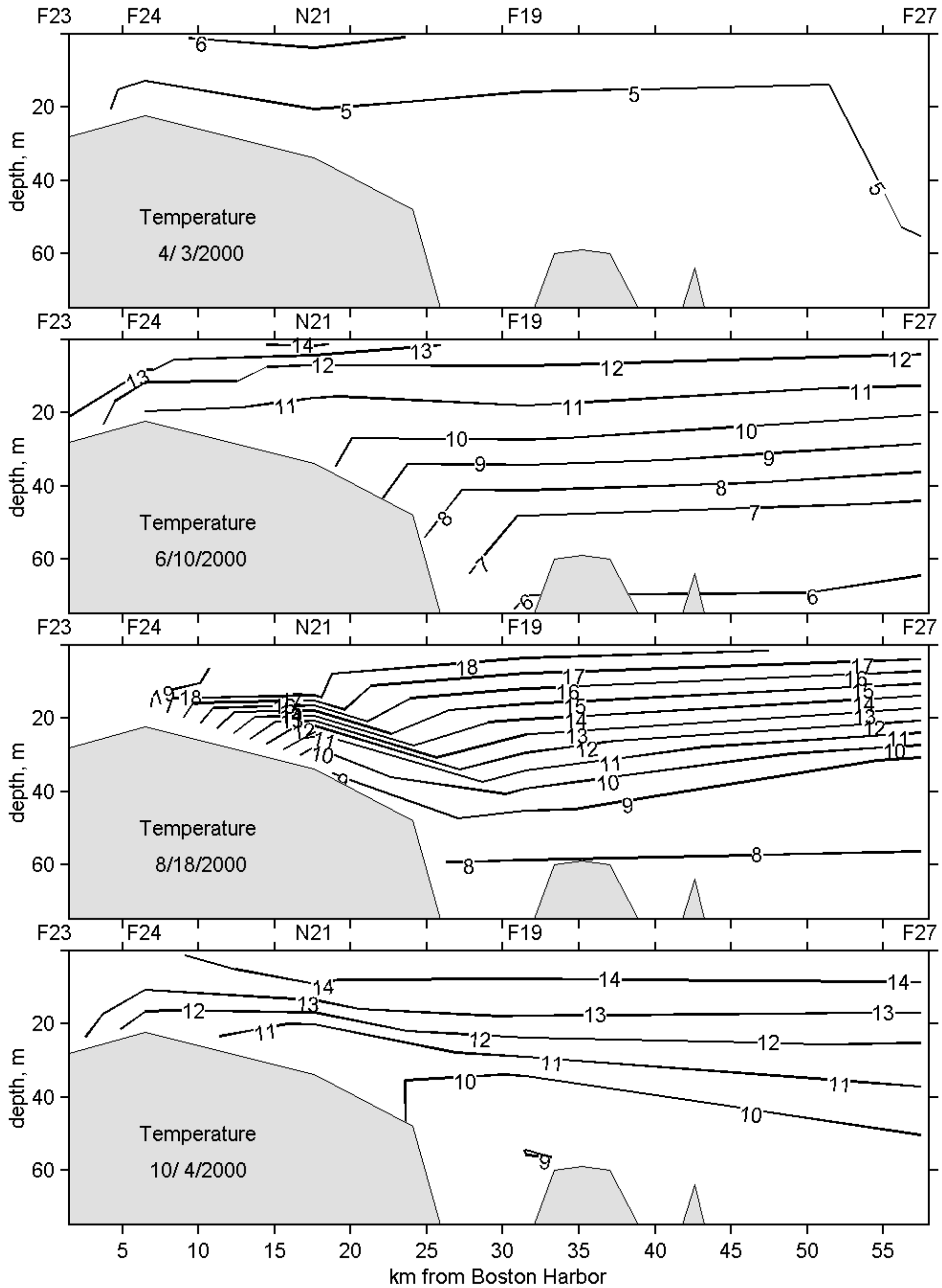

Figure 4-6 Temperature cross-sections from Boston Harbor to the Gulf of Maine, through the outfall zone.

The top panel shows conditions in April, at the beginning of seasonal stratification. The stratification increases in June, and reaches its maximum in August. In October, surface temperature is decreasing, but the bottom water is continuing to warm. Temperature contours in ^{o}C.

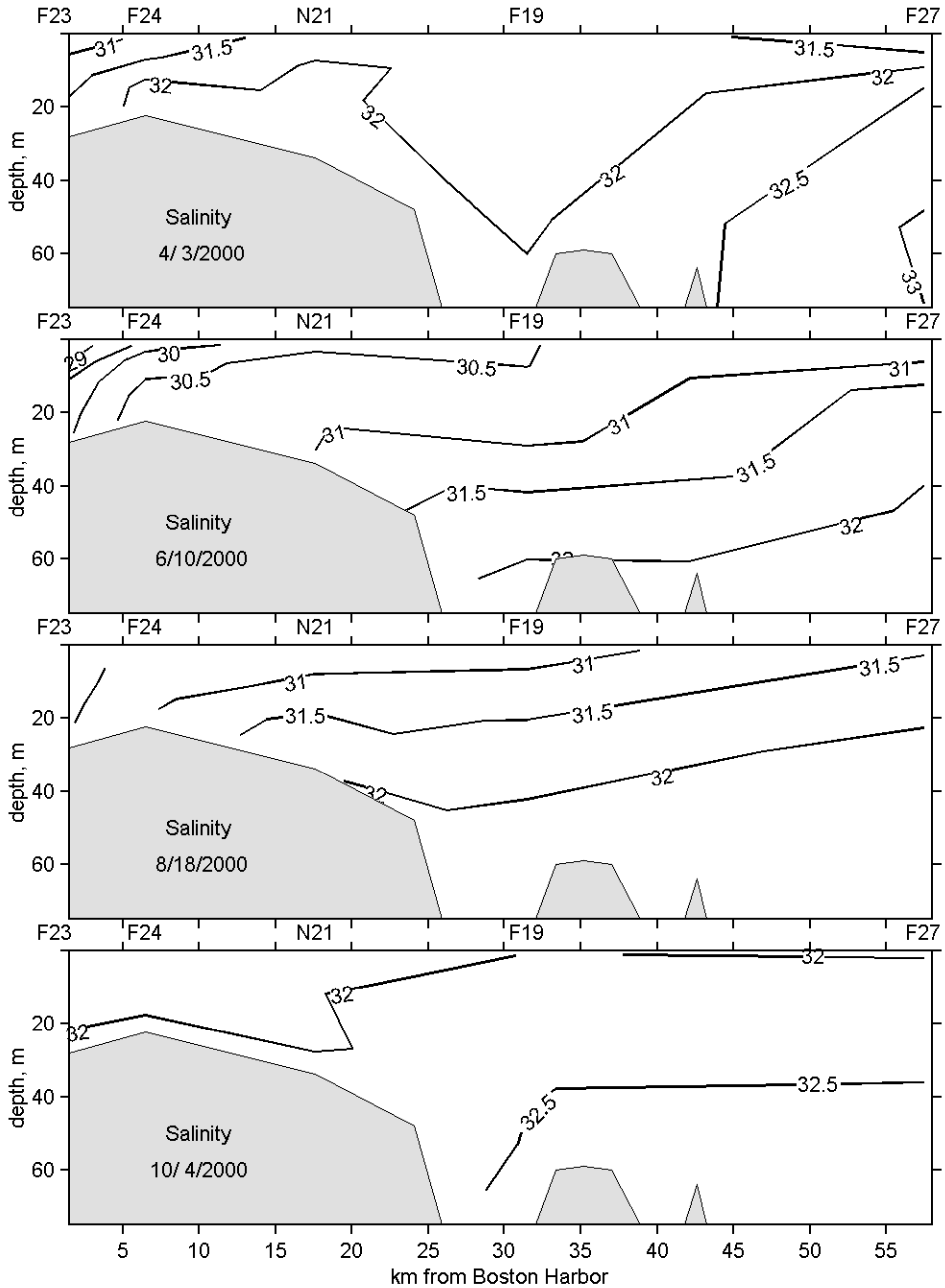

Figure 4-7 Salinity cross-sections from Boston Harbor to the Gulf of Maine, through the outfall zone.

The top panel shows conditions in April, when freshwater inputs are beginning to establish vertical and horizontal salinity gradients. The largest gradients occur during the June survey, which follows a large freshwater inflow from the Charles River. Significant salinity gradients persist through August. Salinity contours in PSU.

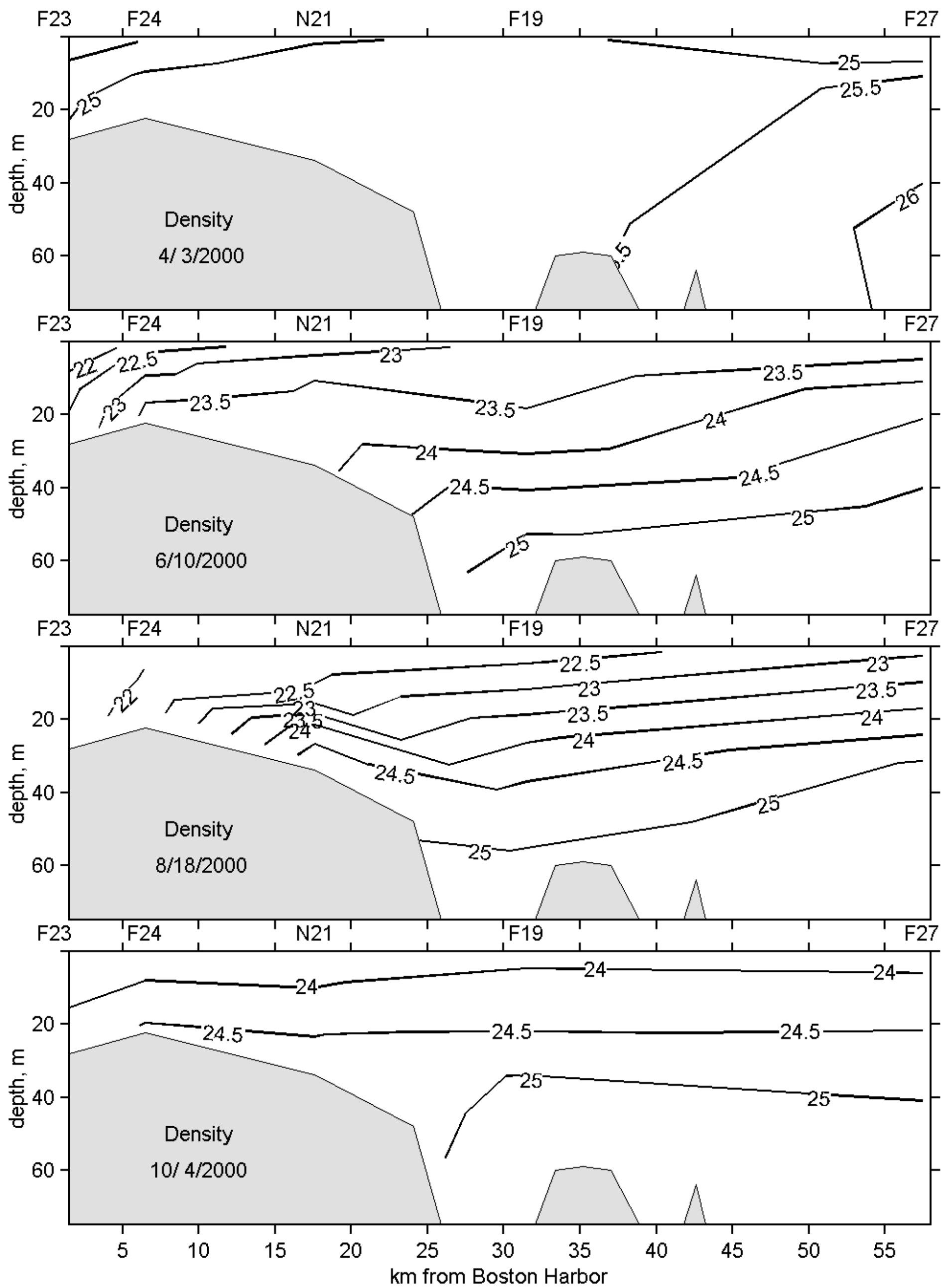

Figure 4-8 Density variations across Massachusetts Bay during four surveys in 2000. Stratification is contributed mostly by salinity during the April survey. The maximum stratification occurs in August, with contributions from both temperature and salinity. Density as sigma-*t*.

4.4 Short time scales

Tides

The large tides of the Gulf of Maine affect the open waters of the bays through tidal mixing (for example, over Stellwagen Bank) and the production of internal tides (Butman *et al.* 1988, Geyer *et al.* 1992, Geyer and Ledwell 1997.)

The extent of horizontal exchange is illustrated by Figure 4-9, a set of progressive vector diagrams provided by Soupy Alexander and Brad Butman at USGS. The plots indicate 1-day trajectories[1] over a one-month period, at near-surface and deep water levels, based on analysis of current meter data. The trajectories include the effects of tides, which cause east-west excursions of several kilometers, as well as motions due to winds and other factors. The key point is that although the long-term average, net velocity is small at the outfall site, there is considerable dispersion, which causes water parcels to be exchanged freely between the outfall site and other parts of the Bay.

The largest displacements in Fig 4-9 are in surface waters in summer. The vertical density gradient present in summer allows surface waters to slip relative to bottom waters and thus move more readily in response to wind and tide.

[1] Note that the currents were measured only at the USGS mooring near the outfall site; progressive vector diagrams would only represent real water parcel trajectories if currents were uniform throughout western Massachusetts Bay. Nevertheless this data presentation is a useful visualization of the variability of the flow at the outfall site.

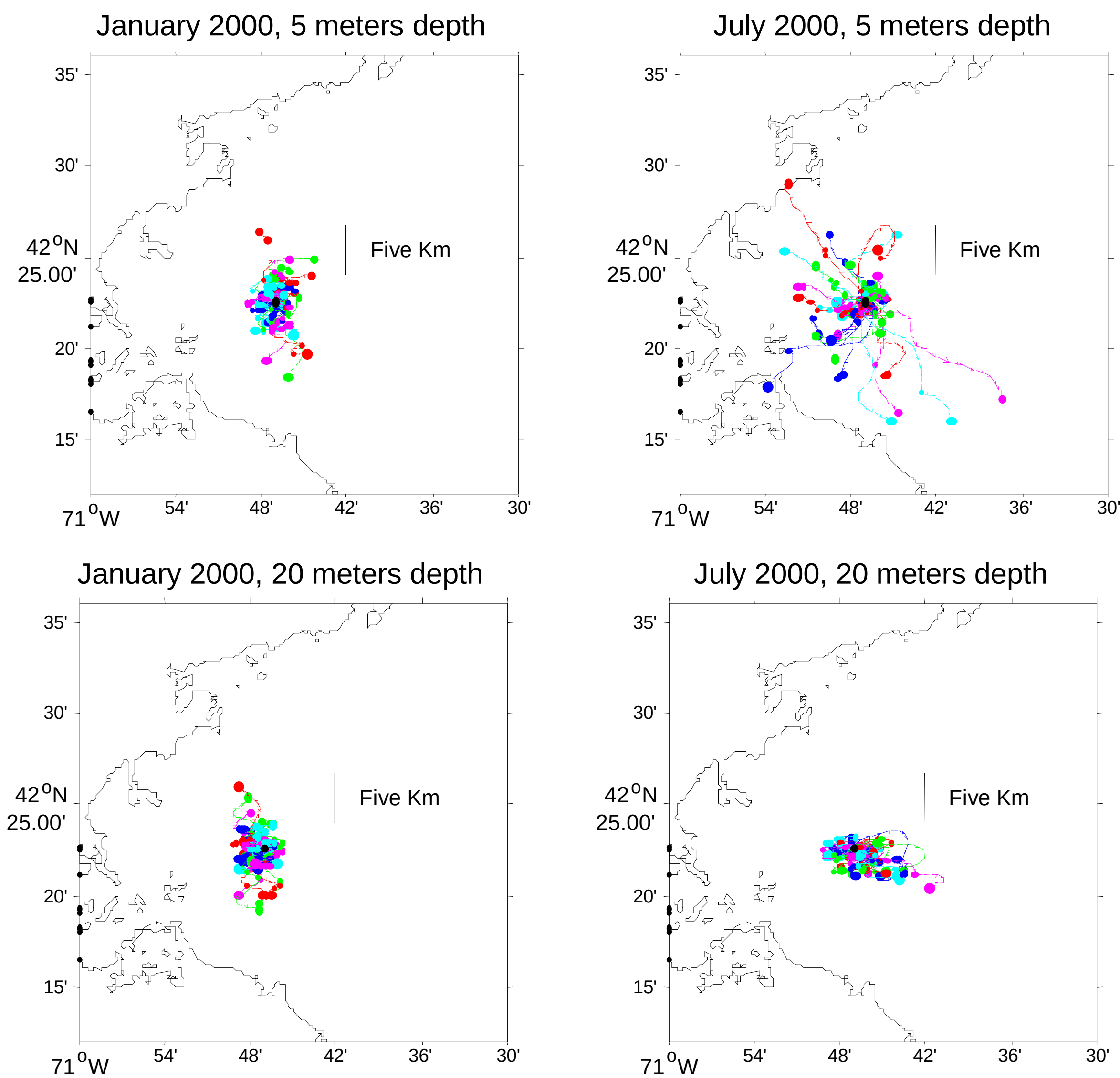

Figure 4-9 Progressive vector diagrams of currents near outfall site.

Trajectories illustrate 24-hour variation in currents from January 2000 (left) and July 2000 (right), near the surface (top panels) and near-bottom (bottom panels.) Currents were measured with the Acoustic Doppler Current Profiler on the USGS mooring. Figures courtesy of Soupy Alexander and Brad Butman, USGS.

Wind

Wind-induced upwelling and downwelling causes large variations in the water properties at the outfall site, by advecting the waters on- and offshore. Persistent, strong southerly or southwesterly winds in summer lead to upwelling. Upwelling causes a decrease in both surface and bottom water temperature, but most notably the surface water. Downwelling causes a significant increase in bottom water temperature. Upwelling and downwelling have some influence on vertical exchange, but their main influence is the horizontal advection of gradients. Figure 4-5 and 4-6 above shows the variability in bottom water temperatures.

Wind effects also include temporary destratification of the water column by large summer storms (for example, Hurricane Bob in 1990.) A stormy early autumn can also lead to early fall turnover.

4.5 Hydrodynamic model results

The ECOMsi hydrodynamic model has been applied to Massachusetts Bay (Signell *et al.* 1996.) It reproduces the physical conditions in the bays well, provided the boundary conditions at the open ocean boundary and the sea-surface heat flux are appropriately modeled or measured (Signell *et al.* 1996, 2000; HydroQual 2002; Figure 4-10 and 4-11.) The model reproduces the southward flow along the coast that is common in spring, as well as the summer/fall reversal of circulation (Jiang *et al.* 2003, see Figure 4-12)

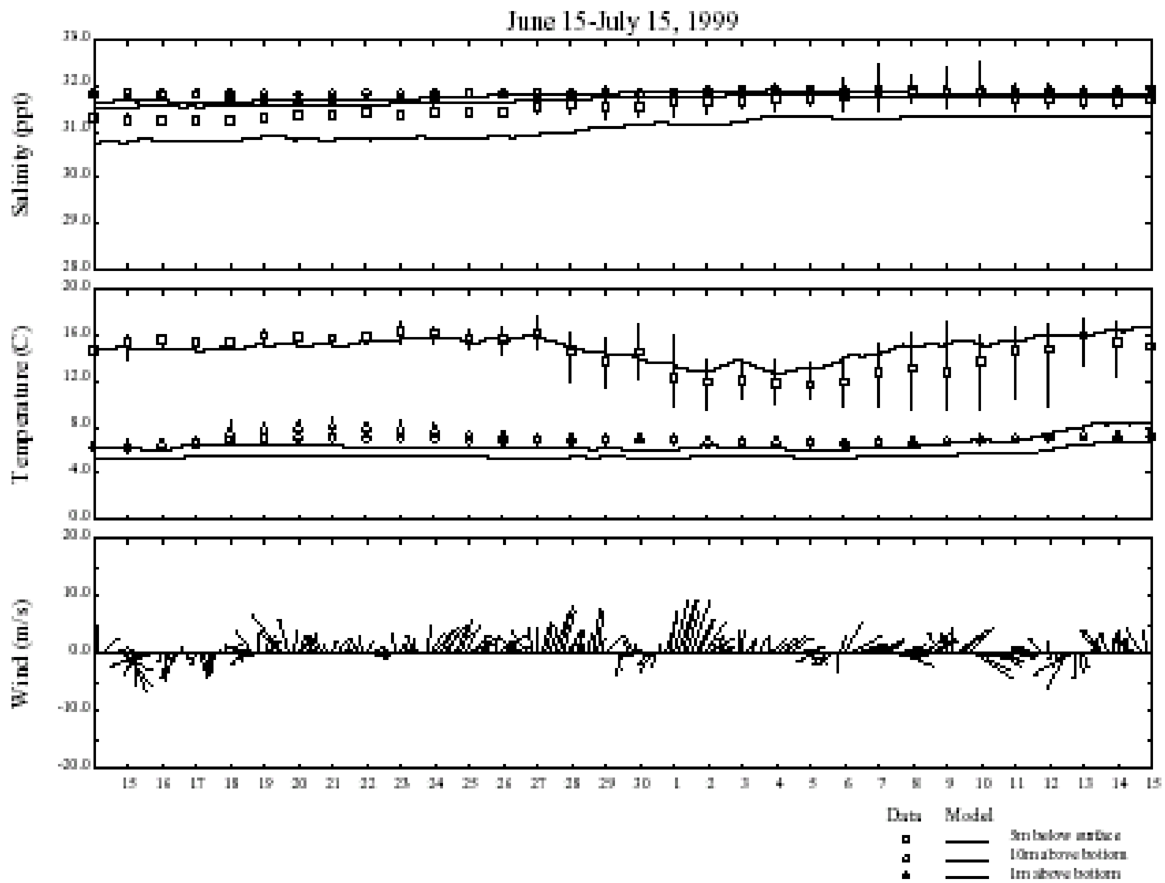

Figure 4-10 Observed and modeled salinity and temperature, and observed winds at the Boston Buoy, June 15-July 15, 1998 (HydroQual 2002.)

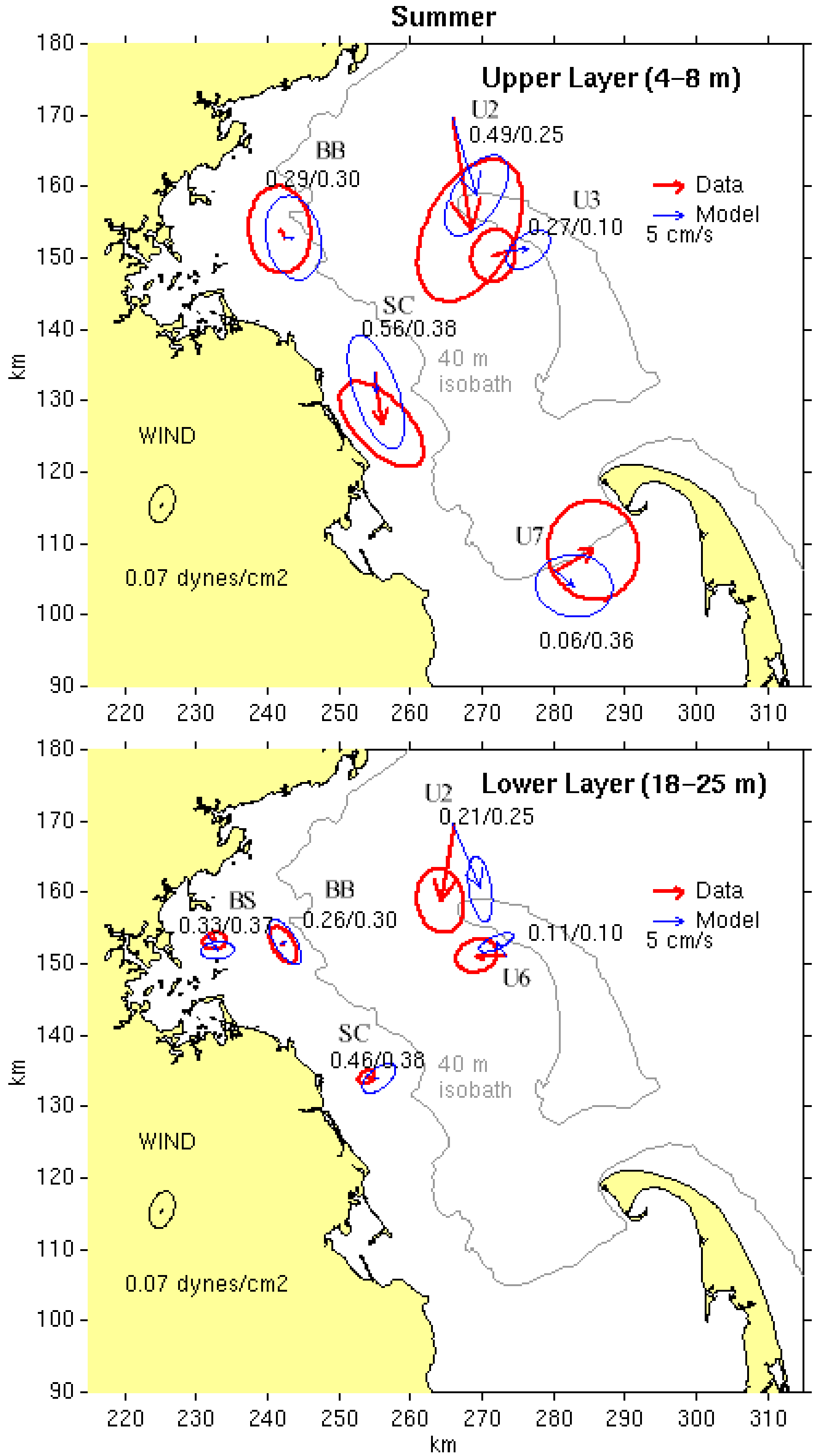

Figure 4-11 Observed and modeled tidal currents, summer 1992 (Signell et al. 2000.)

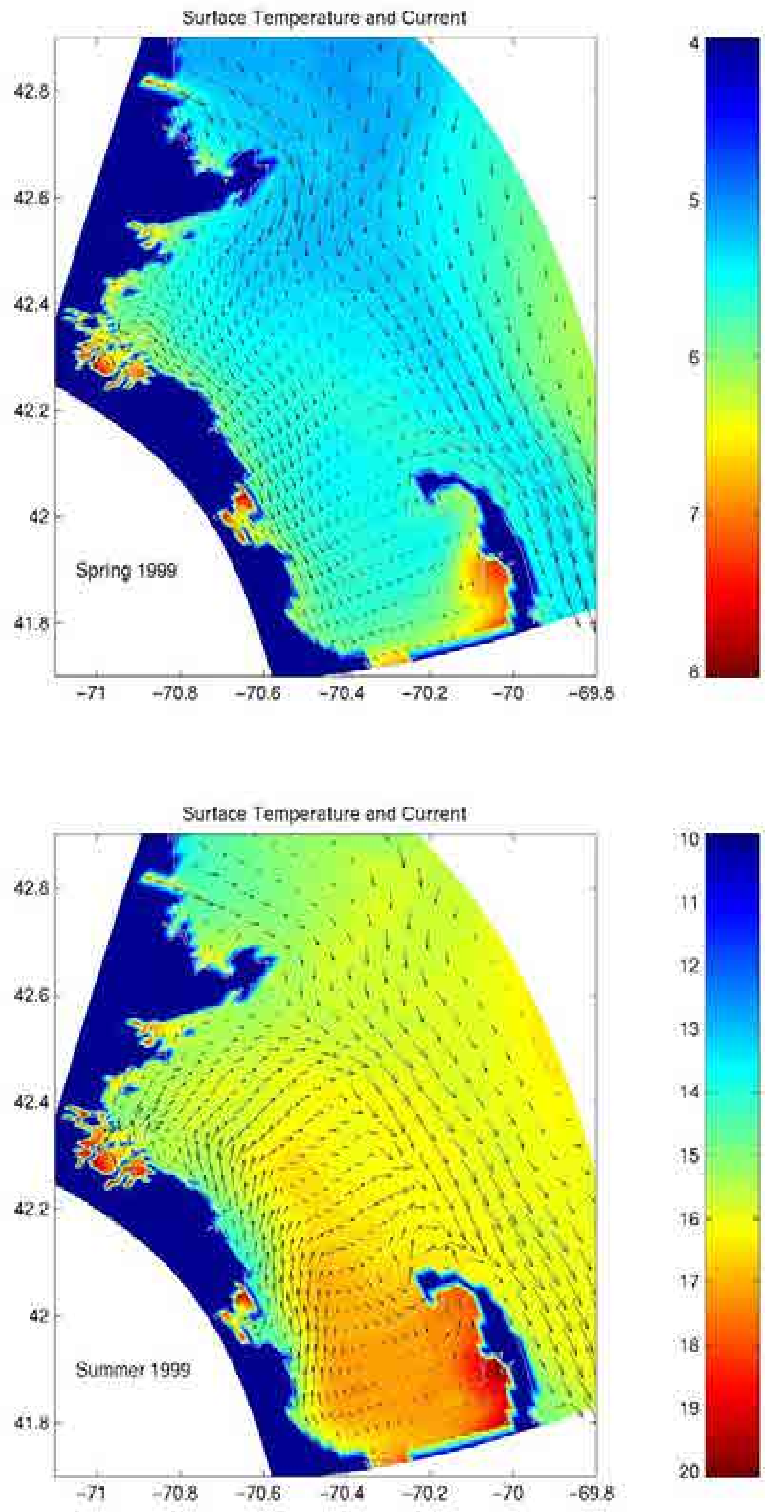

Figure 4-12 Modeled surface temperature and circulation patterns in spring 1999 (top panel) and summer 1999 (bottom panel) showing northward flow along the coast (figure courtesy Mingshun Jiang, UMass/Boston.)

Color shows surface temperature (4-8 C in spring, 10-20 C in summer).

4.6 Effluent dilution and dispersion

The impact of the effluent is minimized by effective dilution. A 2-km long diffuser with 271 ports disperses the effluent into the 30 m deep waters in the Bay, where the effluent mixes rapidly with large volumes of seawater to achieve very low concentrations of any contaminants that remain after secondary treatment. The initial dilution of the effluent is about 100:1. The results of a dye study and other data documenting the initial dilution are presented in Section 5.

In the winter, the effluent plume reaches the surface, while during the stratified season it is trapped below the pycnocline, in the bottom 15-20 m of the water column.

After initial dilution the effluent is dispersed more gradually throughout western Massachusetts Bay. There is essentially no mean flow at the outfall location; bottom currents of around 6 cm/s are very variable in direction (Butman *et al.* 2002.) The primary temporal and spatial scales of variability near the outfall are those of the tides and of local weather patterns. After initial dilution, drifter and model studies indicate that effluent constituents may move toward the shore, or offshore where they are incorporated into the general circulation of the bays (Figure 4-13.)

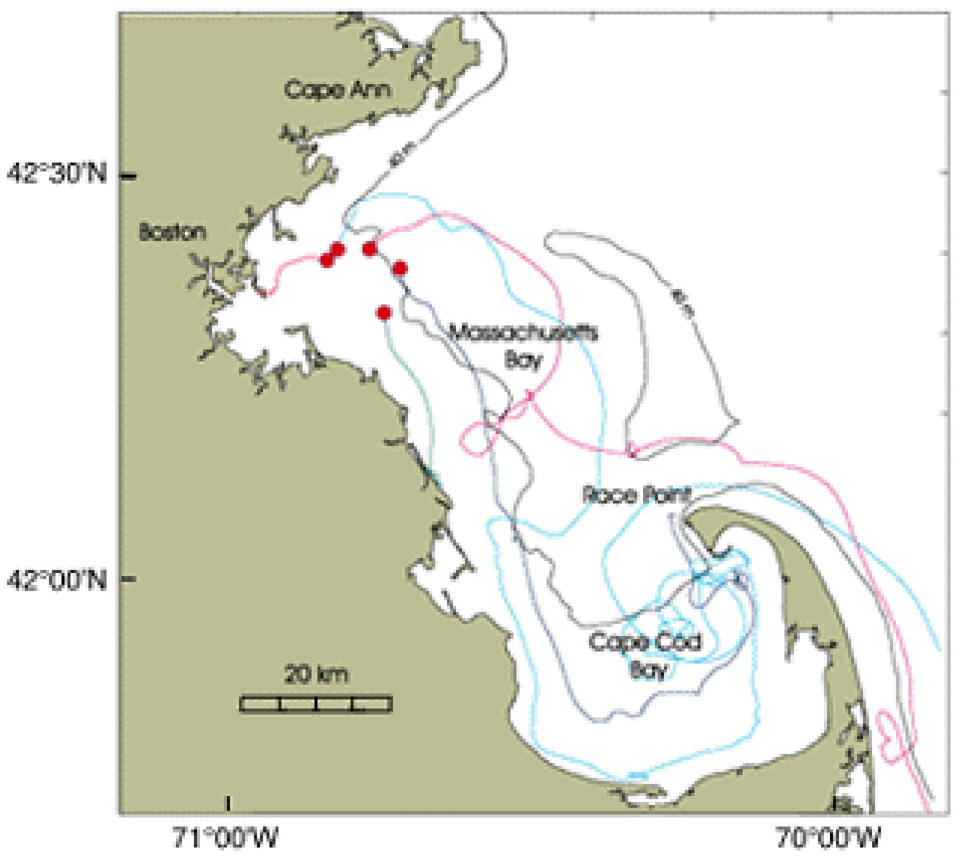

Figure 4-13 Paths of drifters released in May 1990 illustrating the variability of the surface currents in Massachusetts Bay (Geyer et al. 1992.)

Time represented by each track varies from two days (for drifters going ashore in Boston Harbor or Scituate) to three weeks (for drifters entering Cape Cod Bay.)

4.7 The Massachusetts Bay ecosystem seasonal cycle

Although Massachusetts and Cape Cod Bays generally follow the annual cycle typical for coastal waters, monitoring has shown that wind, regional conditions, and other factors greatly influence the pattern. Waters are well mixed and nutrient levels are high during November through April. As light levels increase in early spring, there is often a bloom of phytoplankton; spring blooms may occur earlier than the onset of stratification, or not at all. During the years in which there are spring blooms, they begin in the shallower waters of Cape Cod Bay. Blooms in deeper waters begin two to three weeks later. Spring phytoplankton blooms are typically followed by an increase in zooplankton abundance. The endangered right whale may typically visit Cape Cod Bay to feed during December through May (http://www.coastalstudies.org/research/right.htm.)

Throughout late spring and summer, stratification effectively separates the surface and bottom waters, preventing replenishment of nutrients to the surface and of oxygen to the bottom. Phytoplankton in the surface waters deplete the available nutrients and then undergo senescence. Phytoplankton abundance is also depleted by grazing. Oxygen levels remain high in the surface waters throughout the year, but oxygen levels decrease in the bottom waters due to respiration of sinking particulate matter.

Respiration consumes dissolved oxygen and the levels decline in bottom water decrease though the autumn (September-October) until mixing in late fall replenishes bottom oxygen levels. Advection also affects bottom DO concentrations. Nearfield DO tends to be lowest when the bottom waters are warm and salty, possibly reflecting advection from the Gulf of Maine of low DO waters having those temperature and salinity characteristics (Libby *et al.* 2000.)

In the fall, cooling surface waters and strong winds promote mixing of the water column. Oxygen is replenished in the bottom waters, and nutrients brought to the surface stimulate a fall phytoplankton bloom. The fall bloom is often stronger than the spring bloom. Typically, fall blooms end in the early winter, when declining light levels limit photosynthesis. Plankton die and decay, replenishing nutrients in the water column.

Warmer years appear to have weaker spring blooms as described in Section 5. Stronger stratification results in more depletion of surface nutrients in summer; this may lead to stronger fall blooms since more nutrients are available after turnover (Jiang *et al.* 2003.) Cool years such as 2001 tend to have lower phytoplankton and zooplankton abundance (Jiang *et al.* 2003.)

4.8 Spatial variability

The spatial variability in biological parameters is driven by bathymetry and proximity to the open ocean boundary. Shallow enclosed bays such as Boston Harbor have higher levels of nutrients and chlorophyll than do open waters. Stellwagen Bank is highly productive because strong tidal currents over the bank mix nutrients throughout the water column. Likewise, southeastern Cape Cod Bay tends to have higher chlorophyll (Figure 4-15) because of its shallow depth. More detailed results on spatial variation in biological parameters are given in Section 5.

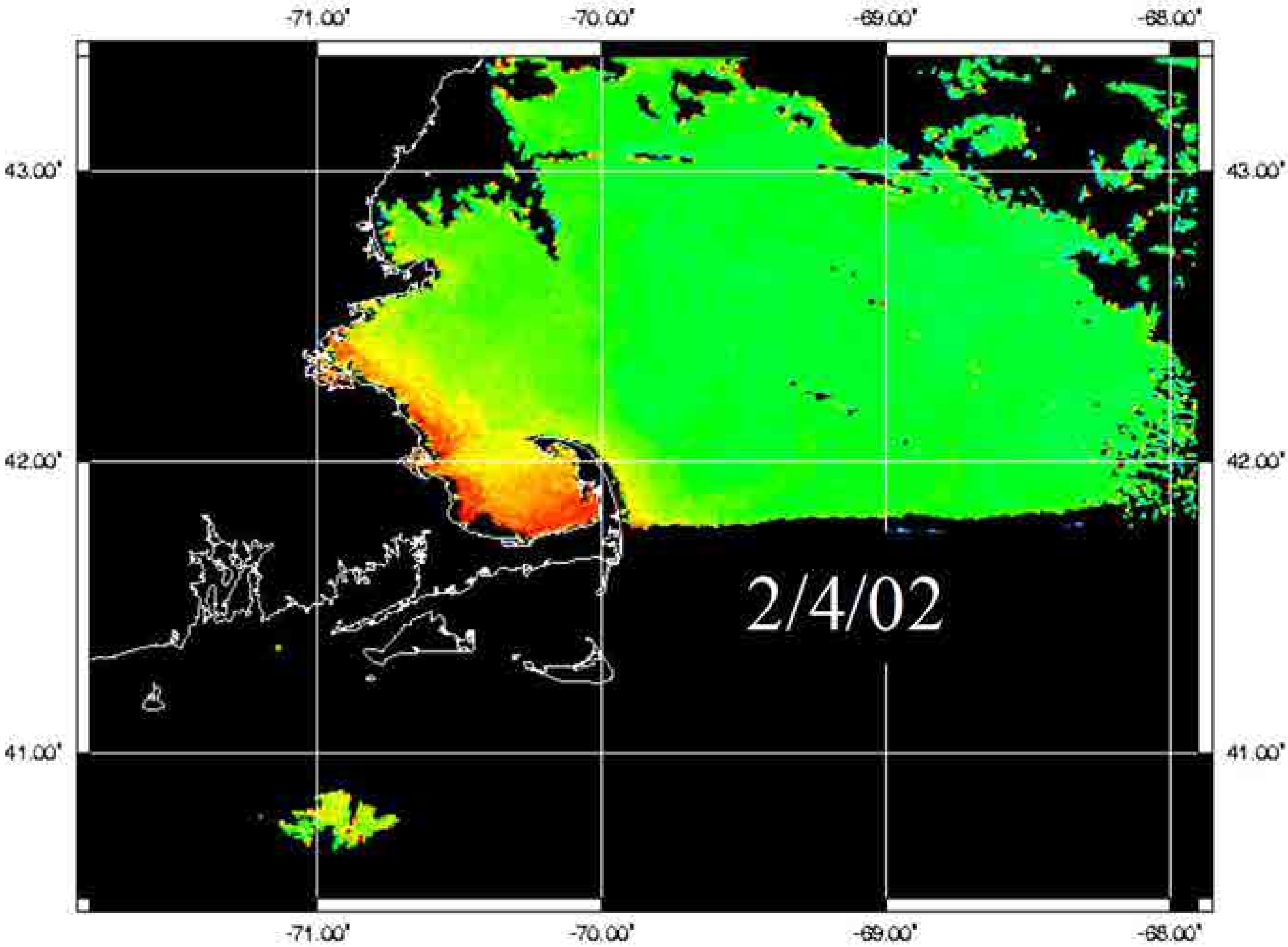

Figure 4-14 SeaWIFS satellite ocean color image from February 2002.
Red (or darker gray) shows high surface chlorophyll concentrations.

4.9 Water quality model results

A three-dimensional water quality model of the bays has been constructed (HydroQual and Normandeau, 1995, HydroQual 2000, 2001, 2002, Jiang *et al.* 2003.) This model reproduces the general seasonal cycle and spatial variability of nutrients, oxygen, and chlorophyll (Figure 4-16 and 4-17). Model results indicate that the values of these parameters in western Massachusetts Bay and in Cape Cod Bay are quite sensitive to the values at the boundary with the Gulf of Maine.

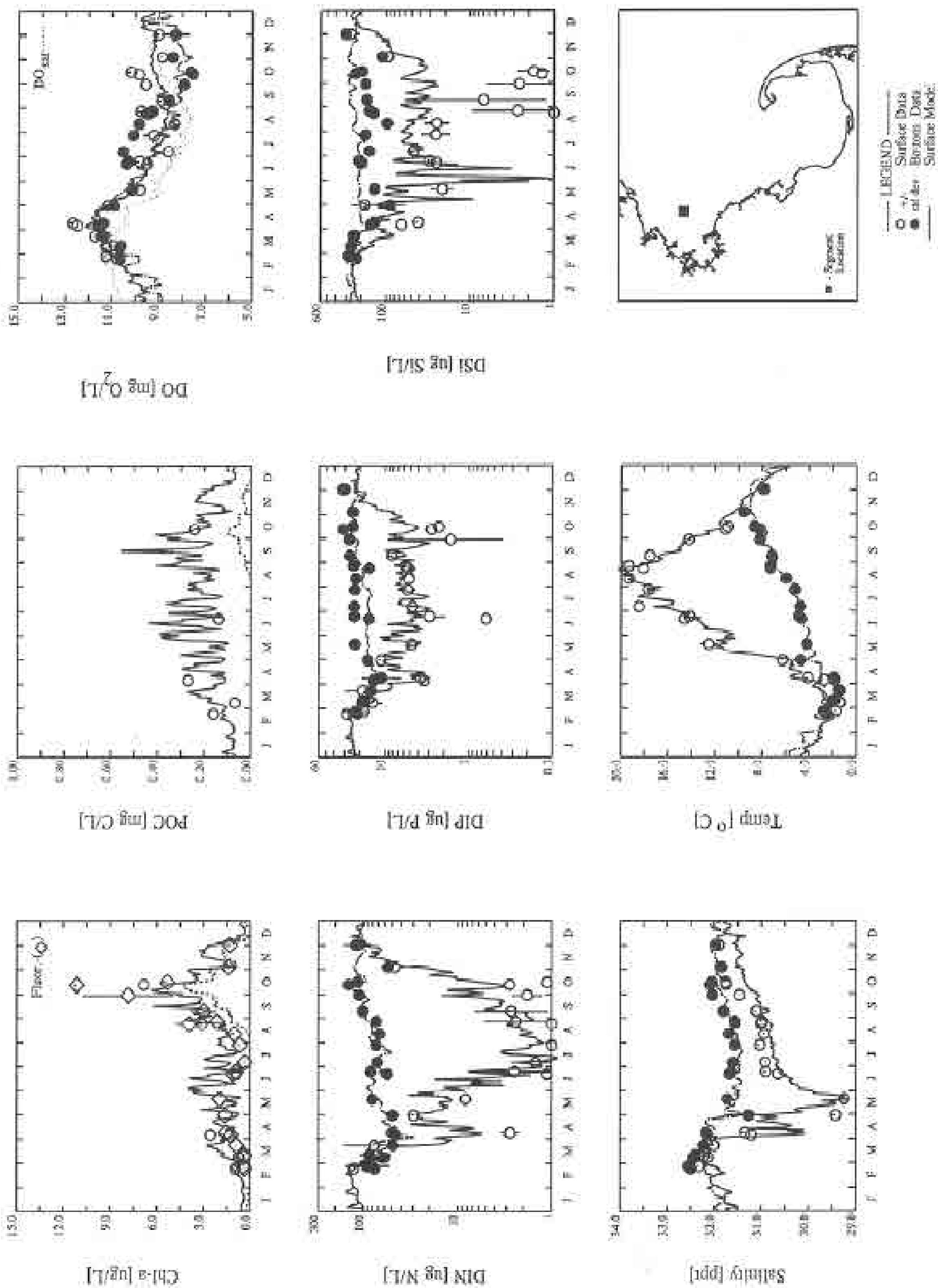

Figure 4-15 Comparison of Bays Eutrophication Model results and data for various water quality parameters in nearfield, 1993 (HydroQual 2001.)

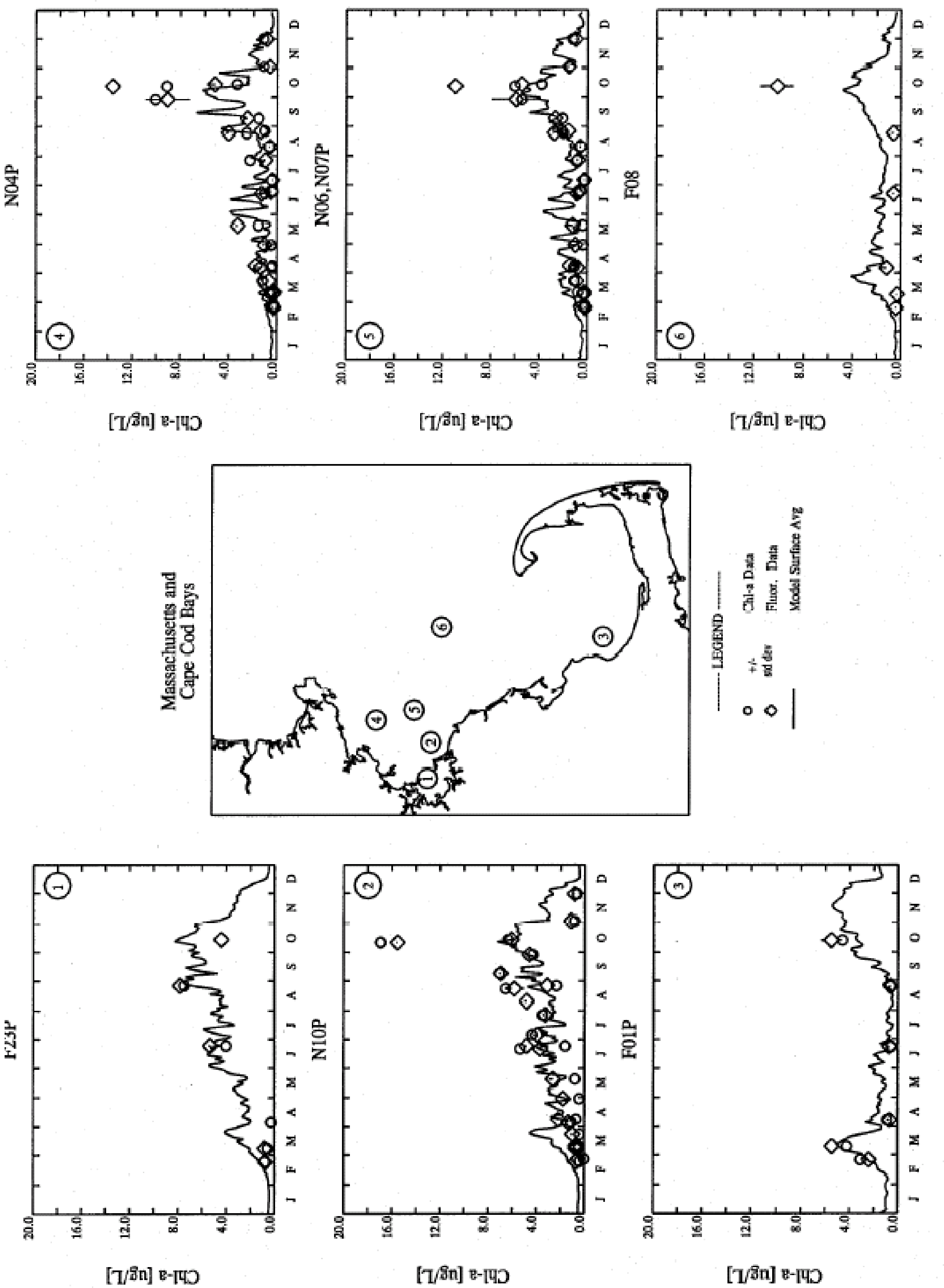

Figure 4-16 Comparison of Bays Eutrophication Model results and data for chlorophyll for six locations, 1993 (HydroQual 2001.)

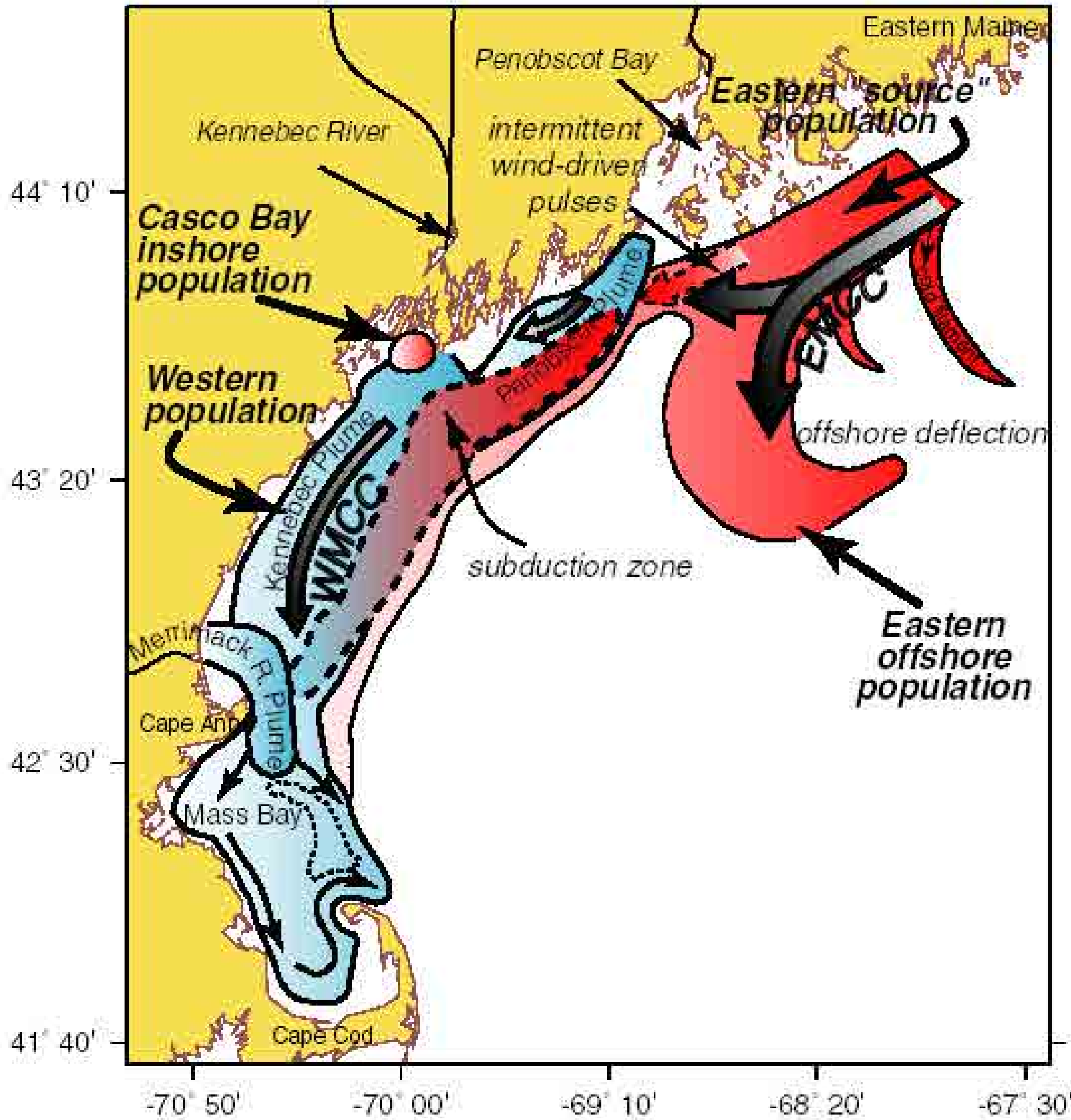

Figure 4-17 Conceptual model of red tide (Anderson *et al.*, 2002.)

Depending on winds during an offshore bloom, populations of *Alexandrium* may either be transported into the Bay by winds from the northeast, also referred to as downwelling-favorable conditions.

4.10 Regional scale biology

Variations in the biology and physics in the Gulf of Maine have a strong effect on the Massachusetts Bay/Cape Cod Bay system. The exchange with the boundary – most importantly, whether the Maine coastal current enters Massachusetts Bay or stays outside Stellwagen Bank – determines nutrient and oxygen levels in the interior of the bay, and the residence times of water in Massachusetts Bay and Cape Cod Bay. Nuisance algae such as *Alexandrium fundyense/tamarense* can be transported into the bay from the Gulf of Maine.

The open ocean boundary, because of the large transport of water across it, is the major source of nutrients to the bays. For example, HydroQual (2000) estimated that in 1992 the Gulf of Maine contributed 92% of the total nitrogen entering the bays, with MWRA effluent contributing 3% and other sources (mostly atmospheric) contributing 5%.

Dissolved oxygen near the outfall is highly correlated with oxygen levels in deep water near the boundary. The effect of the Gulf of Maine on the dissolved oxygen and nutrient levels is described in more detail in Section 5.

Nuisance blooms can be linked to the larger circulation in the Gulf of Maine: for example, winds, currents and spring runoff during May can determine whether red tide enters Massachusetts Bay or is transported out to sea (Anderson, 1997, Anderson *et al.* 2002, Figure 4-17.)

As described in more detail in section 5, phytoplankton and zooplankton species composition and abundance tend to vary on a baywide or regional scale. Except in Boston Harbor, species observed are typical of the open waters of the northwest Atlantic Ocean. Some have predictable seasonal cycles, while others (such as certain nuisance species) appear only intermittently.

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5. RESULTS OF WATER COLUMN MONITORING

Scott Libby, Kenneth Keay, Andrea Rex, Wendy Leo, Candace Oviatt, Jefferson Turner, David Borkman, Stephen Emsbo-Mattingly, Carlton Hunt, David Taylor, Michael Mickelson

This section summarizes the findings of 11 years of water column monitoring in Massachusetts Bay near the outfall, in Cape Cod Bay, Boston Harbor, coastal stations and the "boundary" which includes Stellwagen Bank and the sills to north and south.

The data are used to address the ambient monitoring questions (MWRA, 1991). Results of monitoring for aesthetics, bacteria, and a dye study carried out to measure the dilution of the outfall are presented. Then, monitoring data for nutrients and the potential effects of nutrients from the outfall on dissolved oxygen, algal blooms, and plankton communities are discussed.

5.1 Aesthetics and Bacteria

→ *Are pathogens transported to shellfish beds at levels that might affect shellfish consumer health?*
→ *Are pathogens transported to beaches at levels that might affect swimmer health?*

→ *Has the clarity and/or color of the water around the outfall changed?*
→ *Has the amount of floatable debris around the outfall changed?*

Field sampling personnel make visual observations when sampling in the nearfield. These observations are summarized in survey reports. In the summer stratified season, the outfall discharge is not visible at the surface. On very calm winter days, samplers sometimes see subtle circular areas of calmer water over each diffuser site. They do not see slicks, areas of excess algal growth, or sewage-related "floatables." Net tows during every survey in the outfall area were started in 1999 before the outfall came on-line. The contents of the net tows are photographed and identified. The net tows occasionally collect refuse typical of land-runoff, but no more than before the outfall began discharging.

Bacteria sampling is carried out monthly at locations shown in Figure 5-1 for fecal coliform and *Enterococcus*. Monitoring has detected a slight increase in bacteria counts after the outfall began (Table 5-1). The highest counts are typically at stations directly over the diffuser line.

Table 5-1 Bacteria Counts at the Outfall Site. The FDA shellfishing standard is less than 14 fecal coliform colonies per 100 ml.

	Geometric mean bacteria counts (colonies/100 ml) at the outfall site	
	Fecal coliform	*Enterococcus*
Before outfall start-up	2.0	1.0
After outfall start-up	2.2	1.1

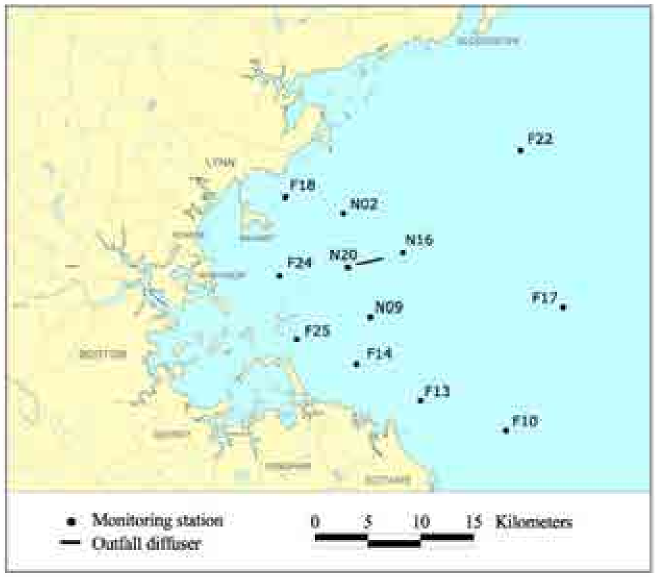


Figure 5-1 Sampling Sites for Bacteria. Samples are collected at surface and subpycnocline.

5.2 Plume tracking

→ *Are the model estimates of short-term (less than 1 day) effluent dilution and transport accurate?*
→ *Do levels of contaminants in water outside the mixing zone exceed State Water Quality Standards?*

During summer 2001, a dye study of effluent dilution was conducted Figure 5-2 and Figure 5-3). Physical and computer model studies had set a predicted minimum dilution of approximately 1:70 at edge of the hydraulic mixing zone, that is, the transition point between the area where dilution is a result of turbulence generated by the outfall and the area in which dilution is the result of oceanographic processes. In the summer, the distance from the outfall to the edge of the hydraulic mixing zone can be less than 20 meters. In the field study, dilution was determined by adding a solution of the dye Rhodamine WT to the effluent at the treatment plant and measuring dye concentrations at the treatment plant and the outfall site. Naturally occurring plume tracers were also measured.

During the certification study, there was moderate stratification of the water column, as is typical of the early summer. Temperature was the major influence on the pycnocline.
The core of the plume was found between 15 and 20 meters depth.

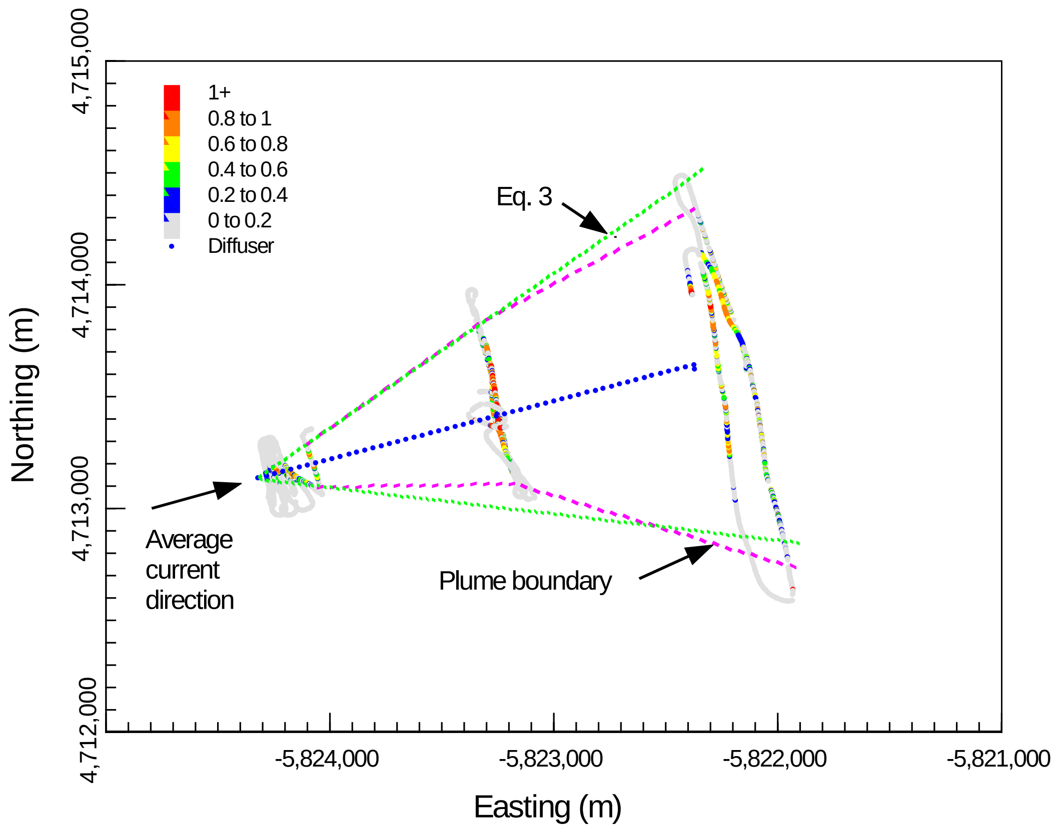


Figure 5-2 Vessel track lines and dye concentrations (ppb) measured during the three hydraulic mixing surveys. Actual lateral spreading of the plume agreed with mathematical predictions.)

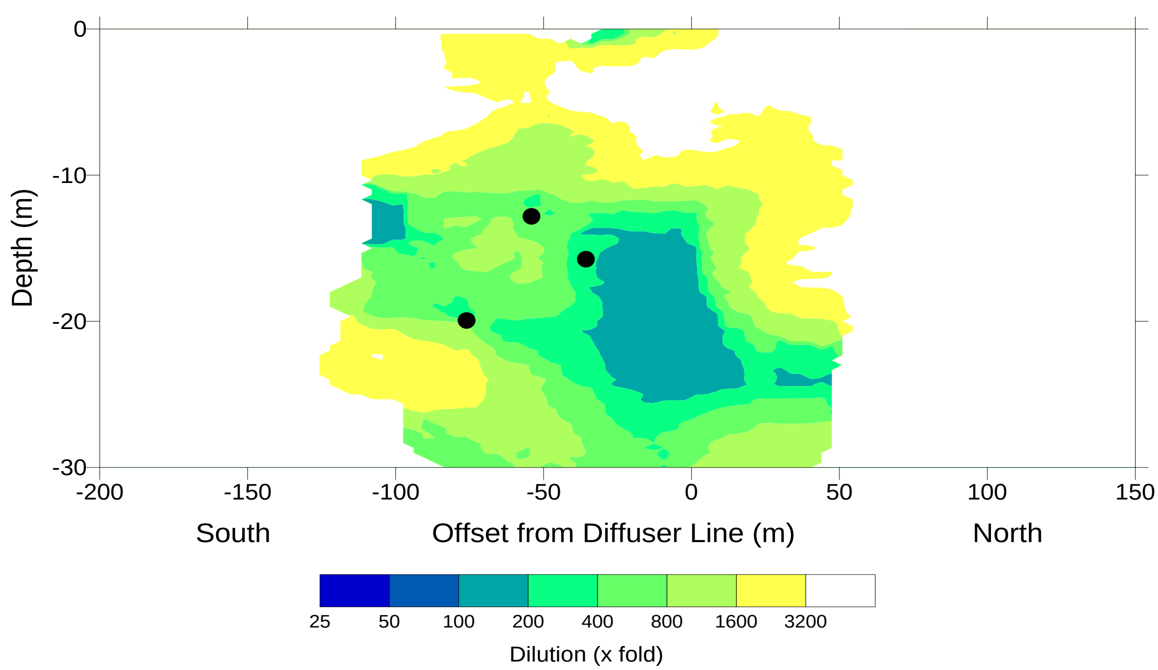


Figure 5-3 Example of dilutions measured in cross-section of plume during dye study. Dots show location of discrete samples.

The study found there is good agreement between the model and field results (Table 5-2) and that the outfall met the minimum dilution assumed by the permit. Dilution, thickness of the wastefield, height to the top of the wastefield, and height of minimum dilution matched well. Water quality in the plume after initial mixing met all state and federal marine water quality criteria.

Table 5-2 Comparison of model predictions and plume measurements in summer 2001.

	Model predictions	Field results
Dilution	104	102
Thickness of wastefield (m)	18.8	20
Height to top of wastefield	24.8	28
Height of minimum dilution	16.6	18

5.3 Nutrients

→ *Have nutrient concentrations changed in the water near the outfall?*
→ *Have nutrient concentrations changed at farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are they correlated with changes in the nearfield?*

An understanding of a general sequence of water quality events in Massachusetts and Cape Cod Bays has emerged from the monitoring data, although the timing and year-to-year manifestations of these events vary. In the winter-spring period a phytoplankton bloom sometimes occurs as light increases, temperatures rise, and nutrients are available in a well-mixed water column. Later in spring, the water column stratifies, nutrients in the surface waters are depleted, and the spring bloom ends. The summer is characterized by strong stratification, depleted nutrients, and a relatively stable mixed-assemblage phytoplankton community. Dissolved oxygen declines in the bottom waters over the summer. Stratification prevents the bottom water oxygen from being replenished from the surface; warmer temperatures and higher respiration rates lower bottom dissolved oxygen. In fall, stratification deteriorates, supplying nutrients to surface waters. Often there is a fall phytoplankton bloom. The lowest bottom dissolved oxygen concentrations are just prior to the fall overturn of the water column–usually in October. By early winter, the water column is well mixed, resetting to winter conditions.

This general sequence has continued since the bay outfall became operational on September 6, 2000 with a few deviations from baseline trends. For example, the winter/spring blooms in Massachusetts Bay in 2001 and 2002 were relatively early and the fall bloom in 2000 exhibited extraordinarily high chlorophyll concentrations, but not atypically high POC, production, or phytoplankton abundance. The winter/spring and fall blooms were regional events as indicated by the far reaching extent of elevated chlorophyll levels shown in SeaWiFS satellite imagery. These deviations are examined in more detail below.

In some of the figures in this section, monitoring stations are grouped by area to summarize the variation of each section of the bays. Figure 5-4 shows the location of the stations in each group.

Data presented for the boundary focuses on the 'inbound' water at stations F26 and F27 off Cape Ann.

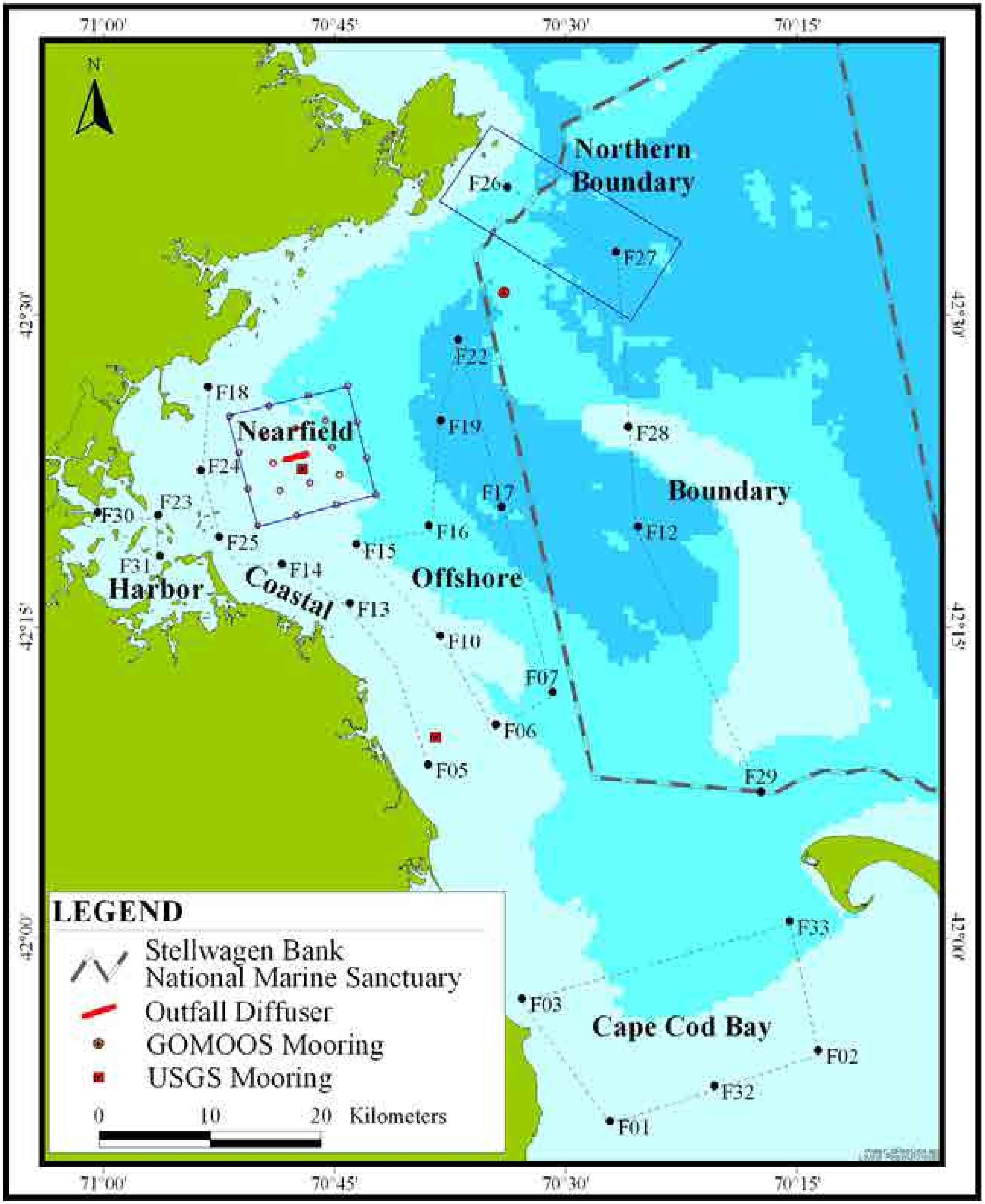


Figure 5-4 Sampling stations and definition of geographic regions referred to in text.

Model simulations predicted that when the effluent was transferred from Boston Harbor to Massachusetts Bay, effluent concentrations would be greatly reduced in the harbor, would increase locally within the plume in the nearfield, and have little impact on concentrations in the rest of Massachusetts and Cape Cod Bays (Figure 5-5) (Signell *et al*., 1996). The spatial patterns in NH_4 concentrations during October 1999 when the discharge was still in the harbor, and October 2000 after the bay outfall started up, clearly confirmed the model dilution simulations Although NH_4 is not a truly conservative tracer of the effluent plume due to biological utilization, it is a good indicator of the effluent plume over relatively short spatial (<20 km) and temporal (hours to days) scales.

The changes in NH_4 concentrations before and after the diversion to the bay outfall were used to estimate relative farfield dilution of the effluent (Mickelson *et al.* 2002). The station means from 1992 to 1999 were compared with the mean from 2001.

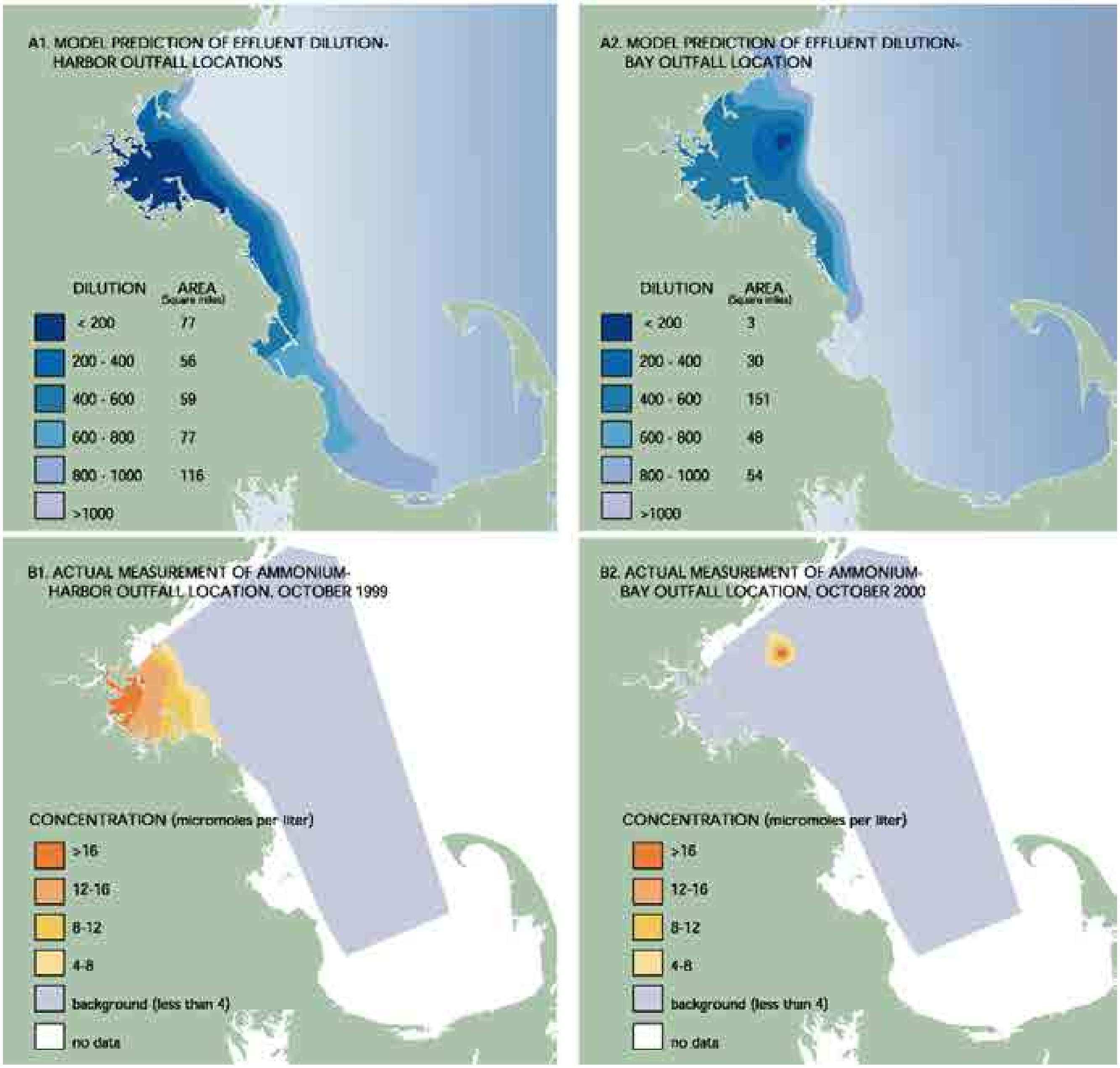


Figure 5-5 Comparison Between Model Predictions for Dilution for the Harbor and Bay Outfall Locations with Actual Ammonia Concentration Measurements Before and After the Outfall went On-line.

Figure 5-6 shows the results of this analysis, which indicated that

→ NH_4 decreased significantly ($p<0.05$) in the harbor and increased in the bay at only those stations within 20 km of the new outfall.
→ The magnitude of change in Boston Harbor was greater in winter whereas the magnitude of change in the bay was greater in summer.

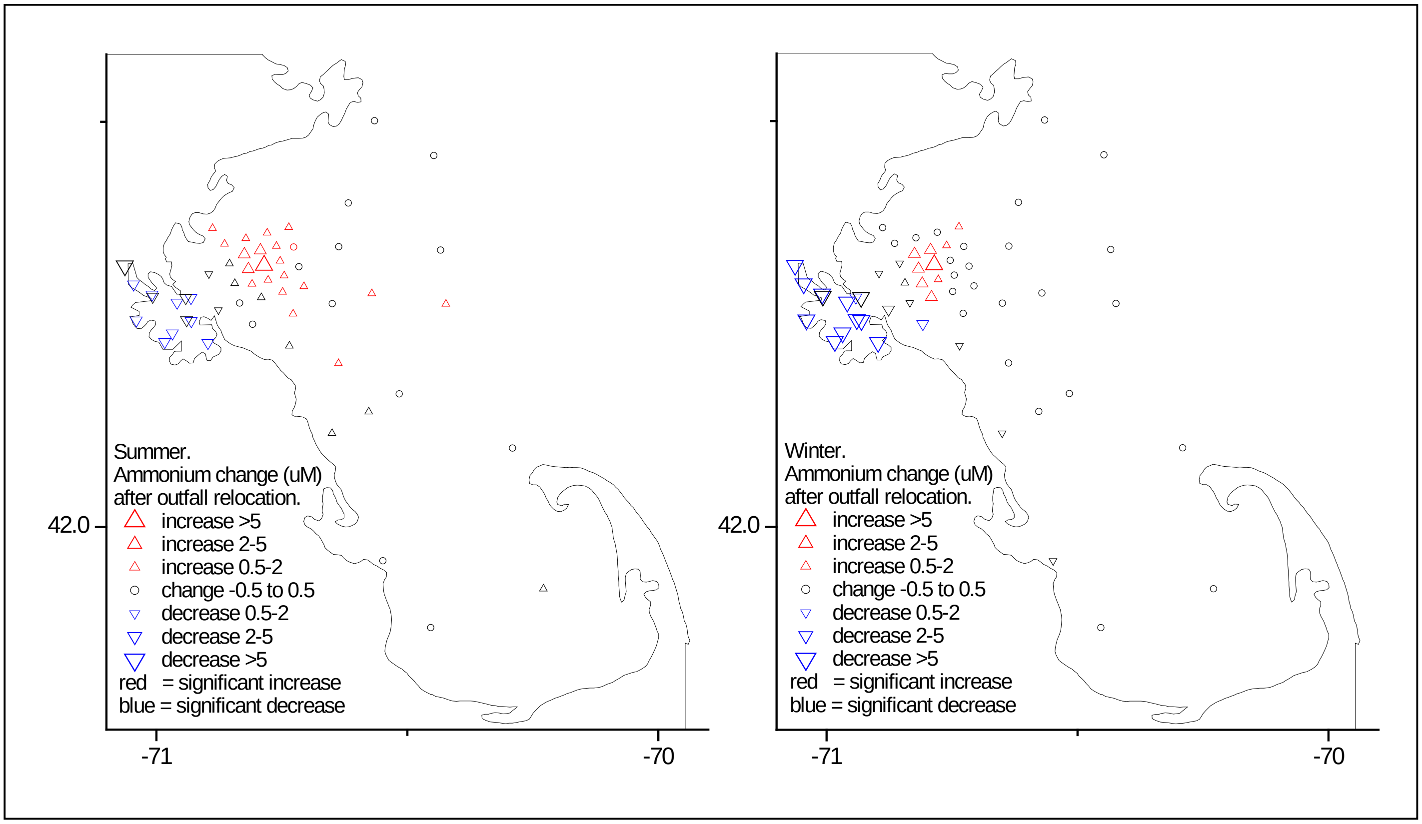


Figure 5-6 Change in NH_4 concentration: 2001 versus baseline in summer (April – October) and winter (November – March).

The dye-dilution study also showed that NH_4 tracks the effluent plume (Hunt *et al*. 2002). During periods of stratification, the NH_4 signature of the plume is contained below the pycnocline. When the water column is well mixed the NH_4 signature reaches the surface (Figure 5-7). NH_4 traces horizontal advection of the plume within and out of the nearfield. In August 2001, salinity and NH_4 data suggested the effluent plume was advected from the nearfield to the south (Figure 5-8). A similar displacement of the plume (direction and distance) was observed in July 2001 during the plume tracking survey as the plume was followed over a period of three days as it moved from the nearfield to waters off of Scituate (Hunt *et al*. 2002).

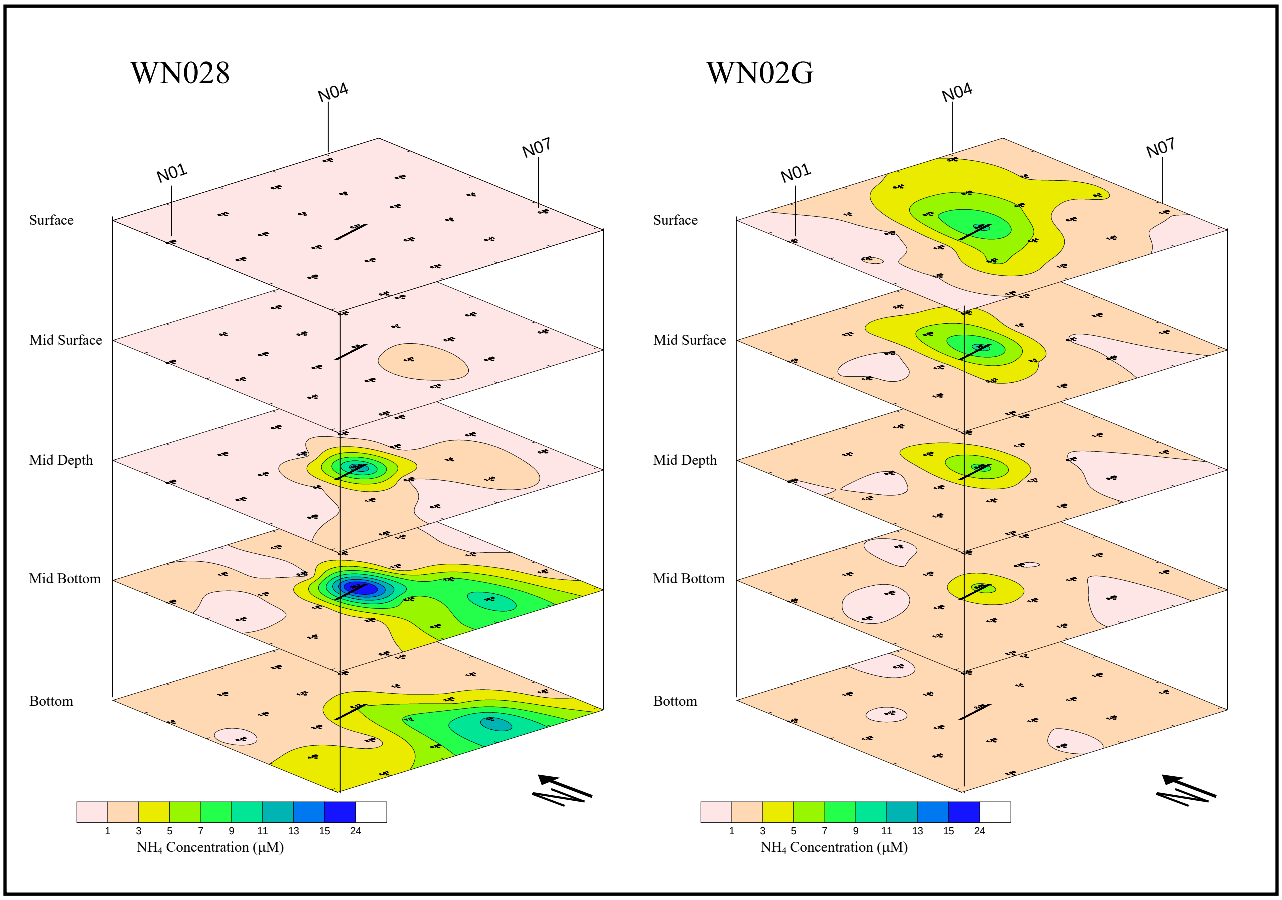


Figure 5-7 Ammonium concentrations at each of the five sampling depths for entire nearfield during August and November 2002.

Note: displayed depths are a representation; actual sampling depths vary for each station.

Figure 5-9 shows how nutrient concentrations changed in different regions after the bay outfall began operating. There was a very sharp decrease in annual mean NH_4 concentration from 2000 to 2001 in Boston Harbor. A sharp decrease in NH_4 concentration was also seen at the coastal stations, which are strongly influenced by water quality conditions in Boston Harbor. The increase in annual mean NH_4 in the nearfield was not as dramatic as the harbor and coastal water decrease. Compared to 1999, the annual mean NH_4 levels have almost doubled in the nearfield. Harbor, coastal, and nearfield NH4 concentrations remained stable from 2001 to 2002. There has been little if any change in NH_4 concentrations in offshore, boundary, and Cape Cod Bay waters from 1992 to 2002. In fact, annual mean NH_4 concentrations in Cape Cod Bay decreased from a maximum of 1.7 µM in 1999 to <1 µM in 2002. The trends in annual mean concentration for other inorganic nutrients have been more erratic as seen in Figure 5-10 for nitrate (NO_3). Year to year variability may have more to do with timing of sampling and occurrence of blooms than any clear trends in background levels.

To summarize, changes in nearfield and farfield nutrient regimes are consistent with model predictions. Although the effluent nutrient signature is clearly observed in the vicinity of the outfall, it is diluted to background levels over a few days and tens of kilometers.

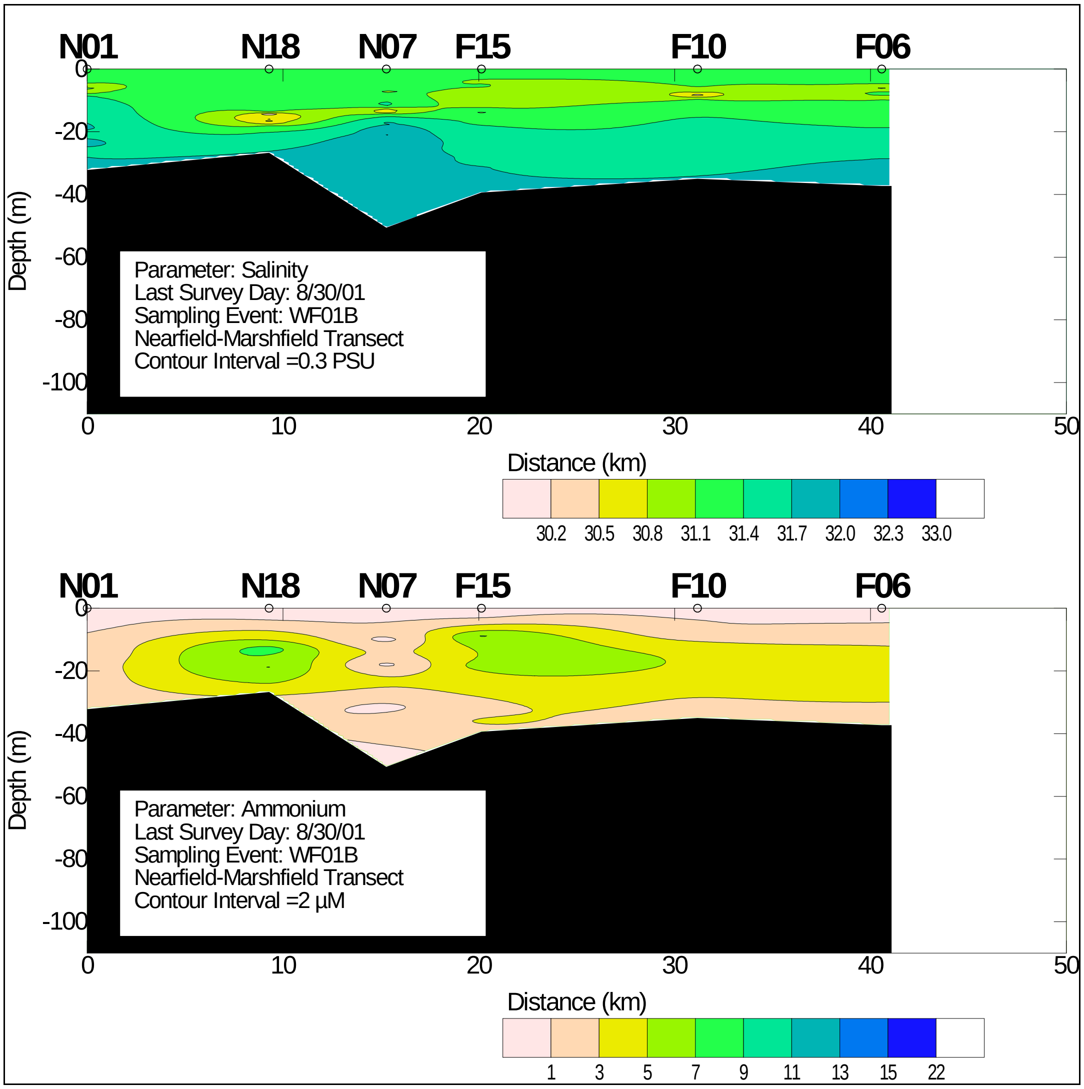


Figure 5-8 Salinity and NH4 along the Nearfield-Marshfield transect in August 2001.

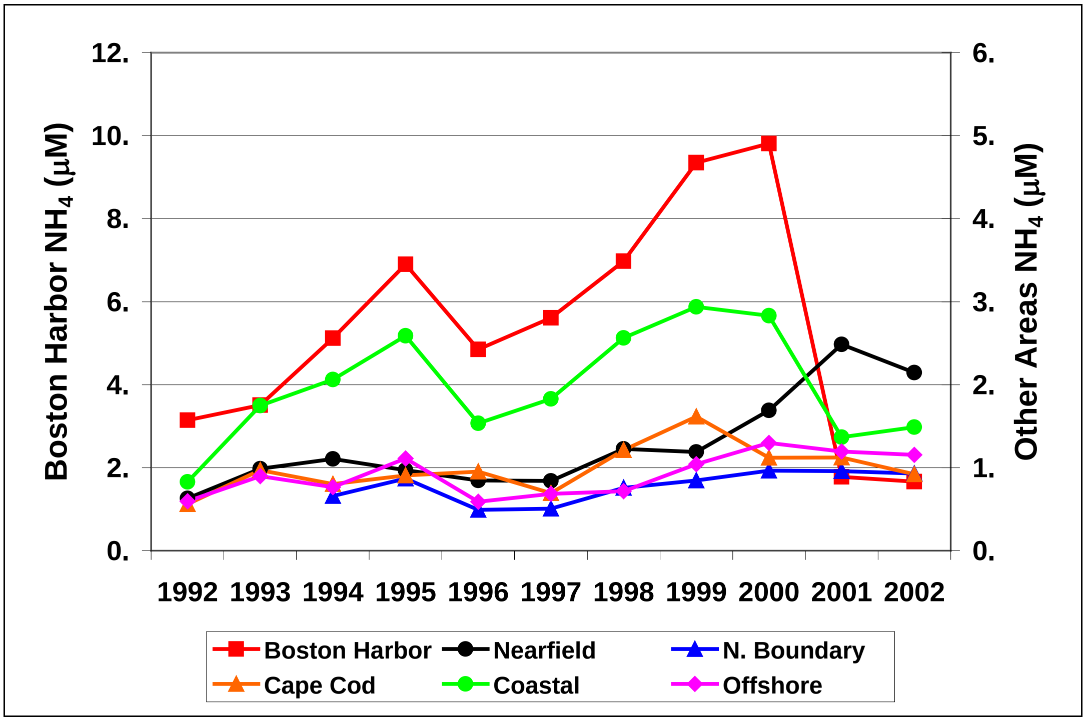


Figure 5-9 Annual mean ammonium concentrations in Massachusetts Bay regions. Note different scale for Boston Harbor data.

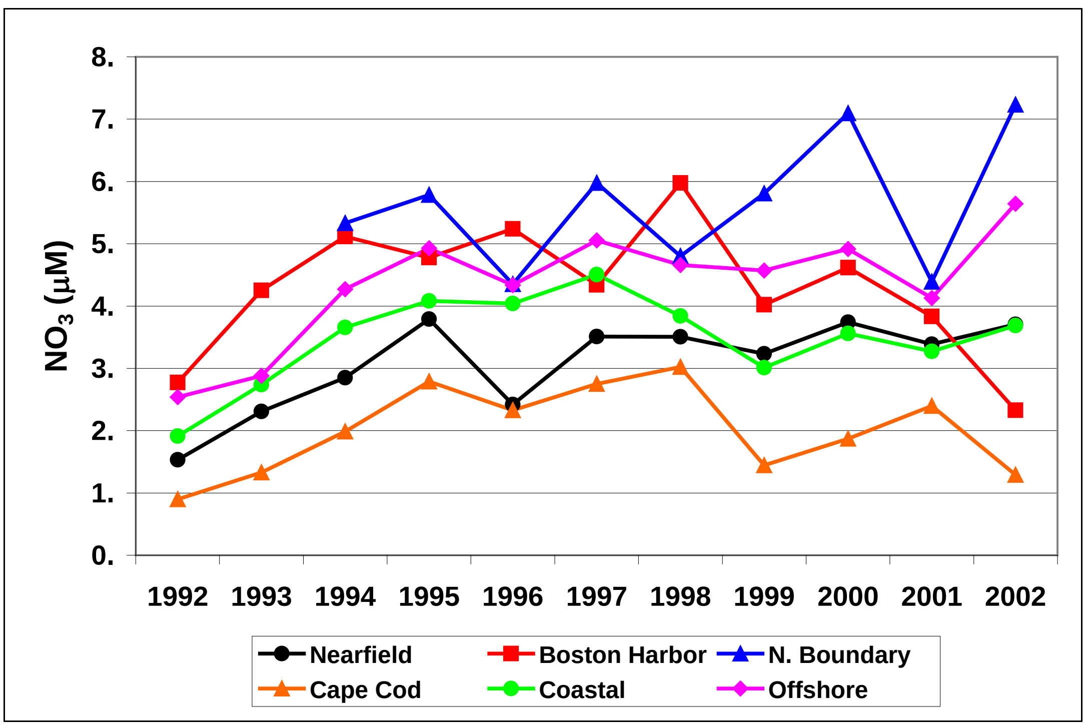


Figure 5-10 Annual mean nitrate concentrations in Massachusetts Bay regions.

5.4 Dissolved Oxygen

→ *Have the concentrations (or percent saturation) of dissolved oxygen in the water changed relative to predischarge baseline or a reference area and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?*
→ *Do the concentrations (or percent saturation) of dissolved oxygen in the water column meet the State Water Quality Standard?*
→ *Have the water column concentrations (or percent saturation) of dissolved oxygen changes at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the nearfield or changes in nutrient concentrations in the farfield?*
→ *Do the water column concentrations (or percent saturation) of dissolved oxygen at selected farfield stations meet the State Water Quality Standard?*

The two primary areas of interest with respect to dissolved oxygen levels are the outfall nearfield and Stellwagen Basin, within Stellwagen National Marine Sanctuary. Stellwagen Basin is the deepest area of Massachusetts Bay where relatively low DO was measured in early sampling. The survey mean bottom water DO concentrations and percent saturation in 2001and 2002 closely followed the cycle observed for the baseline means in both the nearfield and Stellwagen Basin (Figure 5-11 and Figure 5-12). After the new outfall came on-line, the DO cycle continued the same as during baseline: higher concentrations in late winter/early spring, decreasing concentrations through the summer to the fall, and then increasing concentrations following the overturn of the water column in the fall. DO levels were close to the baseline mean in 2001 in both areas and below the mean during 2002. The annual minima in 2001 and 2002 (October) were above the lowest values that were observed in 1994 and 1999 (Figure 5-13).

The nearfield and Stellwagen Basin survey means only dropped below the state DO concentration standard for class SA waters (6 mgL^{-1}) once during baseline (nearfield in 1999). Percent saturation levels dropped below the 80% standard during all but two of the eleven monitoring years (1993 and 1996) in the nearfield and during 1993 in Stellwagen Basin (Figure 5-13 and Figure 5-14). There is no change in this pattern after outfall start-up.

DO concentration and percent saturation survey means in the nearfield and Stellwagen Basin are highly related ($R^2 = 0.81$ and 0.94 respectively). Modeling and statistical analyses show that DO in the nearfield, Stellwagen Basin and boundary station are all correlated (HydroQual 2001 and Geyer *et al*. 2002). Regional processes and advection are the primary factors governing bottom water DO concentrations in Massachusetts Bay (Geyer *et al*. 2002).

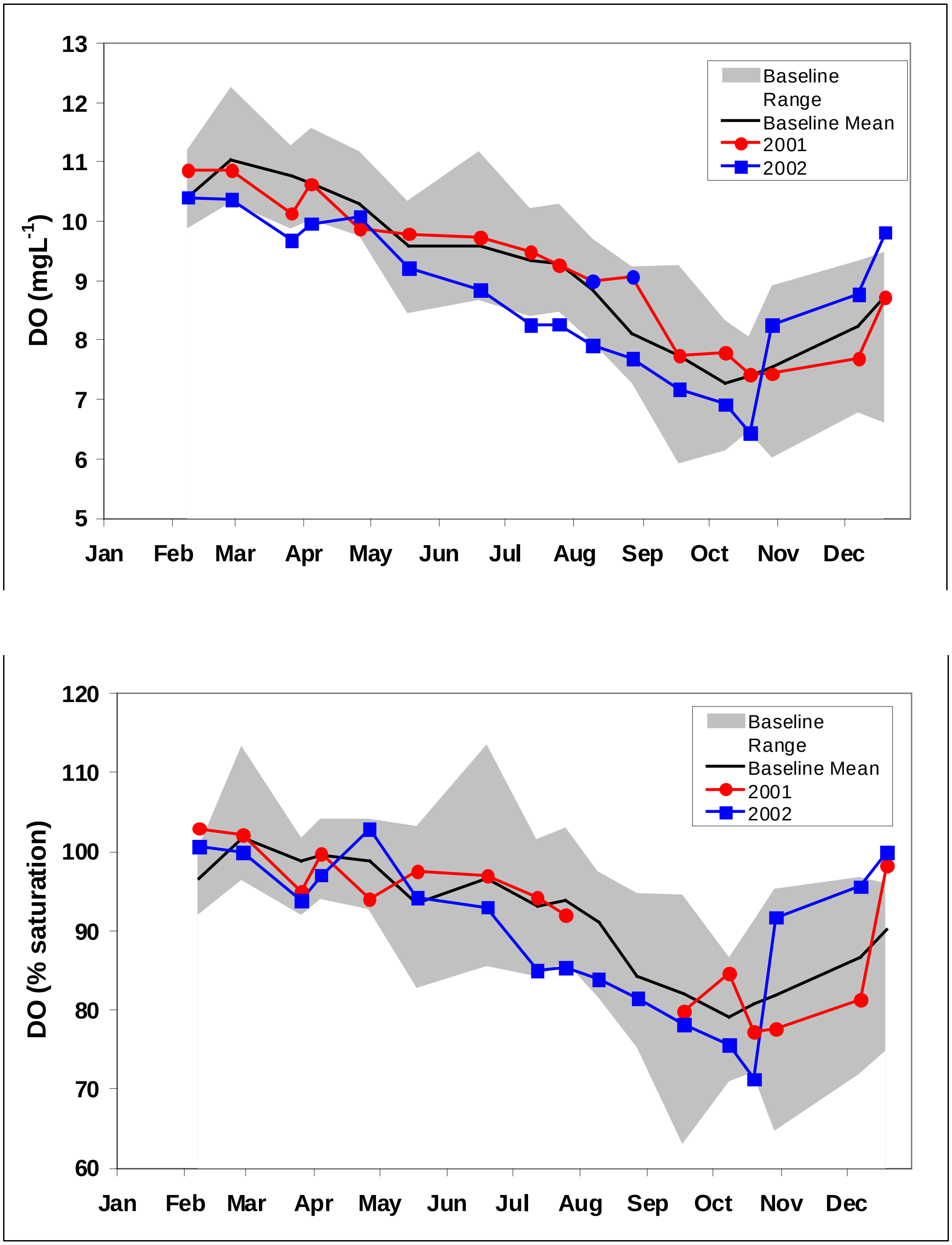


Figure 5-11 Time-series of nearfield survey mean bottom water DO concentration and percent saturation for 2001 and 2002 compared against the baseline range and mean.

Geyer *et al.* 2002 recommended that high resolution DO data be collected in the nearfield and upstream near Cape Ann to help distinguish between local and regional factors affecting nearfield DO. Two moorings in Massachusetts Bay measure DO: the USGS mooring in the nearfield and the Gulf of Maine Ocean Observing System mooring at the northeast boundary of the farfield (see Appendix A for locations). An evaluation of data from these moorings is in Appendix A. The mooring data and shipboard measurements corresponded well ($r^2 > 0.9$). When some technical issues are resolved, these moored time-series measurements should provide useful information to assess local and regional factors affecting DO, and fill in the data gaps between surveys, ultimately allowing a substantial decrease in the frequency of shipboard surveys.

Monitoring data show no change in dissolved oxygen concentrations (or percent saturation) in the nearfield or Stellwagen Basin since the effluent was diverted to the bay outfall. State Water Quality Standards have sometimes been not been met during the periods of minimum DO concentrations, but this was also the case during the baseline period. Bottom water DO levels in Massachusetts Bay appear to be governed by large scale regional processes, and the impact of the diversion to the bay outfall on DO is expected to be minimal.

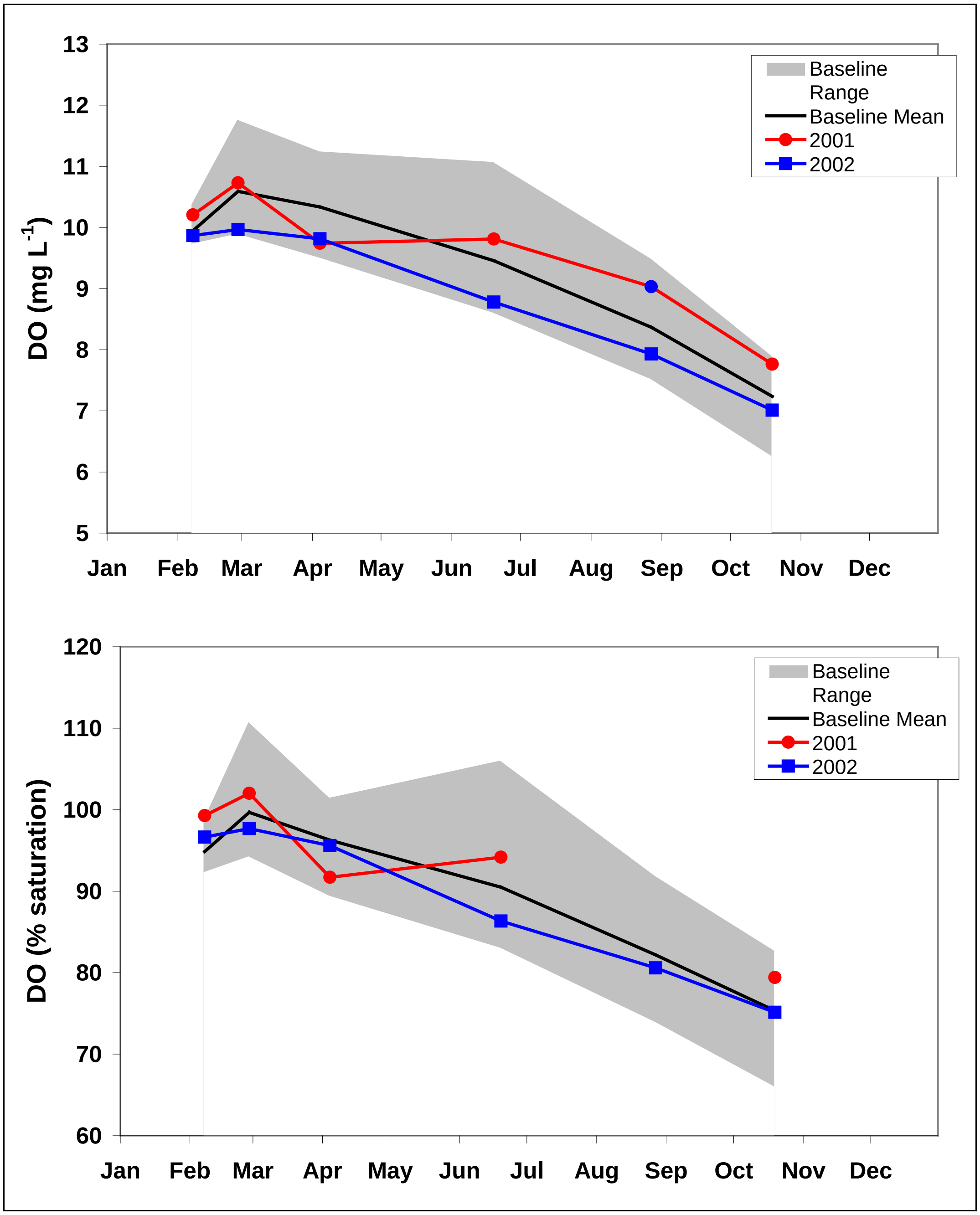


Figure 5-12 Time-series of Stellwagen Basin survey mean bottom water DO concentration and percent saturation for 2001 and 2002 compared against the baseline range and mean.

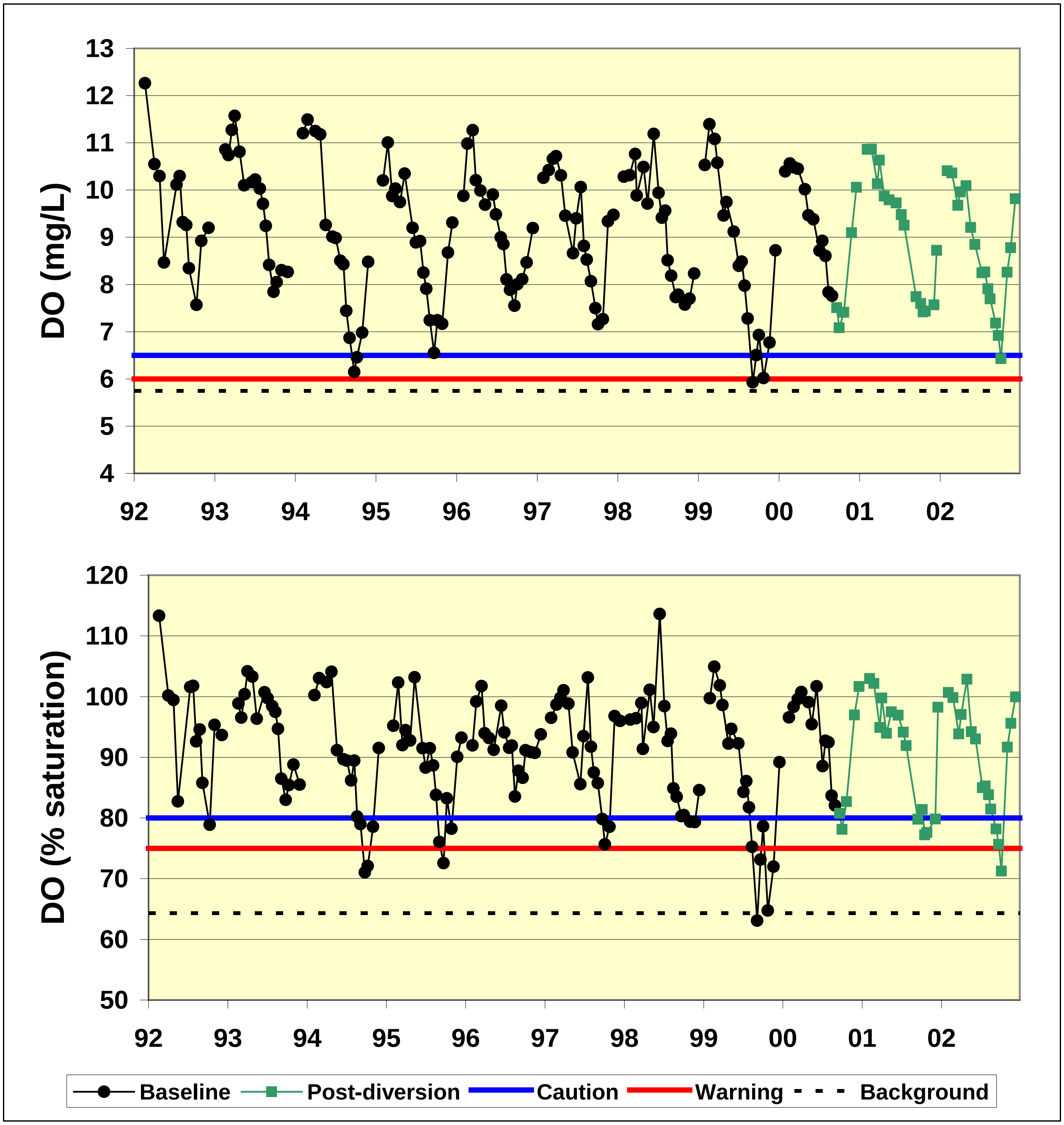


Figure 5-13 Survey mean bottom water dissolved oxygen concentration and percent saturation in the nearfield compared to contingency threshold levels.

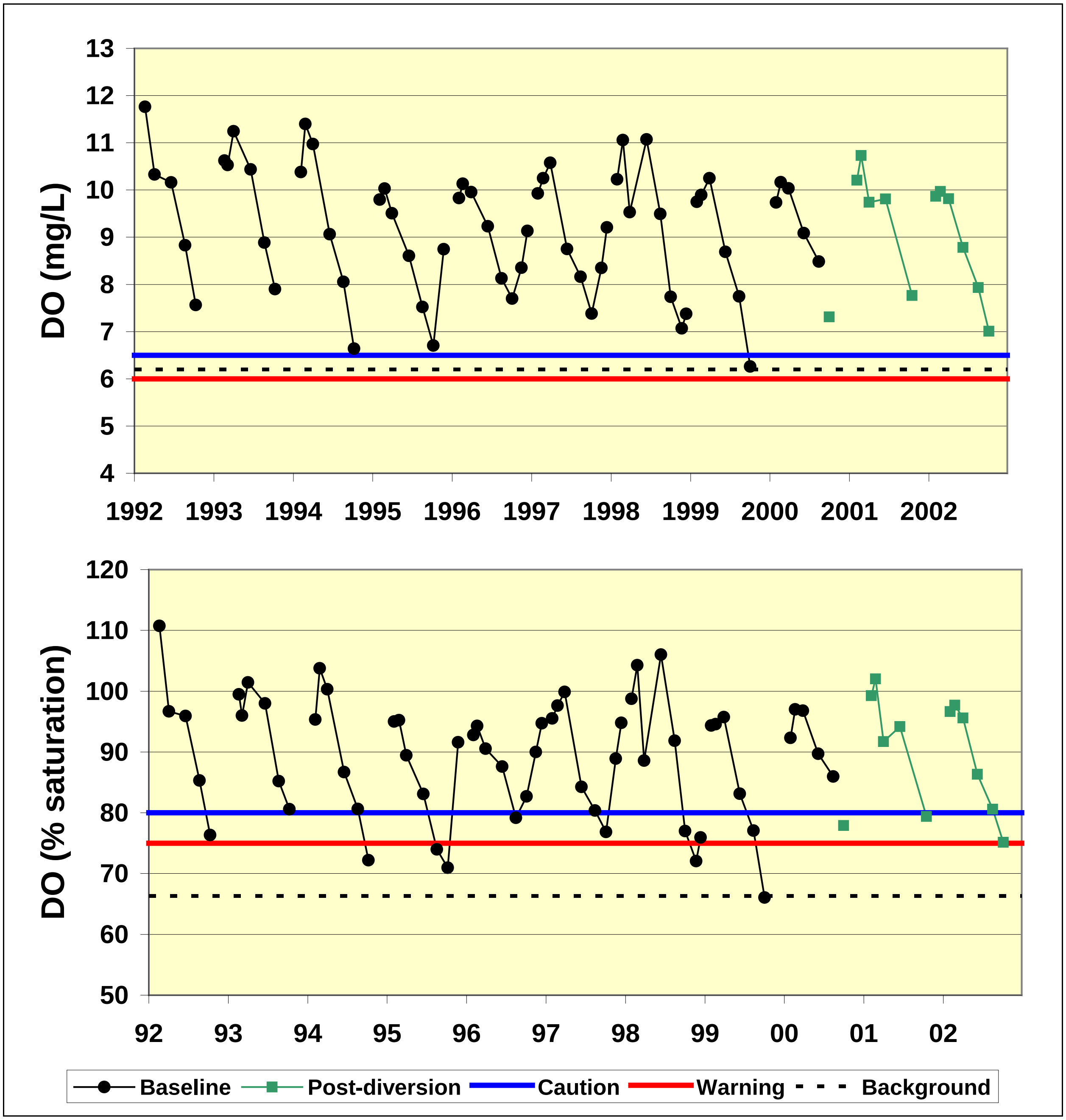


Figure 5-14 Survey mean bottom water dissolved oxygen concentration and percent saturation in Stellwagen Basin compared to contingency threshold levels.

5.5 Chlorophyll

→ *Has the phytoplankton biomass changed and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has the phytoplankton biomass changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the near-field or changes in nutrient concentrations in the farfield?*

In 2001 and 2002, chlorophyll concentrations generally followed the baseline mean. Two deviations from this trend were in early February and late fall (Figure 5-15). High concentrations in early February during 2001 and 2002 coincided with elevated production rates and early winter/spring blooms. In December 2001, mean survey chlorophyll concentration reached its annual maximum coincident with peak production in the nearfield. In 2002, the fall bloom occurred in August and September, but chlorophyll did not peak until a secondary fall bloom in November. Although the early February and late fall 2001/2002 chlorophyll values were relatively high (150 - 200 mg m^{-2}) in comparison to baseline for those surveys, they were well below the maximum values observed during major winter/spring and fall blooms during baseline. For example, during the March 2000 *Phaeocystis* bloom, the mean chlorophyll concentration was more than double the winter/spring bloom of 2002 (450 mg m^{-2}) and was the highest survey mean chlorophyll concentration observed for the baseline. The fall blooms in both 1993 and 1999 resulted in chlorophyll levels that were twice as high (~300 mg m^{-2}) as that measured in 2001 and 2002.

In Boston Harbor, 2001 and 2002 areal chlorophyll (Figure 5-15) closely follow the nearfield trend. Values were at or above baseline maxima in February, then were close to baseline minima for the remainder of the year except for a peak in August 2002 that coincided with the early fall bloom observed throughout the near coastal waters of Massachusetts Bay. The early February 2002 areal chlorophyll concentration was the highest ever seen in Boston Harbor.

When 2001 and 2002 POC data are compared to baseline, the patterns are similar to chlorophyll. (Figure 5-16). POC concentrations generally followed the baseline mean except for peaks corresponding to the winter/spring and fall blooms. Unlike chlorophyll during the early winter/spring bloom, POC concentrations were higher than the baseline mean, but below the maximum in early February. In 2002, POC concentrations reached a maximum during an April *Phaeocystis pouchetii* bloom. During the summer of 2001 elevated POC values were observed without corresponding increases in chlorophyll, production or plankton abundance. High POC concentrations in August/September 2002 and from mid October to December 2001 were concomitant with high productivity and chlorophyll levels associated with the fall blooms.

In 2001, Boston Harbor POC concentrations were relatively low, and similar to baseline trends. In 2002, however, elevated POC concentrations were coincident with high chlorophyll and productivity (Figure 5-16). The chlorophyll and POC data (along with production data presented in Section 5.7) suggest the harbor may be changing from its previous pattern of algae levels peaking in summer to a more typical temperate coastal water trend dominated by spring and fall blooms.

Chlorophyll concentrations in the nearfield (Figure 5-15) were well within the baseline range. The seasonal and annual threshold values for areal chlorophyll are in Table 5-3. The annual values for 2001 and 2002 are well below the caution level. The only exceedance was for fall 2000 when elevated chlorophyll concentrations were associated with a regional bloom; the broad spatial extent and intensity of that bloom is evident in SeaWiFS satellite imagery (Figure 5-17).

Table 5-3 Contingency plan threshold values for nearfield areal chlorophyll 2000 to 2002.

Time Period	Caution Level	Warning Level	2000	2001	2002
Annual	107 mg/m^2	143 mg/m^2	--	67 mg/m^2	82 mg/m^2
Winter/spring	182 mg/m^2	--	--	69 mg/m^2	112 mg/m^2
Summer	80 mg/m^2	--	--	45 mg/m^2	50 mg/m^2
Autumn	161 mg/m^2	--	205 mg/m^2	85 mg/m^2	100 mg/m^2

Variations in the strength of the spring and fall blooms are the major factors affecting the annual average chlorophyll (Figure 5-18). The highest annual mean values occur in 1999 and 2000 when major blooms were observed in both spring and fall. However, annual mean POC concentrations in 1999 and 2000 were not unusually high, so phytoplankton biomass may not have been substantially higher. Boston Harbor and coastal areas tend to have lower areal averaged chlorophyll because of shallower depths although chlorophyll concentrations are often higher in those regions. In 2002, however, blooms were primarily coastal and the highest annual mean areal chlorophyll was in Boston Harbor. These coastal blooms had the highest annual mean POC that we have observed in the harbor and coastal waters, while the nearfield annual mean POC concentrations were comparable to baseline values.

Satellite (SeaWiFS)-derived chlorophyll concentrations for Massachusetts Bay also show that the annual mean concentration increased from 1998 to 2000 and then decreased in 2001, both within and outside of the Massachusetts Bay (Figure 5-17 and Figure 5-19) Comparison of SeaWiFS and shipboard data on a survey by survey basis as specific station locations highlights both the limitations and future potential for the use of satellite data (see Appendix B). The current algorithms used to process SeaWiFS imagery for coastal waters can lead to discrepancies with shipboard measurements in the magnitude of chlorophyll concentrations. The seasonal and interannual patterns, however, are similar.

In the nearfield, graphical comparisons of survey and annual mean chlorophyll and POC values suggest that there has not been a substantial change since the diversion of effluent. In Boston Harbor, 2001 and 2002 data show a change in the seasonal chlorophyll and POC patterns and in the magnitude of the values; the patterns have become similar to the nearfield and other temperate coastal waters.

Mean chlorophyll and nutrients show no clear relationship to each other. The data from the three stations where productivity is measured is evaluated in the following section, and provides more insight into the potential effect of changes in nutrient levels in the nearfield and Boston Harbor.

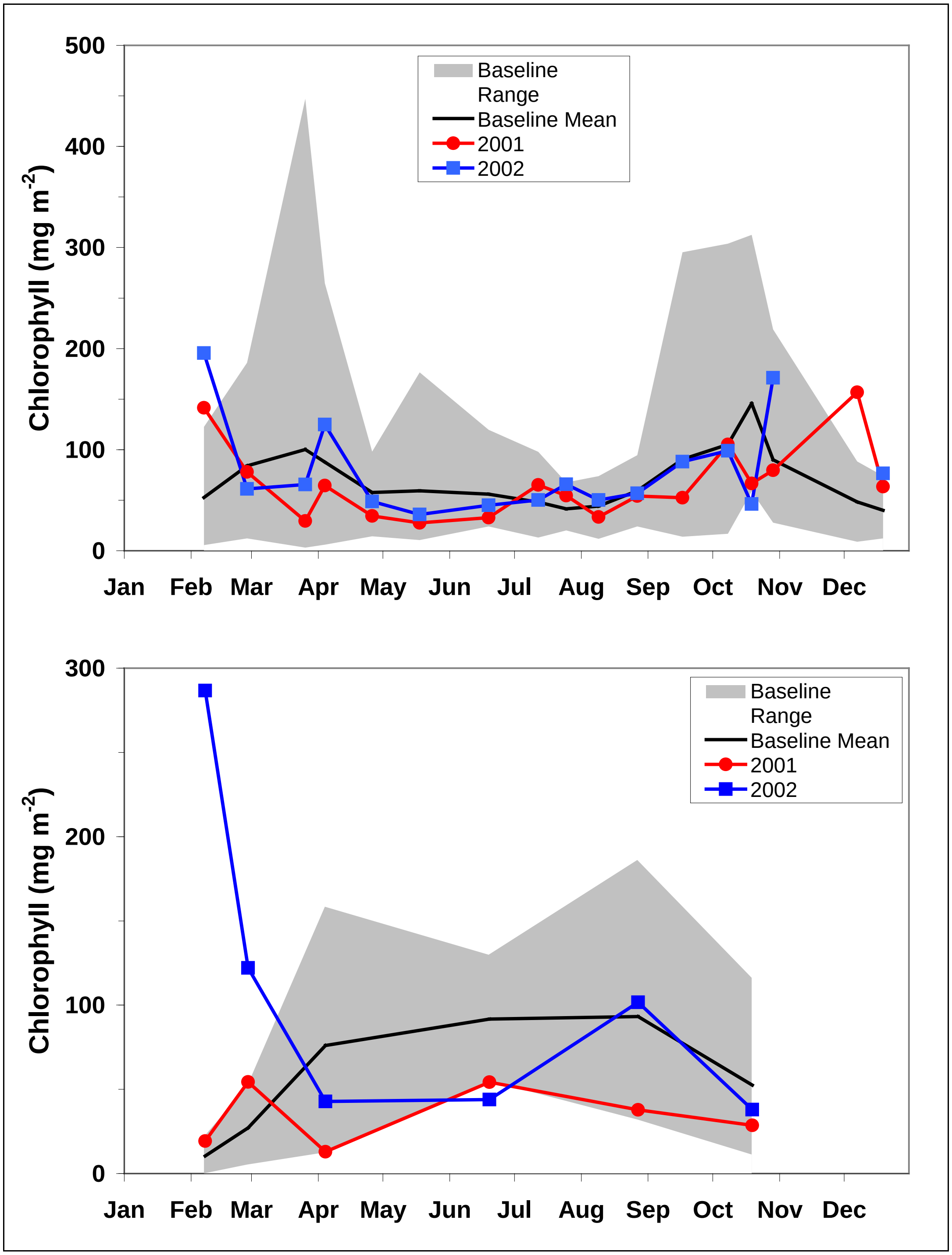


Figure 5-15 Time-series of survey mean areal chlorophyll concentrations in the nearfield (top) and Boston Harbor (bottom) in 2001 and 2002 compared against the baseline ranges and means.

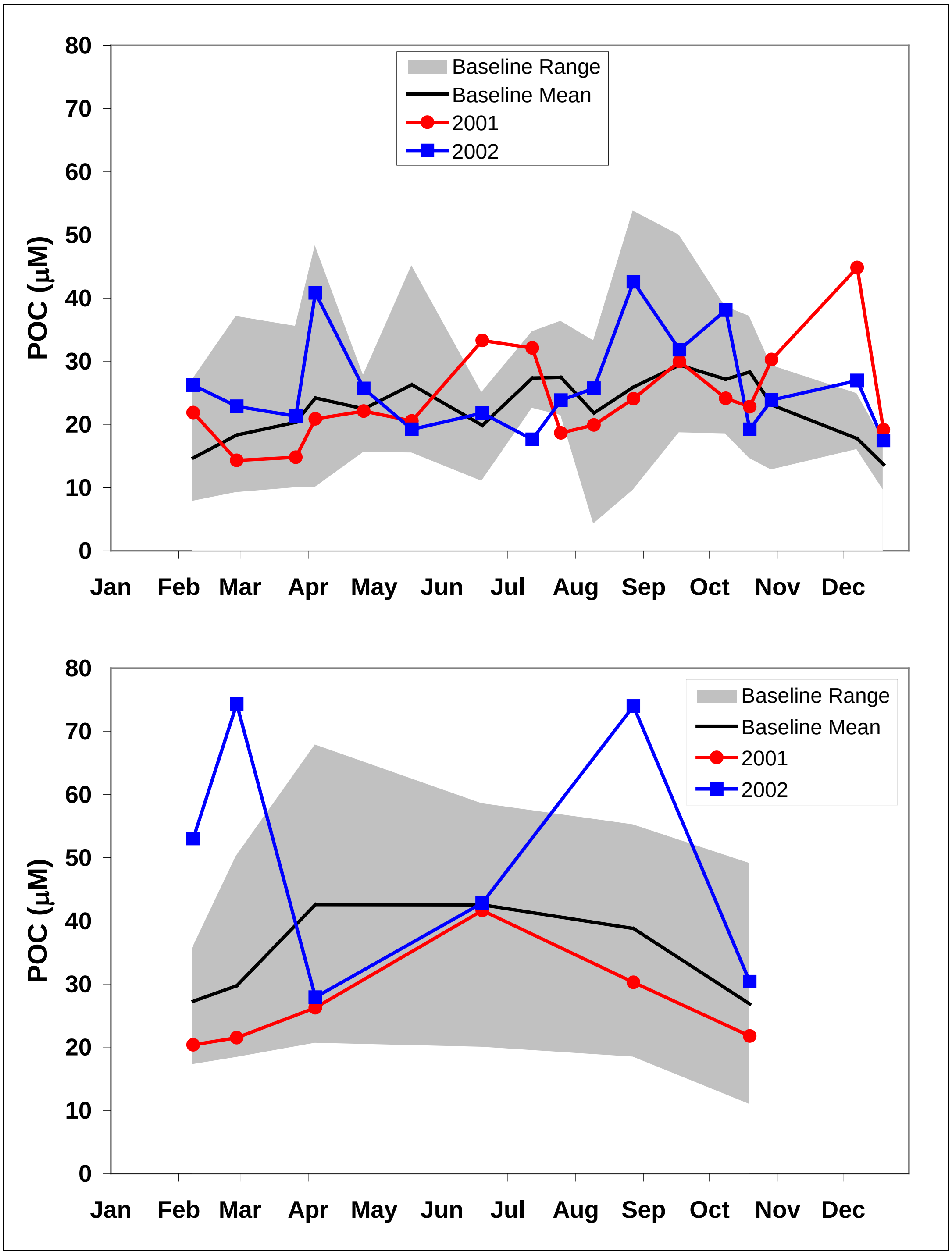


Figure 5-16 Time-series of survey mean areal POC concentrations in the nearfield (top) and Boston Harbor (bottom) in 2001 and 2002 compared against the baseline ranges and means.

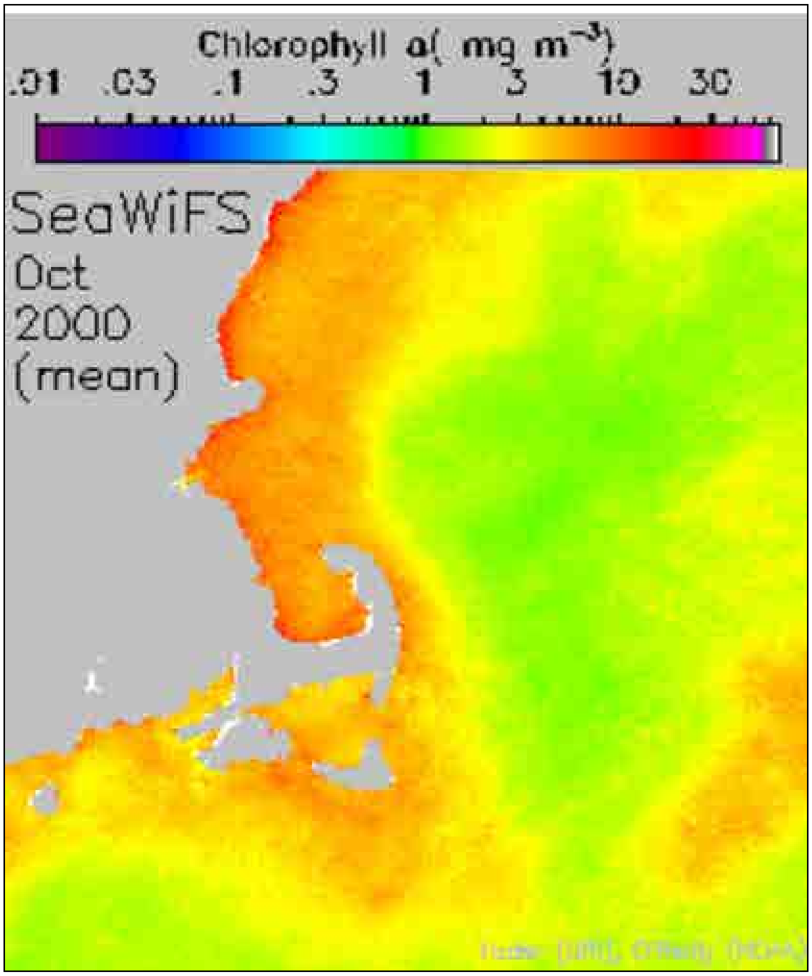


Figure 5-17 Monthly composite of SeaWiFS chlorophyll images for the southwestern Gulf of Maine for October 2000 [J. Yoder (URI) and J. O'Reilly (NOAA)].

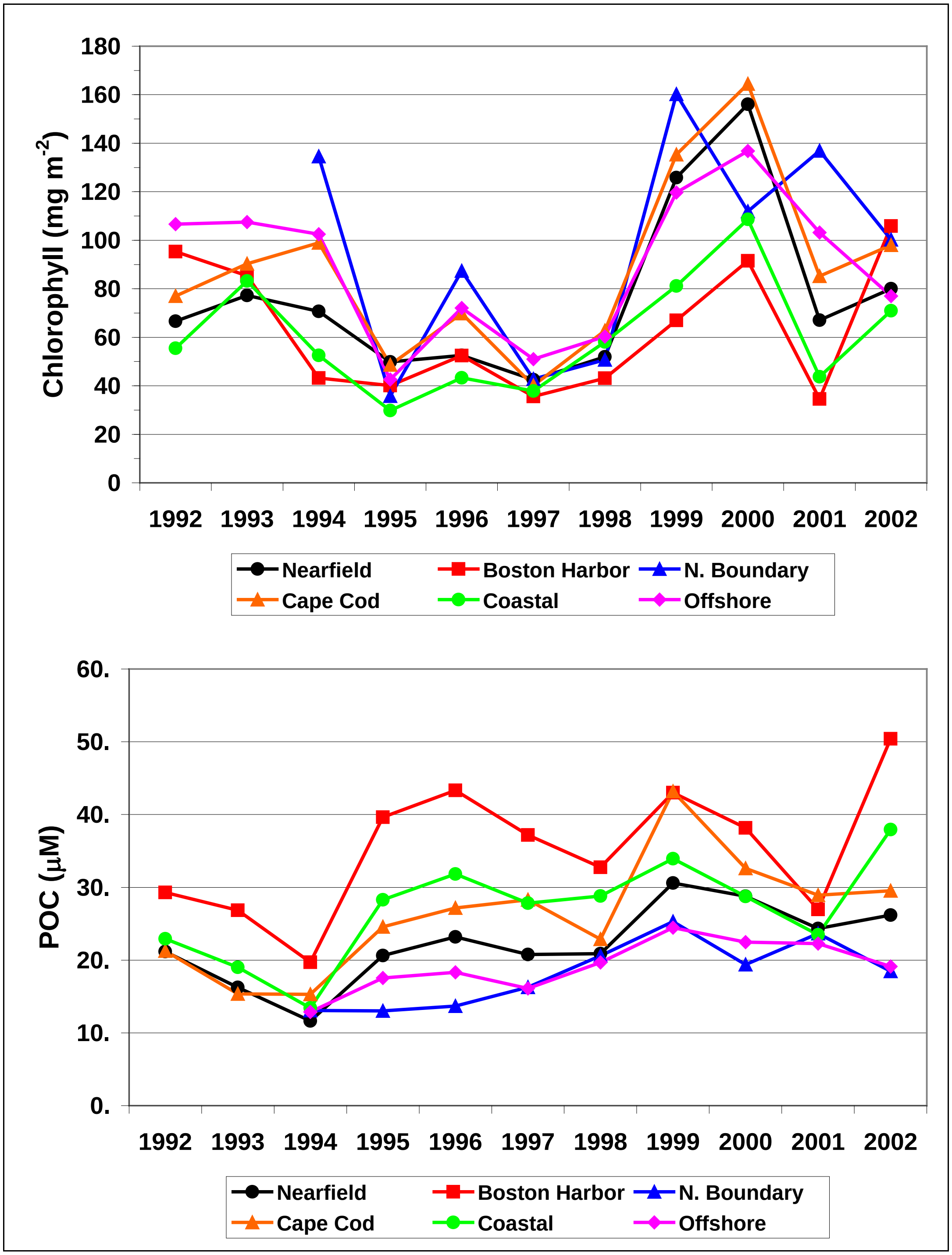


Figure 5-18 Annual mean areal chlorophyll and POC concentrations in Massachusetts Bay regions.

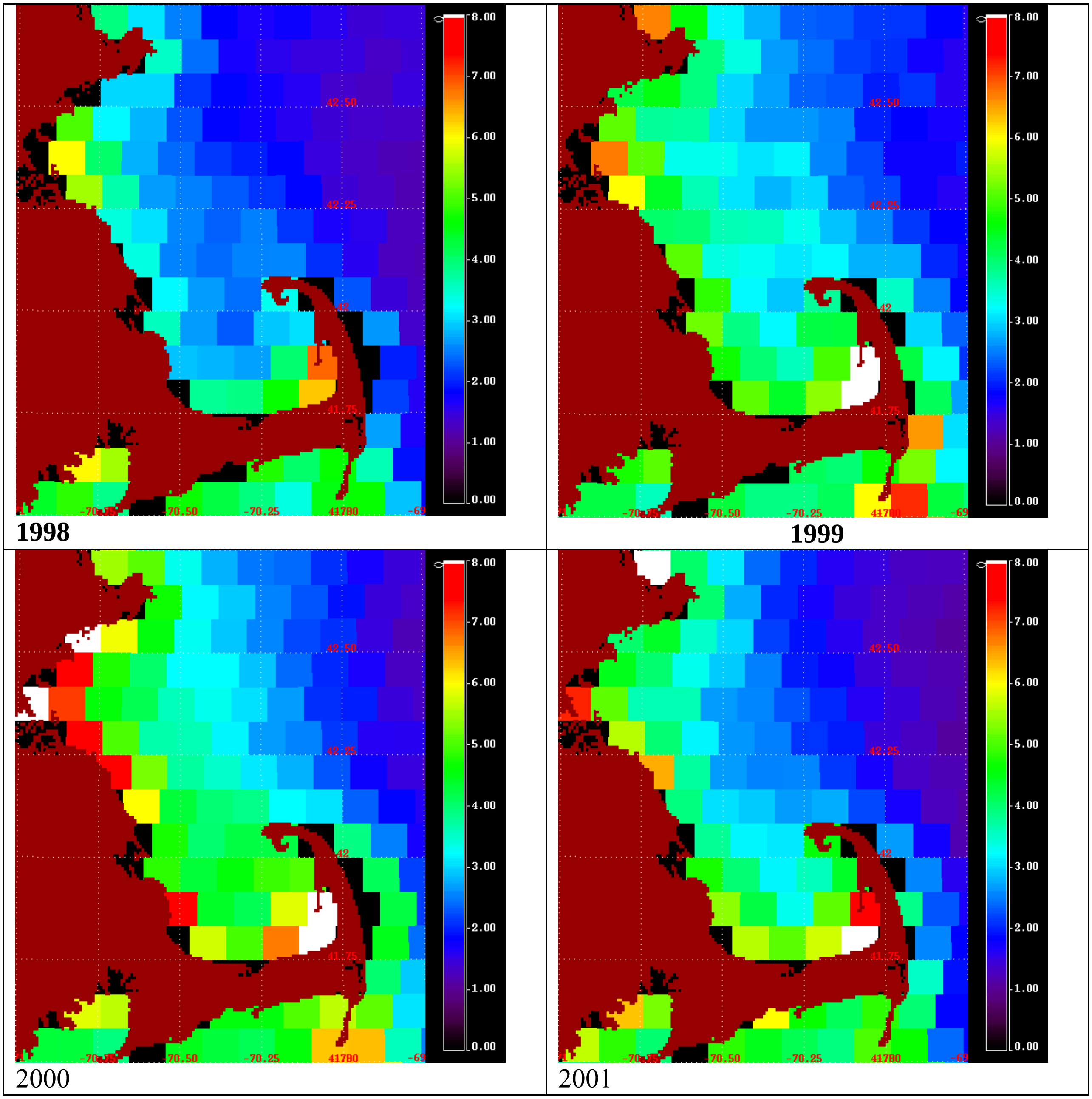


Figure 5-19 Annual mean chlorophyll concentration derived from SeaWiFS data. (See Appendix B for details.)

5.6 Productivity

Productivity monitoring questions have been slightly reworded to reflect the focus of the monitoring efforts at two stations in the nearfield and one at the mouth of Boston Harbor.

→ *Have the phytoplankton production rates changed in the vicinity of the outfall and if so, can these changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has the primary productivity changed at the mouth of Boston Harbor and if so, are the changes correlated with changes in nutrient concentration?*

"Potential annual productivity" is calculated as if all the measurements were taken on full-sunlight days, and so is an estimation of maximum productivity. The estimations of potential annual productivity indicated an increase in values at nearfield sites and a larger decrease at the mouth of Boston Harbor (Figure 5-20). On a seasonal basis the spring and fall bloom peaks increased at nearfield sites adjacent to the outfall. See Figure 3-1 for a map of locations. During the spring at N18 the station nearest the outfall, primary productivity rates increased from about 3 to 3.6 g Cm-2 d-1. At the northeast corner station (N04) the rates increased from 2.3 to 2.8 g C m^{-2} d^{-1} (Figure 5-21). During the fall a similar pattern of increased productivity occurred for the two nearfield stations (Figure 5-22).

The timing and magnitude of the spring bloom is a function of numerous ecological and physical factors. Its magnitude is inversely related to water temperature during the bloom period (Figure 5-23), which was hypothesized to be the result of increased grazing by higher zooplankton abundance at higher temperatures. As more data were collected, the zooplankton vs. temperature relationship became less significant (Figure 5-24). The data were further analyzed by separating it into years with and without *Phaeocystis* blooms on the assumption that *Phaeocystis* may not be grazed as effectively by zooplankton as are other algal species. In these correlation analyses, the reduced magnitude of the bloom and increases in zooplankton abundance were highly correlated with warmer temperatures. Likewise in non-*Phaeocystis* years, zooplankton abundance is well and negatively correlated with production and chlorophyll during the spring bloom (Figure 5-25), consistent with zooplankton grazing control of the magnitude of the spring bloom.

Over the seasonal cycle the pattern of productivity has changed at the mouth of Boston Harbor. The productivity has changed from a eutrophic pattern with high summer time rates to a pattern more typical of temperate waters with spring and fall peaks and lower summer time rates (Figure 5-26). Spring and fall peaks approach 3 g C m^{-2} d^{-1} and summer rates have decreased from 3 to 1 g C m^{-2} d^{-1}. Differences between pre and post diversion are not statistically significant, probably because there are only two samples (2001 and 2002) for spring and annual comparisons and three samples (2000-2002) of data for the fall comparisons.

At nearfield stations, post-diversion mean production is higher than baseline, again not statistically significant. This increase coincides with an increase in ammonium (NH_4) concentrations in the nearfield and an apparent increase in the amount of dissolved inorganic nitrogen (DIN) utilized during the spring bloom. By comparing early February nutrient concentrations to post bloom concentration, an apparent decrease or delta value can be calculated to indicate relative biological utilization (Figure 5-27). At nearfield stations the change in delta DIN over the spring bloom period was ~8 µM prior to diversion to the bay outfall. After diversion, delta DIN increased to 11.5 µM at N18 and 8.8 µM at N04. This increase was primarily due to increases observed in delta NH_4 for both station from less than 1 µM NH_4 to about 6 µM at N18 and 2.5 µM at N04. The NH_4 -rich effluent in the nearfield could be fueling the apparent increase in production observed during the first two years of the bay outfall, which will continue to be monitored.

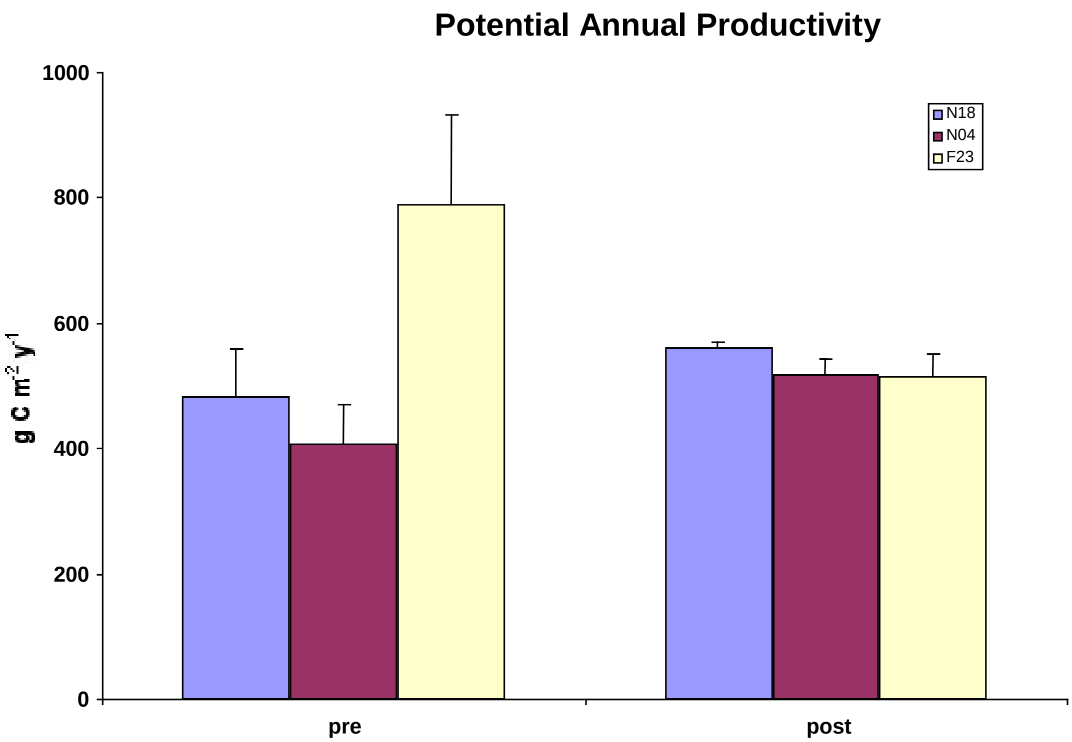


Figure 5-20 **Potential annual productivity at the nearfield sites adjacent to the outfall and at the mouth of Boston Harbor. See map (Figure 3-1) for station locations.**

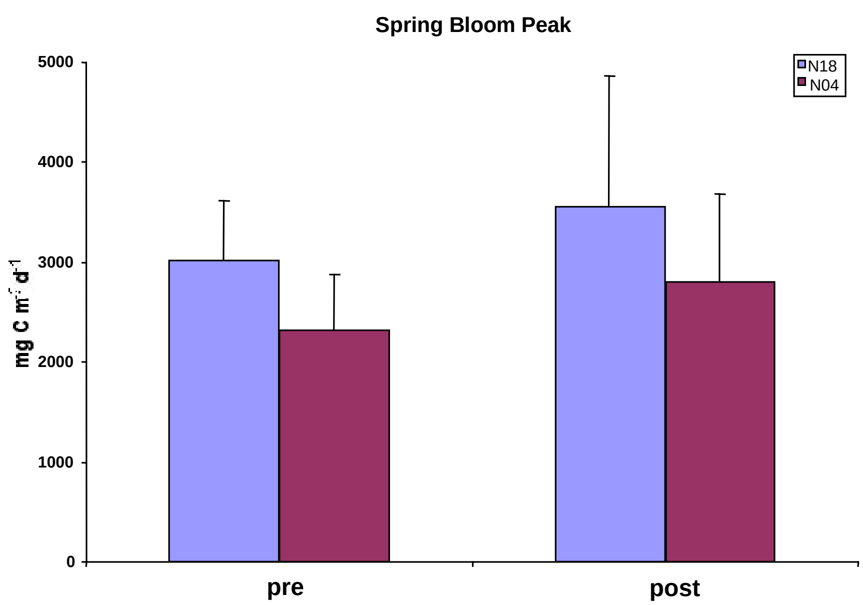


Figure 5-21 **Changes in the nearfield spring bloom peak production pre and post outfall relocation. Station locations are on Figure 3-1.**

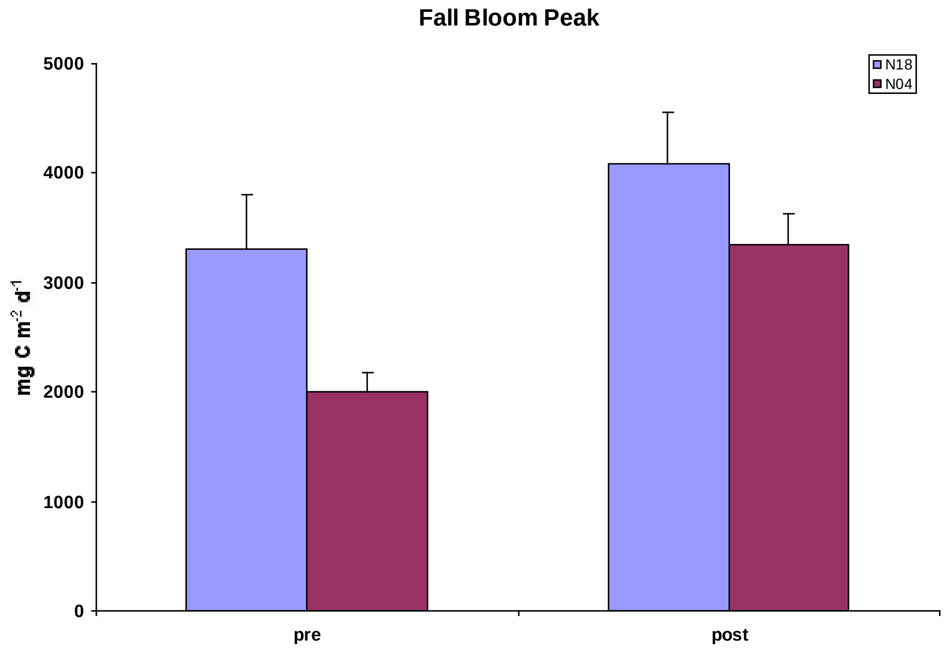


Figure 5-22 Changes in the nearfield fall bloom peak production pre and post outfall.

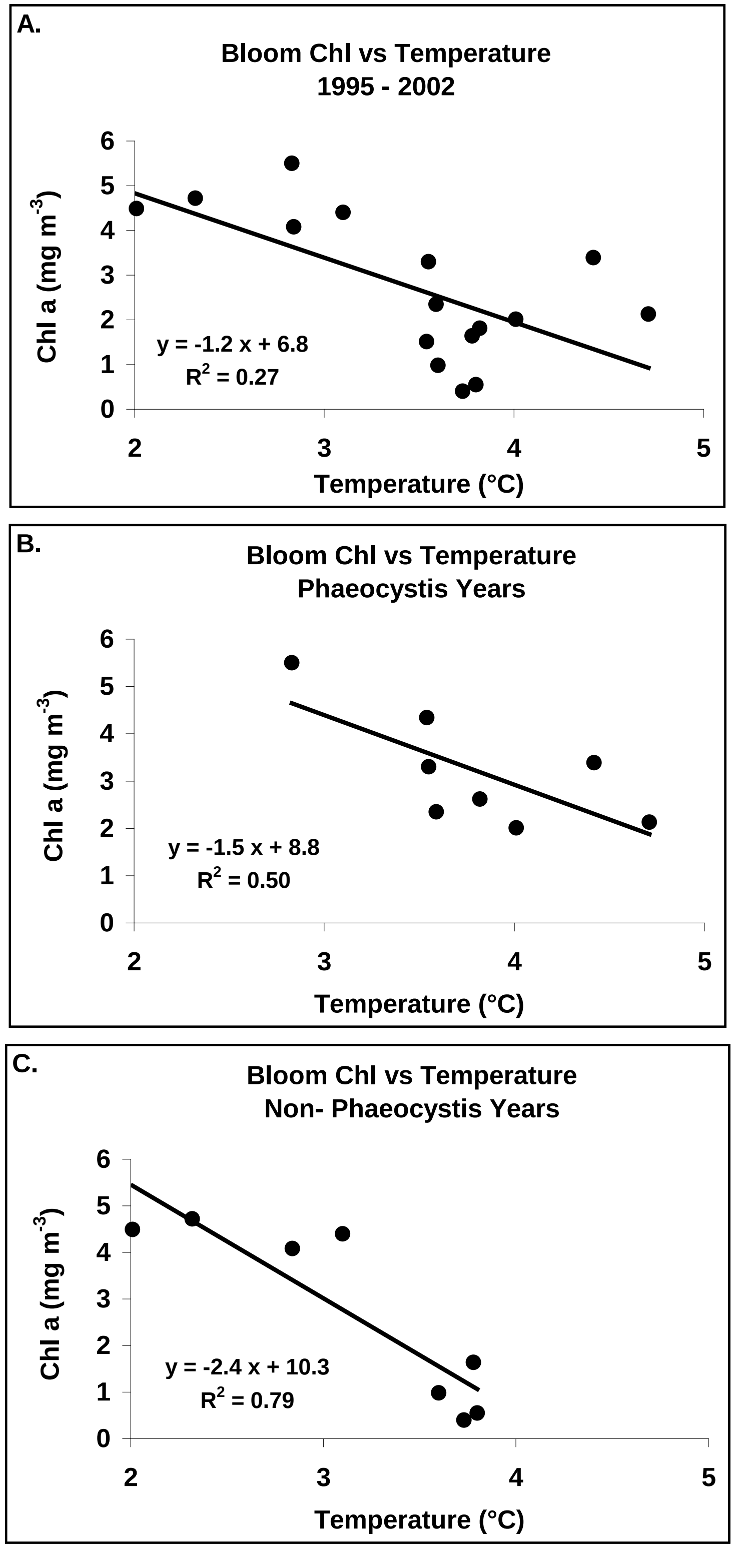


Figure 5-23 Nearfield average chlorophyll vs. surface temperature during the spring bloom period.

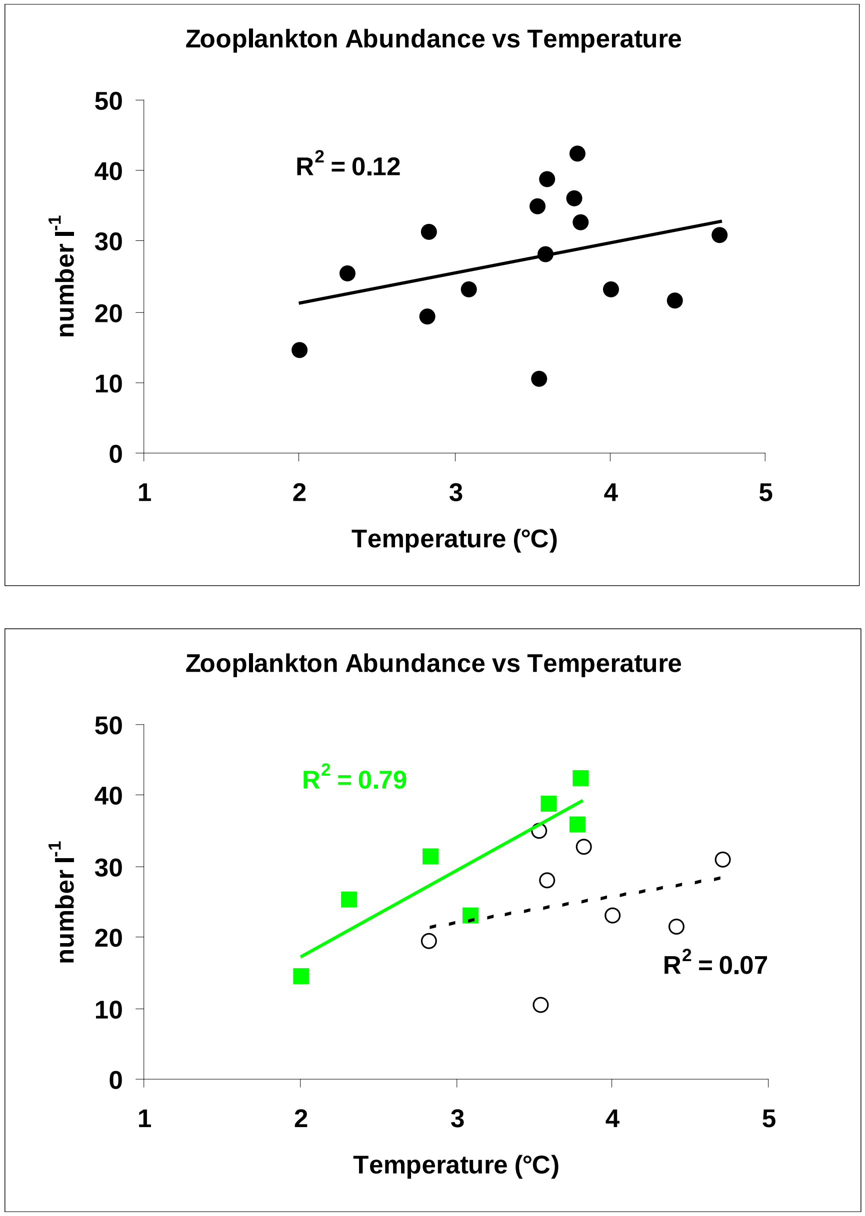
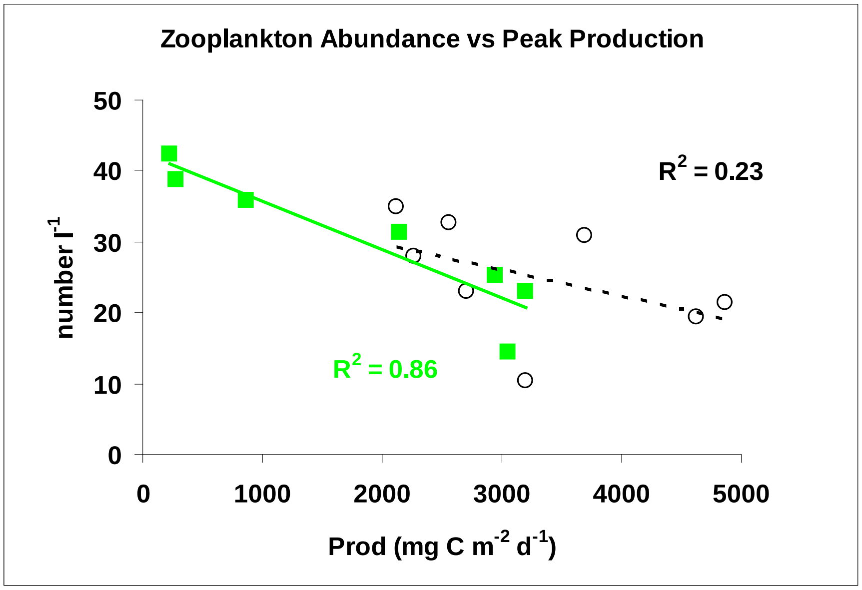


Figure 5-24 Nearfield average total zooplankton vs. surface temperature during the spring bloom period. Non-*Phaeocystis* year data (95, 96, 98, and 99) in green squares and *Phaeocystis* year data (97, 00, 01, and 02) in black open circles.



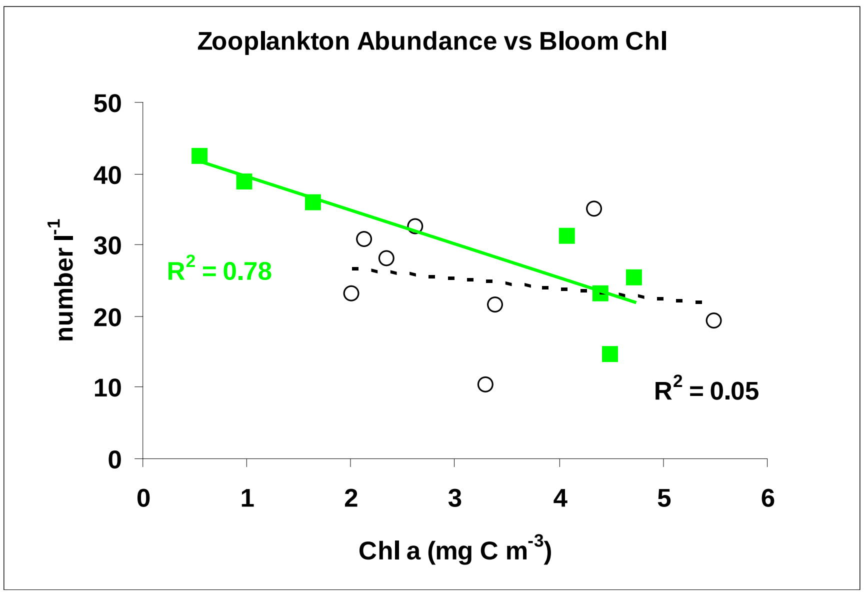


Figure 5-25 Nearfield average total zooplankton vs. peak production and chlorophyll during the spring bloom period. Non-*Phaeocystis* year data (95, 96, 98, and 99) in green squares and *Phaeocystis* year data (97, 00, 01, and 02) in black open circles.

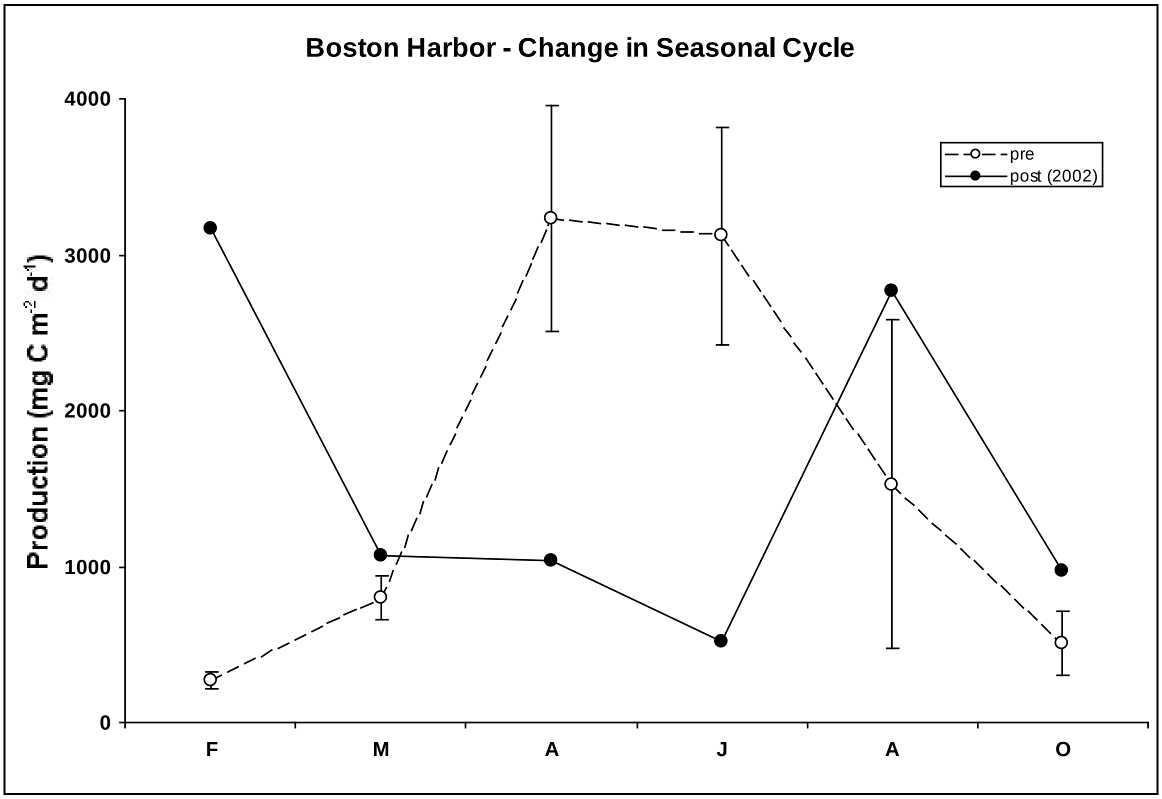


Figure 5-26 Seasonal patterns of productivity pre and post out fall at the mouth of Boston Harbor (station F23).

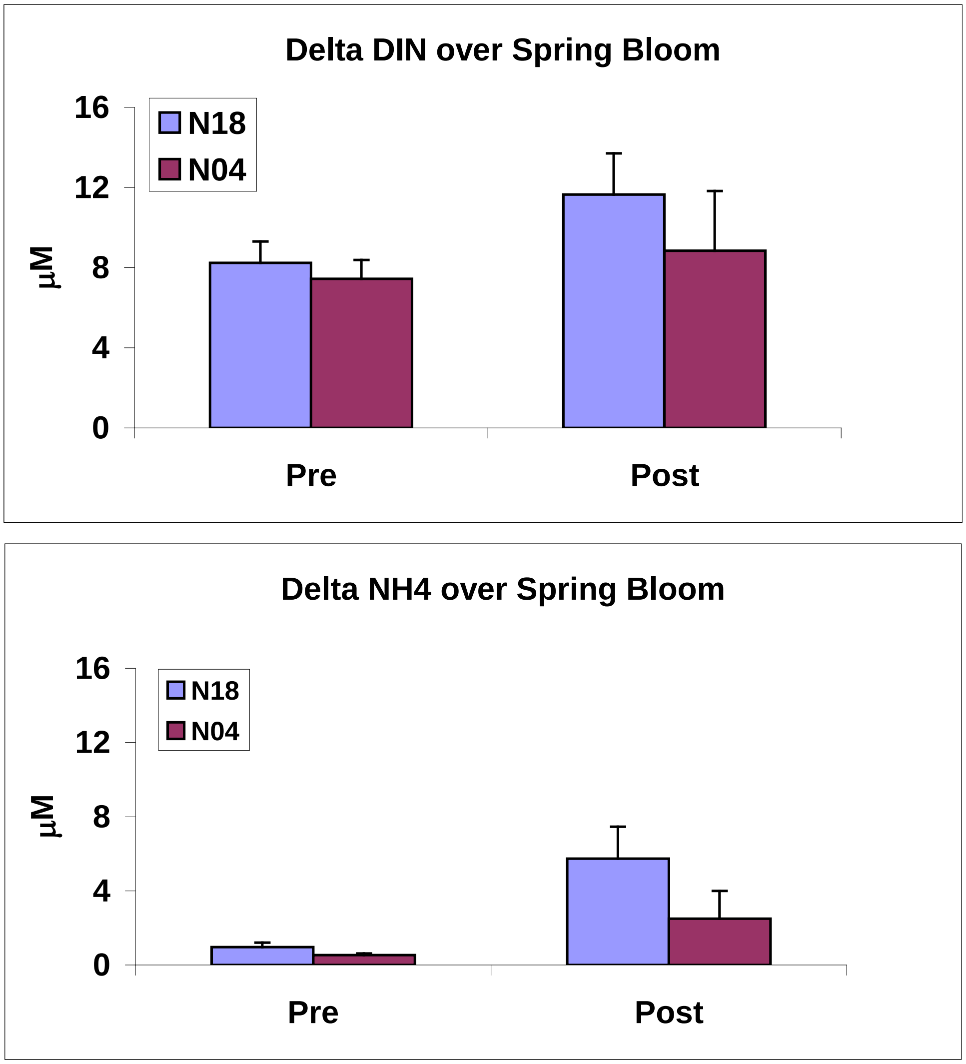


Figure 5-27 Decrease in DIN and NH_4 during the spring bloom pre and post diversion. Station locations are in Figure 3-1.

5.7 Phytoplankton

→ *Has the phytoplankton biomass changed and, if so, can changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has the abundance of nuisance or noxious phytoplankton species changed?*

→ *Has the species composition of phytoplankton or zooplankton changed in the vicinity of the outfall and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has the phytoplankton and zooplankton species composition changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the near field or changes in nutrient concentrations in the farfield?*

Phytoplankton communities are mixtures of many species, with the abundance and composition of the community changing in response to each species' response to changing environmental influences on the habitat (e.g. annual change in irradiance, temperature, nutrient, grazer abundance). A "normal" seasonal succession in Massachusetts and Cape Cod Bay has been observed in the 1992-2000 baseline monitoring data. In whole-water phytoplankton samples, microflagellates are usual numerical-dominants throughout the year, and their abundance generally tracks water temperature, being most abundant in summer and least abundant in winter. In addition to microflagellates, the following taxa are dominant in Massachusetts and Cape Cod Bays during the periods identified below:

Winter (primarily February) – diatoms abundant, including *Chaetoceros debilis, C. socialis, Thalassiosira nordenskioldii,* and *T. rotula;*

Spring (March, April, May) – usually (except during *Phaeocystis* years) including assorted species of *Thalassiosira, Chaetoceros*, as well as the dinoflagellate *Heterocapsa rotundatum,* and (especially nearshore) cryptomonads;

Summer (June, July, August) – microflagellates are at peak abundance, with cryptomonads, *Skeletonema costatum* (especially nearshore), *Leptocylindrus danicus, Rhizosolenia delicatula, Ceratulina pelagica*, and various small-sized species of *Chaetoceros*;

Fall (September through December) – diatoms are abundant, including *Asterionellopsis glacialis, Rhizosolenia delicatula, Skeletonema costatum, Leptocylindrus minimus, L. danicus*, as well as cryptomonads, and assorted gymnodinoid dinoflagellates.

Superimposed over the background dominance of microflagellates and common diatoms, in some years, there are outbursts of a single species such as *Asterionellopsis glacialis* in fall of 1993, or *Phaeocystis pouchetii* in spring of 1992, 1994, 1997, 2000, 2001, and 2002 or congeners such as the frequent summer-fall blooms of *Ceratium longipes/tripos*. The interannual variability associated with both magnitude and occurrence of blooms as represented by total phytoplankton abundance is shown in Figure 5-28. Although such blooms may be intermittent, they tend to occur regionally and are usually observed throughout Massachusetts and Cape Cod Bay and beyond. Why such species bloom in some years but not others remains unclear.

The differences in the 2001 and 2002 nearfield phytoplankton annual cycle, relative to baseline observations, were explored by hierarchical examination (*i.e.*, from total phytoplankton to specific groups) of the major components of the nearfield phytoplankton. Assemblages in 2001 and 2002 were generally similar to those found during other baseline monitoring years. During both post-diversion years, nearfield total phytoplankton abundance was usually at or slightly below the baseline mean value (Figure 5-29). The primary exceptions were elevated phytoplankton abundance in late July, a prolonged late October through December diatom bloom in 2001, and the late summer/early fall diatom bloom in 2002. Total phytoplankton abundance was below the baseline minimum in October of 2002 during a period when fall blooms are usually observed.

There is no indication of an outfall effect on abundance or species composition of phytoplankton in the nearfield or regionally in the bays. Phytoplankton abundance in the winter/spring bloom has remained close to the baseline mean. Nearfield phytoplankton biomass and production have increased, though not significantly, and MWRA monitoring continues to explore how an increase may be related to increased nutrients in the nearfield. The atypical timing of the fall blooms in both 2001 (late) and 2002 (early) is interesting, but appears to be associated with physical and biological factors unrelated to the outfall. In 2001, the water column remained stratified late into the fall resulting in a delay in the fall bloom until late October and November. In 2002, the fall diatom bloom occurred in August and into September, much earlier than the typical late September/October period. The early occurrence of the fall bloom in 2002 may have been due to predation of zooplankton by ctenophores (*Mnemiopsis leidyi*), which were observed in high numbers from late August through November. There was a sharp decline in nearfield zooplankton abundance from early to late August 2002 to abundances lower than observed during the baseline (Figure 5-30). Zooplankton abundance remained low the remainder of the year. These very low zooplankton abundances imply that grazing pressure on phytoplankton was minimal, conducive to a bloom. An hypothesis that the bloom may have been further enhanced by the input of additional nutrients into the nearshore waters via the outfall and/or upwelling, which may have entrained both nutrient-rich bottom waters and the effluent plume into the upper water column is being further explored.

Analyses of productivity patterns during *Phaeocystis* and non-*Phaeocystis* years suggested the possibility of a bottom-up control of zooplankton abundance. Nearfield *Phaeocystis* abundance in 2001 and 2002 was much lower than during the 2000 bloom. These blooms were observed throughout the bays. In 2001, the highest *Phaeocystis* abundance was observed at the northern boundary stations, decreasing to the nearfield. This gradient suggests that the 2001 *Phaeocystis* bloom was regional and may advected into Massachusetts Bay from the Gulf of Maine, consistent with patterns of chlorophyll in SeaWiFS imagery. During the springs of 2000 and 2001, *Phaeocystis* blooms were observed in the Gulf of Maine on surveys for the ECOHAB (ECology and Oceanography of Harmful Algal Blooms) program. It is too early to tell if any substantial change in the plankton of Massachusetts Bay will occur in the wake of the outfall diversion, but the variation in frequency of *Phaeocystis* blooms seem to be due to regional phenomena and part of the natural variability for this species.

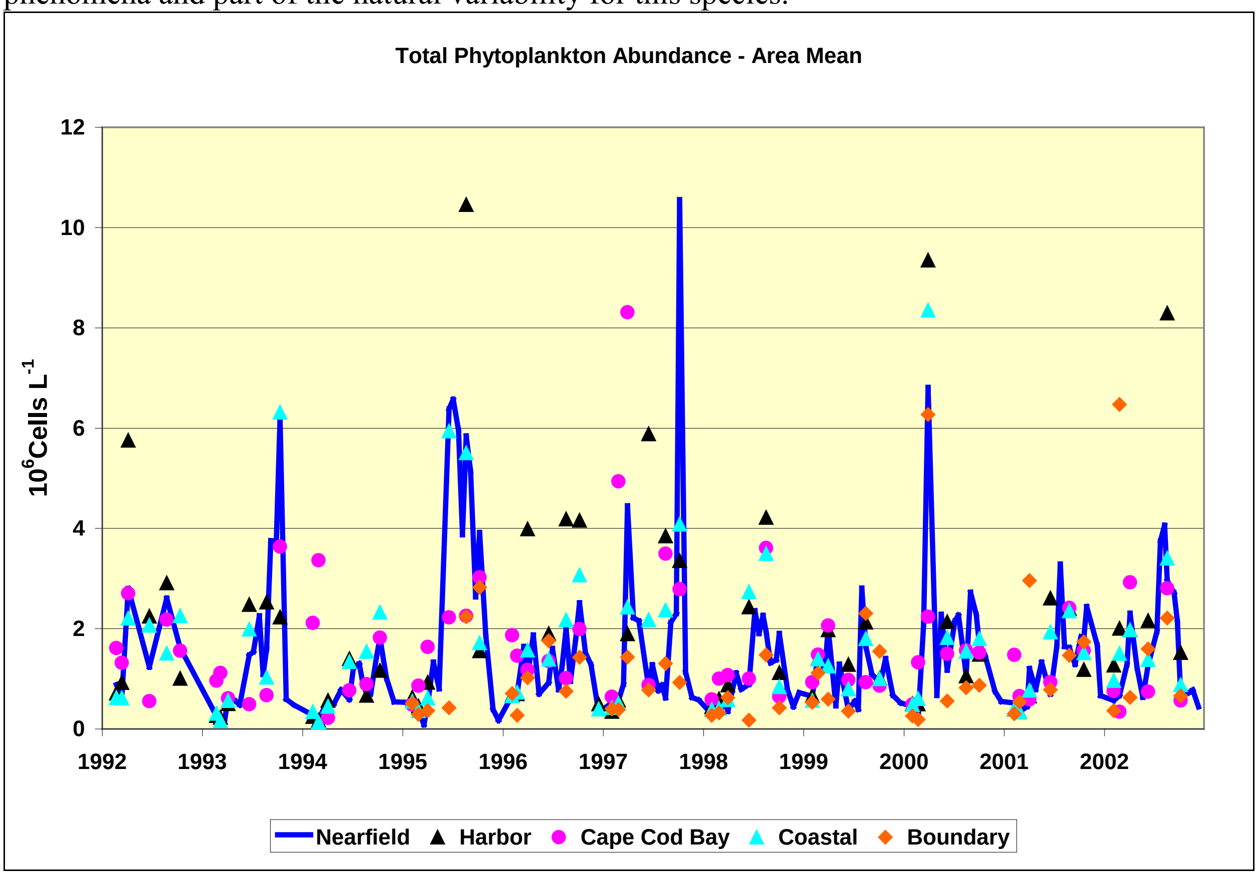


Figure 5-28 Total phytoplankton abundance by region, 1992-2002.

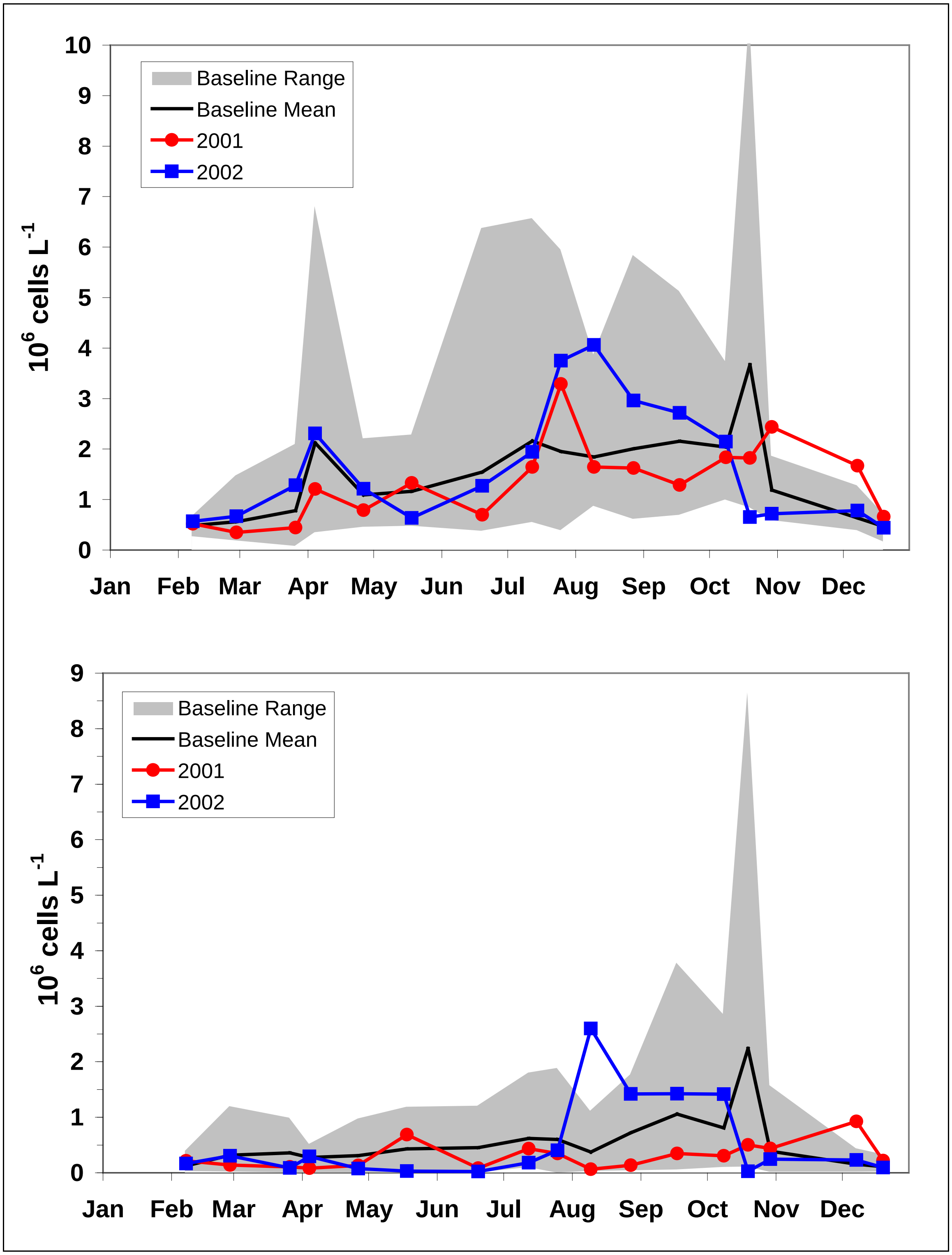


Figure 5-29 Total phytoplankton (top) and diatoms (bottom) in the nearfield for 2001 and 2002 in comparison to baseline period (1992-2000).

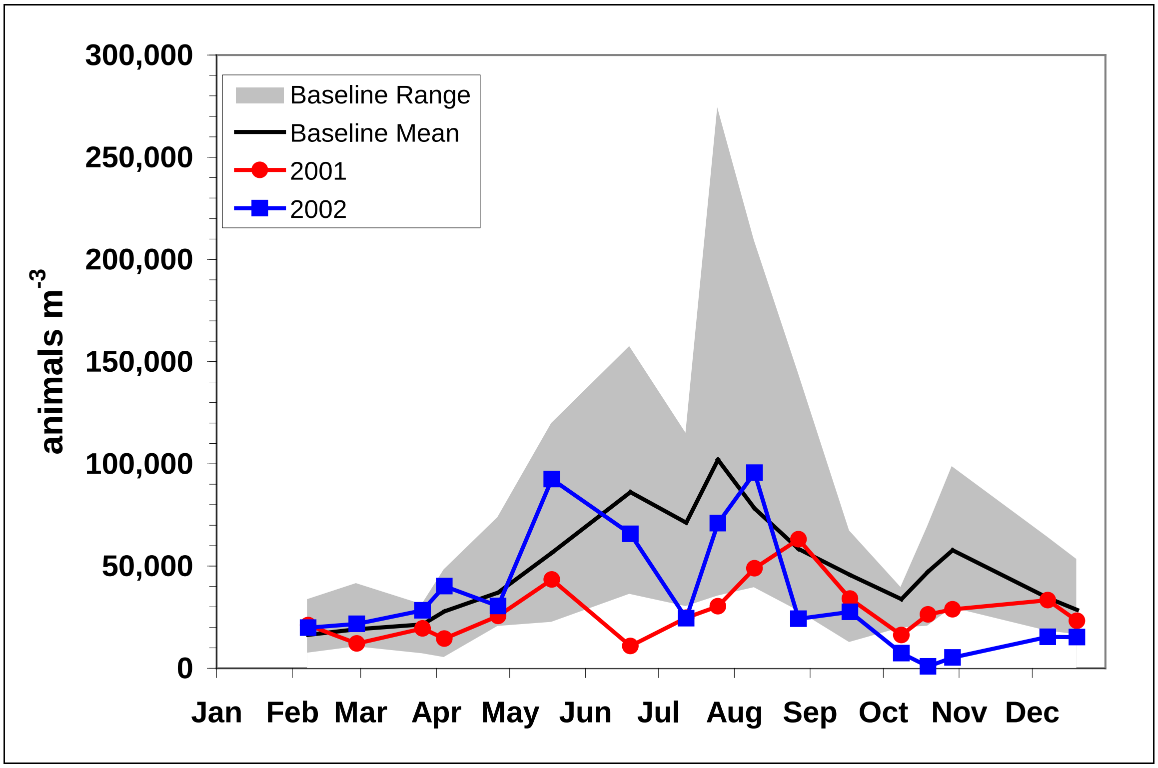


Figure 5-30 Total zooplankton in the nearfield for 2001 and 2002 in comparison to baseline period (1992-2000).

5.8 Zooplankton

→ *Has the species composition of phytoplankton or zooplankton changed in the vicinity of the outfall and, if so, can these changes be correlated with effluent or ambient water nutrient concentrations?*

→ *Has the phytoplankton and zooplankton species composition changed at selected farfield stations in Massachusetts Bay or Cape Cod Bay and, if so, are the changes correlated with changes in the near field or changes in nutrient concentrations in the farfield?*

Zooplankton communities in Massachusetts and Cape Cod Bays are dominated by numerous species of copepods, all of which have widespread distributions in the Gulf of Maine, and some of which are found throughout the east coast of the US. MWRA's zooplankton monitoring is unusual in its use of finer mesh nets (0.1 mm) than are routinely used in other studies (0.3 mm and larger). Because of this, MWRA's data are dominated by smaller zooplankters such as unidentifiable copepod nauplii and small copepodites, and adults of the small copepod *Oithona similis*, which are not captured at all or are under-reported in other studies. Larger taxa seen in MWRA's monitoring as well as other studies in the Bays include the estuarine species *Acartia tonsa, Acartia hudsonica*, and *Eurytemora herdmani,* as well as oceanic species *Calanus finmarchicus*, *Paracalanus parvus,* and species in the genera *Centropages* and *Pseudocalanus*.

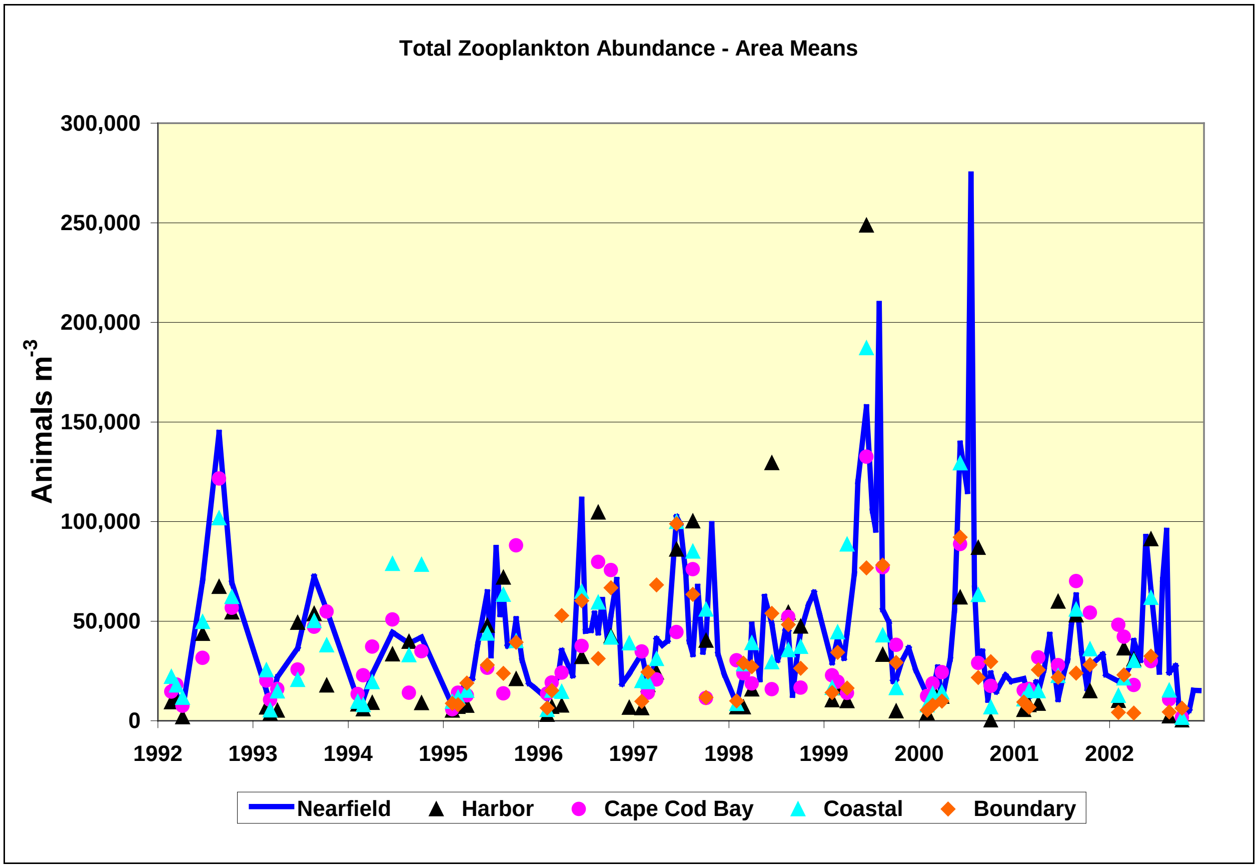


Figure 5-31 Zooplankton Abundance By Region, 1992-2002

Polychaete and barnacle larvae are also seasonally important constituents of the zooplankton communities in Massachusetts Bay (Kropp *et al.* in prep).

Total zooplankton abundance tends to follow a predictable temporal pattern, with abundance peaking in mid-summer and lower levels in spring and fall (Figure 5-31). The seasonal timing for individual species is variable; for example *Calanus finmarchicus* tends to peak in the nearfield in April and May, while *Oithona similis* peak abundances occur in mid-late summer (Figure 5-32).

MWRA has supplemented its zooplankton collections by participating in pilot studies, also partially funded by EPA and NMFS, evaluating a video plankton data recorder in the Bays (e.g. Davis and Gallagher, 2000) This study used a towed instrument system to continuously characterize temperature, salinity and fluorescence. The system also obtained counts for larger phytoplankton and zooplankton taxa at high spatial resolution, on surveys spanning the Massachusetts Bay and Cape Cod Bays system. In the February 1999 survey, chlorophyll fluorescence and the abundance of the diatom species visualized were positively correlated at length scales up to 15-20 km (that is, counts made taken more than 20 km apart were uncorrelated, counts taken closer together than that tend to be positively correlated). Zooplankton data from the survey were correlated over somewhat shorter length scales of about 10 km, indicating that samples collected more than 10 km apart are likely to be independent of each other (Davis and Gallagher, 2000).

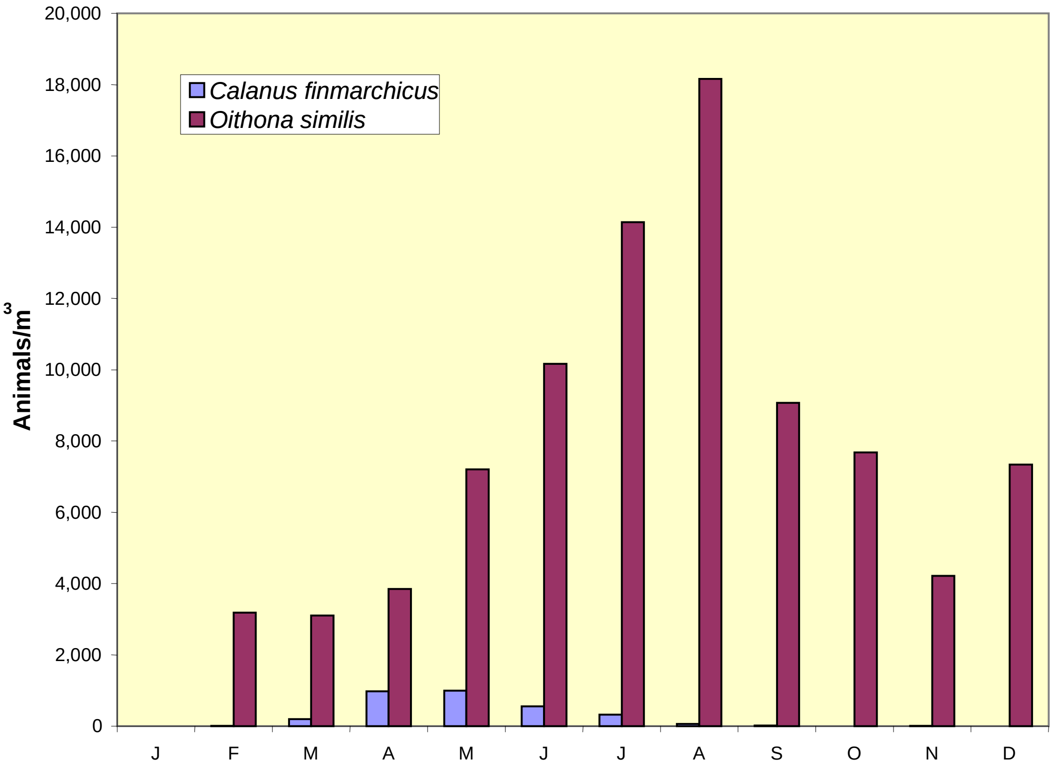


Figure 5-32 Nearfield monthly geometric means for *Calanus finmarchicus* and *Oithona similis*, 1992-2002.

Zooplankton study findings summary

Because of their importance to the food web in general and as important prey for right whales specifically, issues relating to potential impacts of the discharge on zooplankton abundance or community structure have received significant attention (e.g. USEPA 1993, USNMFS 1993. Cibik *et al*. 1998, Lemieux *et al.* 1998, Libby *et al.* 1999). As part of that ongoing process, OMSAP recommended in July 2000 that

> "Since the Massachusetts and Cape Cod Bays system flows like a "conveyor belt" from north to south, MWRA should develop a method for analyzing the current data spatially and temporally to contrast differences between the northern boundary stations and Cape Cod Bay." (OMSAP 2000).

This recommended evaluation was incorporated into the Contingency Plan (MWRA 2001). The "conveyor belt" hypothesis referred to by OMSAP suggested that MWRA's zooplankton data might reflect the overall counterclockwise circulation in the Bays, such that a population of zooplankton would be advected in at the northern boundary, transported through the nearfield (potentially receiving an inoculum of effluent nutrients), and be transported southward, ultimately into Cape Cod Bay. OMSAP suggested that the timing of peaks in important zooplankton species could be sequential, with taxa peaking first at the northern boundary, later in the nearfield and southern Massachusetts Bay, and ultimately reaching Cape Cod Bays. The report addressing the Contingency Plan requirement, analyzing zooplankton data from February 1992-December 2002 is in the final stages of preparation (Kropp *et al.* 2003, in prep) and will be submitted to OMSAP, its subcommittees, and to regulators at the end of June. A brief summary follows.

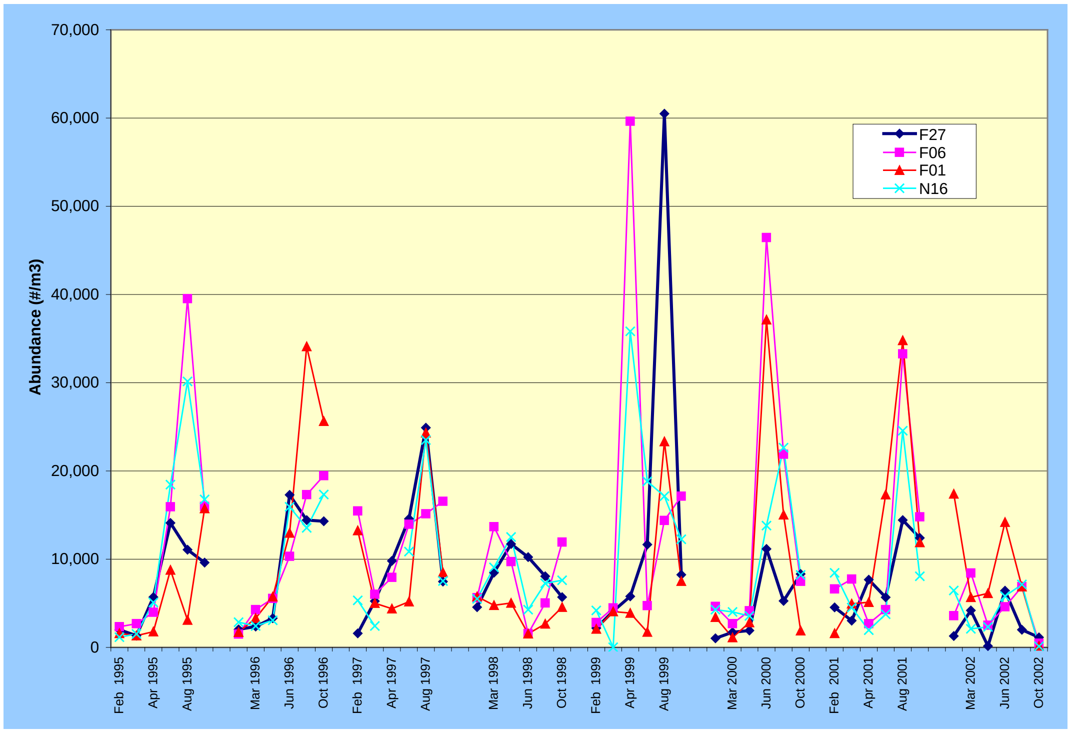
Preliminary results of research sponsored by the Cape Cod Commission and the Center for Coastal Studies (Montoya, 2003) have identified anthropogenic nitrogen stable isotope signatures in zooplankton in Massachusetts Bay south of MWRA's outfall (no N15 data from zooplankton north of the outfall are yet available). These results were obtained in both fall 2001 and winter-spring 2002, lending support to the conveyor belt hypothesis. However, hydrographic measurements and hydrodynamic modeling indicate that a clockwise circulation pattern is sometimes established in the Bays, "reversing" the conveyor belt with implications for the advection of zooplankton through the Bays (Butman 2003, Butman *et al.* 2002).

MWRA's zooplankton data do not support the hypothesis that conveyor belt circulation consistently transports "pulses" of zooplankton from north to south within the Bays. Figure 5-33 plots temporal changes in abundance of *Calanus finmarchicus* and *Oithona similis* from 1995, when boundary sampling began, through 2002 at station F27 at the northern boundary, N16 in the nearfield, F06 from southern Mass Bay, and F01 in Cape Cod Bay. Peak *C. finmarchicus* abundances are often coincident at all stations, or may occur earlier at the southern stations than northern. Similarly, there is no consistent north-south sequence in peak abundances for *O. similis* (Figure 5-33), nor for other important copepod species including adults of *Paracalanus parvus, Pseudocalanus* spp., *Paracalanus/Pseudocalanus* copepodites, and *Centropages typicus*.

To further evaluate community composition in MWRA's zooplankton data, both spatially and temporally, a series of principal components analyses (PCAs) were carried out on the 1992-2002 dataset. The input data included zooplankton species abundance and five abiotic factors, temperature, salinity, chlorophyll fluorescence, dissolved oxygen, and transmissivity (Table 5-4.)

Table 5-4 Variables and Codes Used in the Zooplankton Principal Components Analysis

Variables and codes used in the zooplankton principal components analysis	
Parameter	Code
Temperature	TEMP
Salinity	SAL
Dissolved Oxygen	DO
Fluorescence	FLUOR
Transmissivity	TRAN
Acartia hudsonica	Ahuds
Acartia tonsa	Atons
Calanus finmarchicus	Cfinm
Centropages hamatus	Cham
Centropages typicus	Ctyp
Cirripedia spp.	Cirr
Copepod spp. copepodites	CopeN
Eurytemora herdmani	Eherd
Metridia lucens	Mluce
Microsetella norvegica	Mnorv
Oikopleura dioica	Odioi
Oithona atlantica	Oatl
Oithona similis	Osim
Paracalanus parvus	Pparv
Polychaete spp.	Poly
Pseudocalanus spp.	Pnewm
Sum_Evadne_normanii_SPP	Evad
Sum_Podon_Poly_SPP	Podon
Sum_Pseudo_paracalanus_copepodites	Pcop
Temora longicornis	Tlong
Tortanus discaudatus	Tdisc



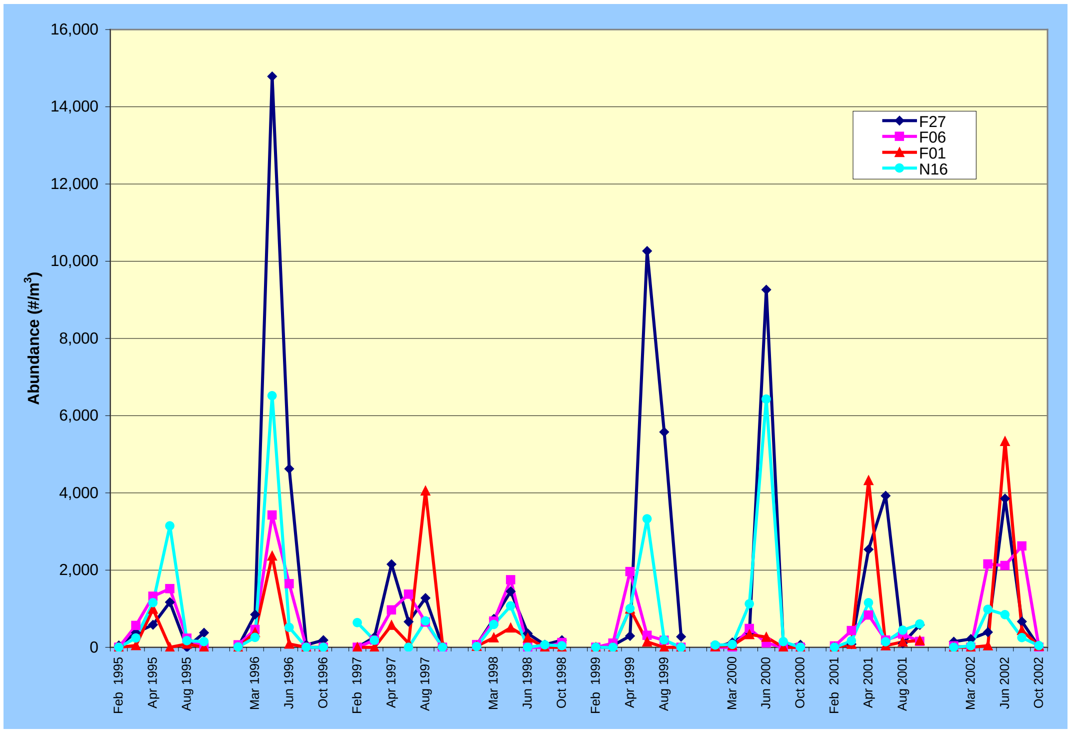


Figure 5-33 Plot of zooplankton abundance by survey for *Calanus finmarchicus* (top) and *Oithona similis* (bottom) at selected stations sampled on the 6 annual farfield surveys from 1995-2002.

The PCA analyses document two major influences on zooplankton community structure. (Figure 5-34). Temperature (TEMP) is positively loaded the first PCA factor, which, which explained 13% of the variation in the dataset. DO is negatively loaded. Cold-water taxa which are abundant relatively early in the year, such as cirripede (Cirr) larvae have negative or weak loadings on factor 1, taxa abundant at slightly warmer temperatures in April or May, like *Calanus finmarchicus* (Cfinm) (Figure 5-34) have relatively weak Factor 1 loadings, while taxa with summer peaks in abundance like *Oithona similis* (Osim) have positive Factor 1 loadings. These suggest that Factor 1 is associated with the seasonal progression in zooplankton communities.

The second major source of variability identified by the PCA appears to be related to an estuarine/offshore gradient in community structure (Figure 5-34). Taxa abundant in somewhat turbid, low salinity, Harbor waters like *Acartia hudsonica* (Ahuds) have positive loadings on Factor 2, which explains 9% of the variability in the data. Taxa more abundant in higher salinity, clearer offshore waters like *Oithona similis* and *Paracalanus parvus* (Ppar) have negative Factor 2 loadings. This estuarine/offshore gradient in Factor 2 is also reflected in the loadings for transmissivity (TRANS) and Salinity (SAL).

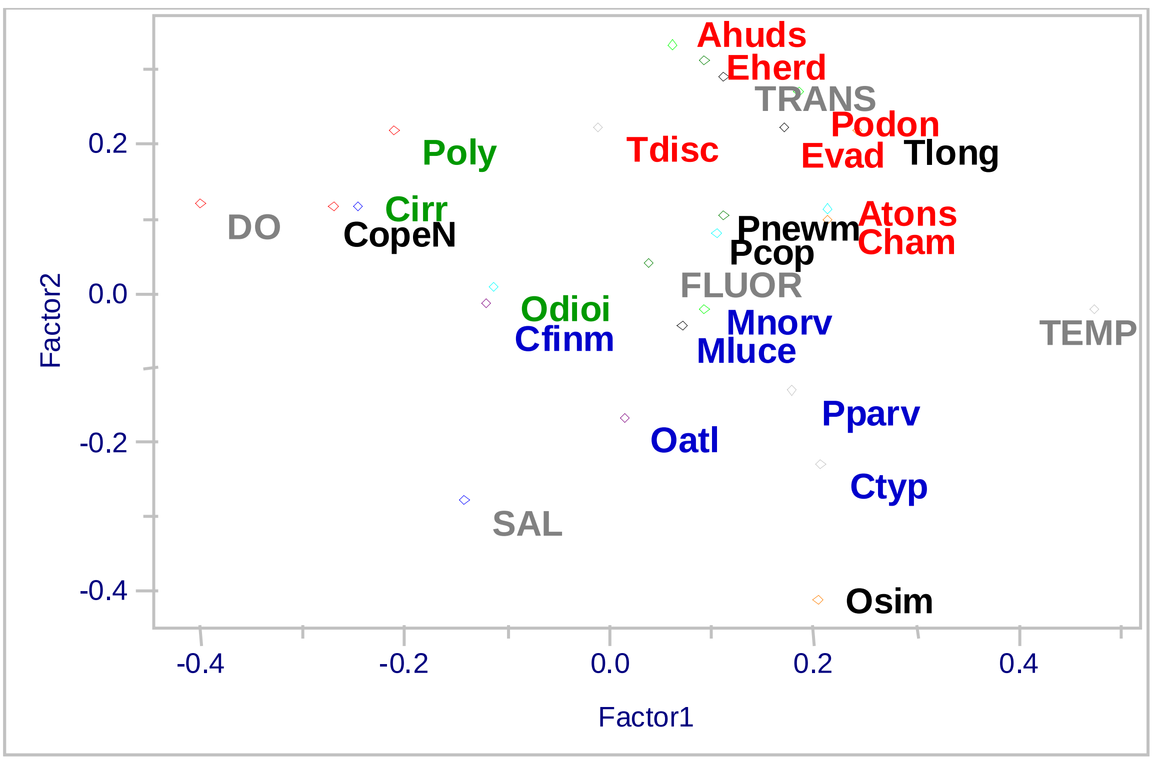
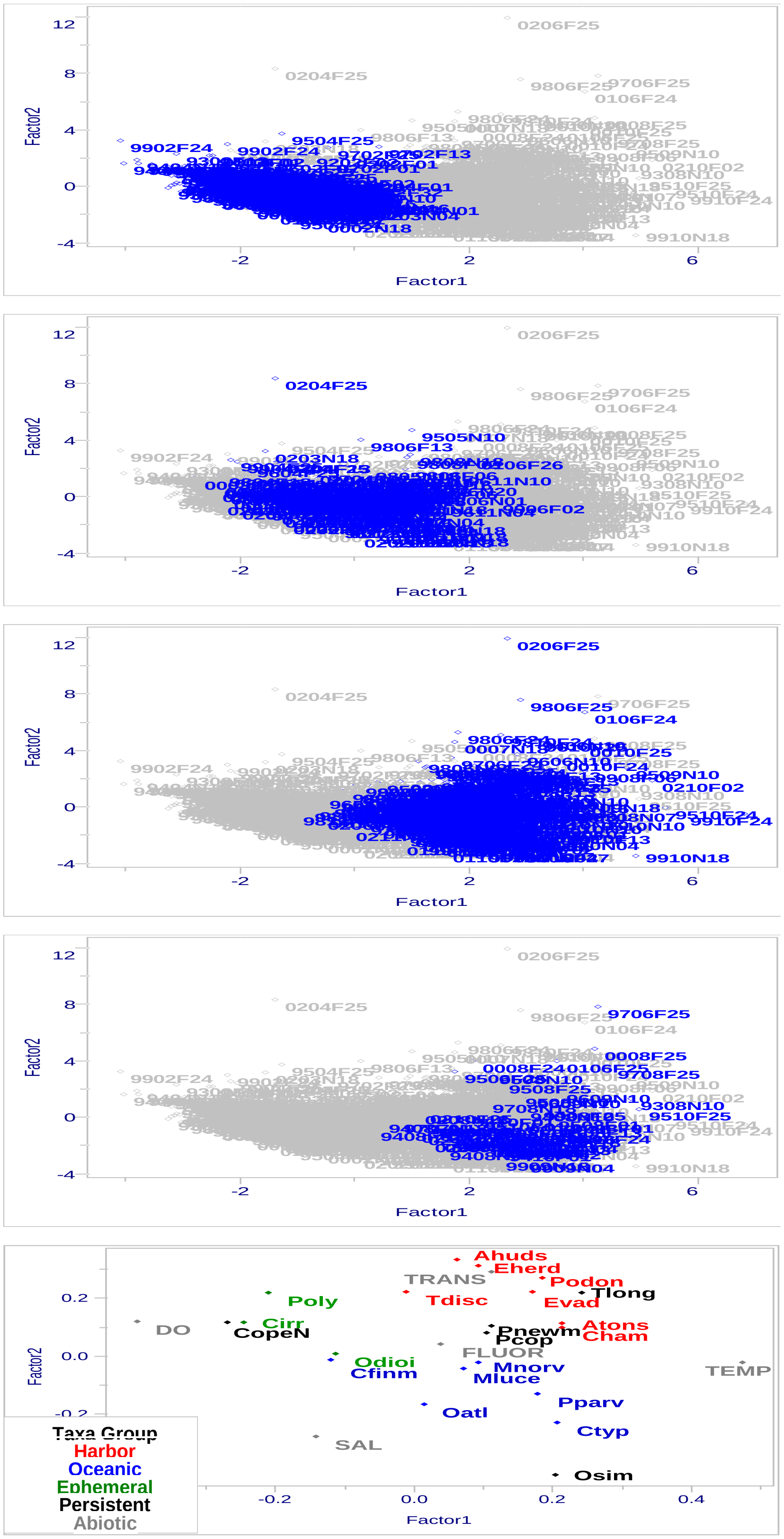


Figure 5-34 Loadings plot resulting from PCA analysis of MWRA zooplankton samples collected from 1992 to 2002. Abiotic factors are gray, estuarine taxa are red, oceanic taxa are blue, persistent taxa are black, and ephemeral taxa are green.

The distribution of samples in the first two factors of the PCA reflect the interpretation of the factor loading plots. The sample plots in Figure 5-35 document the strong influences of seasonal factors on zooplankton communities. In the top four panels, samples are successively highlighted by the temperature range at which they were collected. The onshore/offshore gradient in zooplankton composition is documented in Figure 5-36. Samples from stations in Boston Harbor and in the coastal regions of Massachusetts Bay (F23, F25, F30 and F31), show seasonal variability along Factor 1 (X-axis), but consistently have positive loadings on the y-axis. Western Massachusetts Bay samples from the nearfield (N04, N16, and N18) show similar seasonal variability along factor 1 but have negative loadings on axis 2.



5-35a. Quartile 1 (n = 272)
Temperature Range: -0.771 - 4.35 C
The tight grouping of samples collected during the winter indicated the strong influence of temperature on the zooplankton composition.

5-35b. Quartile 2 (n = 162)
Temperature Range: 4.35 - 9.47 C
The group shifts to the right and begins to spread out as the temperature warms. These samples were mostly collected in March through June.

5-35c. Quartile 3 (n = 308)
Temperature Range: 9.47 - 14.6 C
The group shifts further to the right and spreads out as the temperature warms. These samples were mostly collected in June through November. Regional patterns arise – F 24 and F25 between the nearfield and Boston Harbor plot towards the upper right indicating a harbor influence.

5-35d. Quartile 4 (n = 62)
Temperature Range: 14.6 - 19.7 C
The group shifts further right and contains samples collected from August through November. The samples located furthest to the right are not necessarily the warmest.

Temperature is the dominant variable on the x-axis. Harbor influences (taxa in red plus transmissivity) draw some samples towards the upper right while oceanic influences (taxa in blue plus salinity) draw samples to the bottom of the plot. PC1 and 2 represent 13% and 9% of the variability, respectively.

Figure 5-35 Seasonal variability in zooplankton communities.

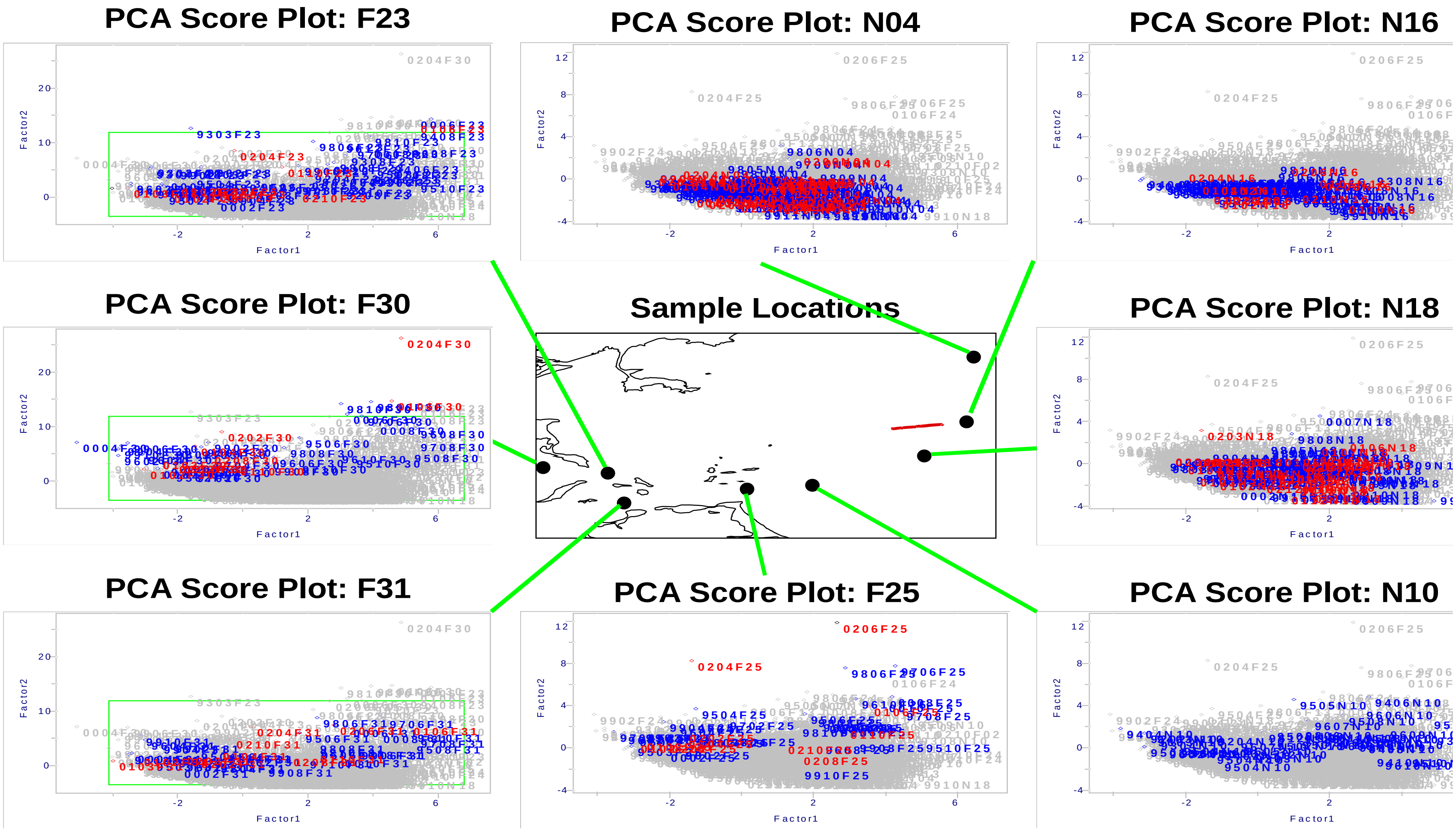


Figure 5-36 Comparison of Boston Harbor and Massachusetts Bay sampling stations from the pre- (1992 to 2000) and post- (2001 to 2002) diversion periods using PCA. Baseline and post-diversion data are colored blue and red, respectively.

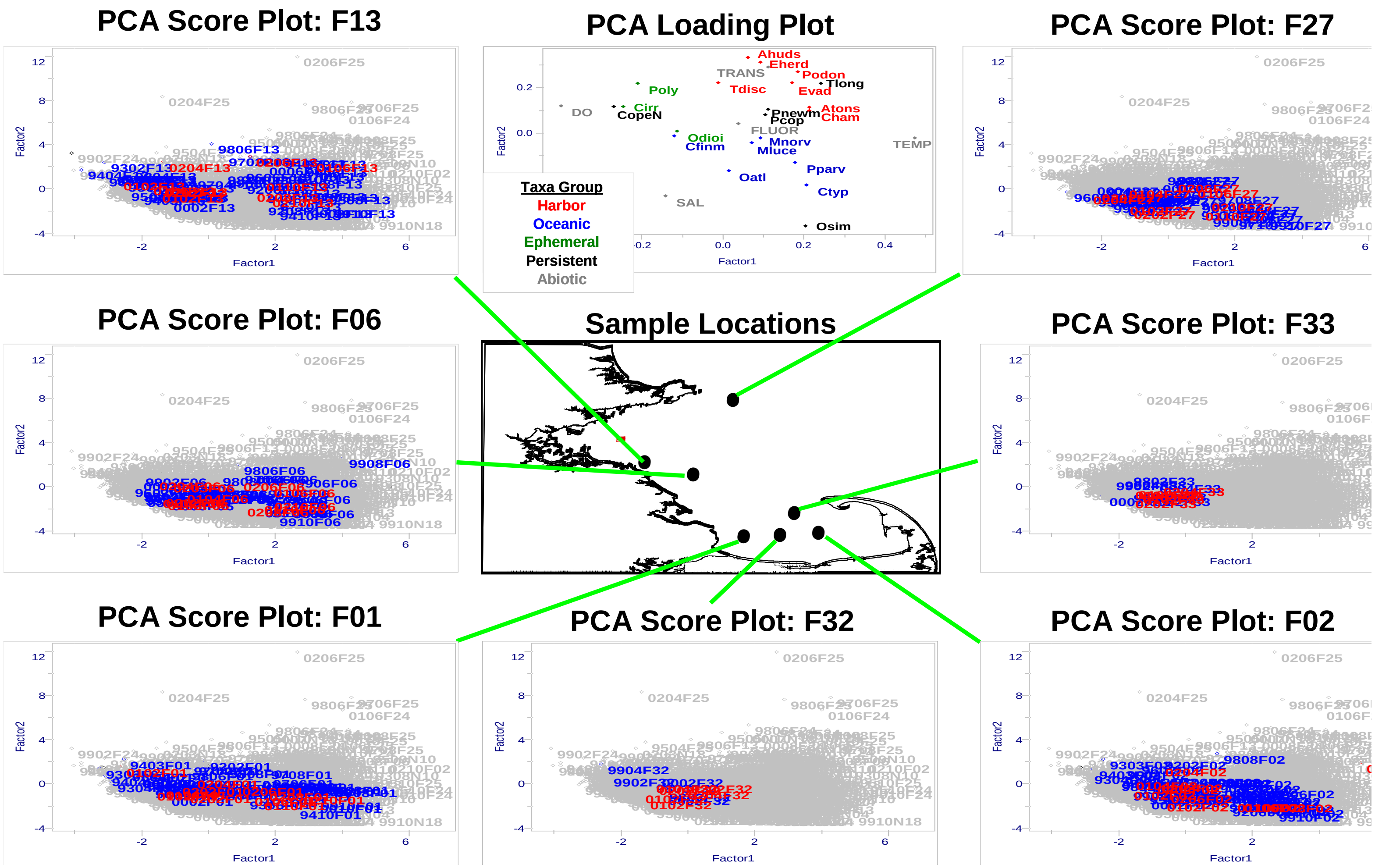


Figure 5-37 Comparison of regional zooplankton sampling stations from the pre- (1992 to 2000) and post- (2001 to 2002) diversion periods using PCA. Baseline and post-diversion data are colored blue and red, respectively.

Figure 5-37 shows similar sample plots for regional stations. With few exceptions (e.g. some samples from coastal station F13), samples from these stations tend to have neutral to negative loading on Factor 2, reflecting the offshore zooplankton communities found there.
As with the scatterplots in Figure 5-35, an inspection of the PCA output (not shown) did not support the linear conveyor belt hypothesis. The zooplankton assemblages at the boundary stations do not "predict" the communities found at stations in mid-Massachusetts Bay or in Cape Cod Bay in subsequent surveys.

Samples in Figure 5-36 and Figure 5-37 are color coded to indicate baseline (blue) or post-diversion (red). While a small number of post-diversion samples from Harbor and near Harbor stations fall outside the baseline distribution of samples, nearly all post-diversion samples from regional stations are very similar to the baseline samples from those stations. This is easiest to see in the tight clusters of points for stations F32 and F33 (Figure 5-37) in Cape Cod Bay, where sampling began in 1998. Since samples are collected at these sites only during February-April farfield surveys, the seasonal variability at these sites during both baseline and post-diversion is limited.

Association with the North Atlantic Oscillation

We are investigating relationships between the changing phases of the North Atlantic Oscillation (NAO) and the abundance of important zooplankton taxa. Preliminary results of this ongoing phase of the study (which will be discussed in more detail at the workshops) indicate a negative association between the winter NAO index and the abundance of some taxa, as seen for *Calanus finmarchicus* in Figure 5-38.

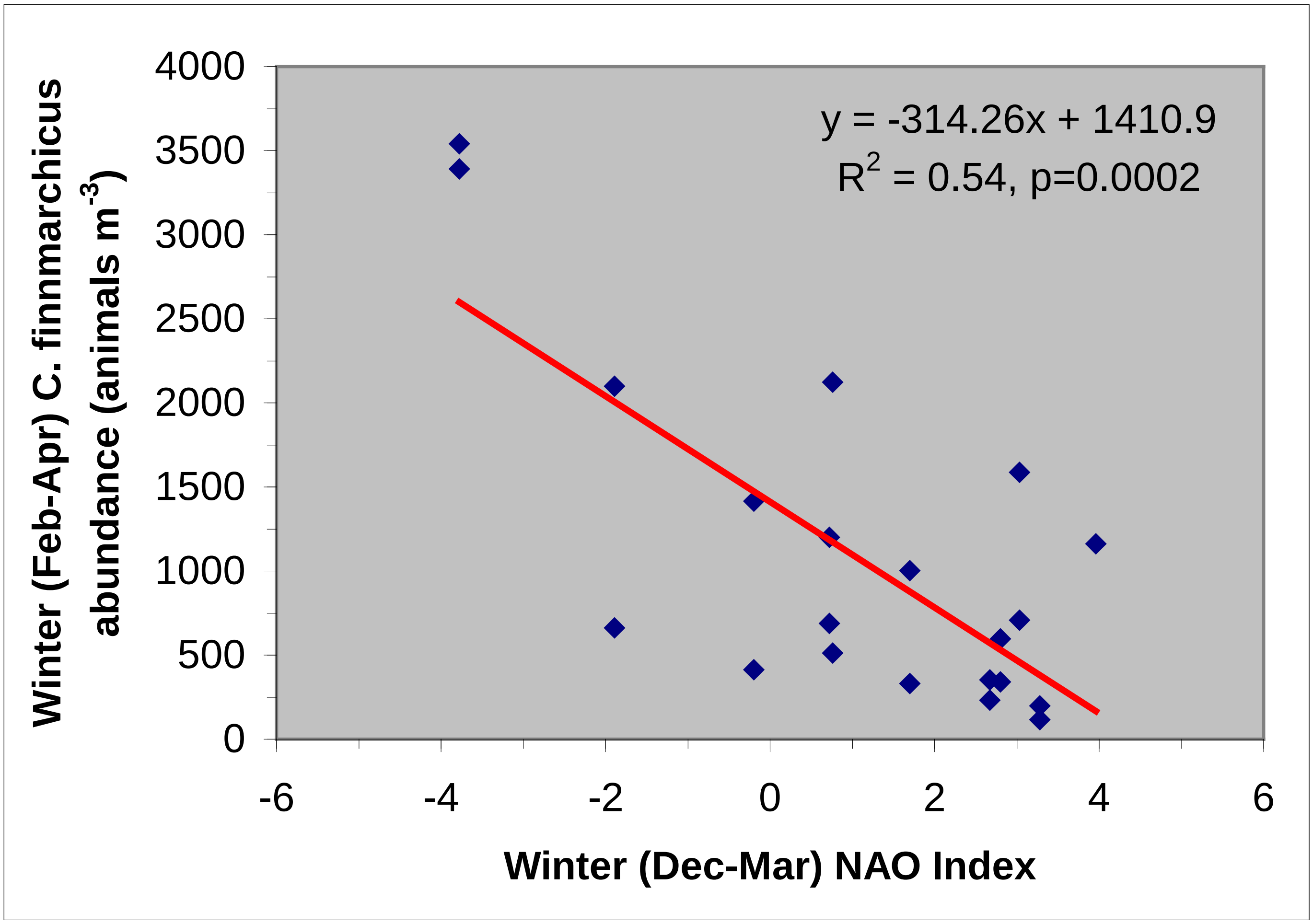


Figure 5-38 Scatterplot between winter-spring nearfield abundances of *Calanus finmarchicus* (1992-2002) and the NAO index for that winter.

Zooplankton conclusions

1. Boston Harbor, Massachusetts Bay and Cape Cod Bay have common coastal zooplankton assemblages found throughout the Gulf of Maine.
2. Strong seasonal and estuarine/offshore gradients are observed in multivariate analyses of zooplankton community structure.
3. Large-scale factors such as the North Atlantic oscillation may influence the abundance of zooplankton taxa in the Bays.
4. Through December 2002, the zooplankton data show no impact attributable to the relocated MWRA discharge.
5. MWRA's zooplankton monitoring data do not appear to support the simple one-way conveyor belt hypothesis suggested by OMSAP. Peaks in the abundance of important taxa occur tend to occur simultaneously at all stations, or can occur in Cape Cod Bay stations before increased abundances are seen in Boundary or Massachusetts Bay stations.

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6. SUMMARY AND CONCLUSIONS

Carlton Hunt

Through its monitoring of treatment plant effluent, Boston Harbor, and Massachusetts Bays over the past decade, MWRA has developed a substantial understanding of many of the effects of the Boston Harbor Project, and the relocation of the effluent discharge to Massachusetts Bay.

6.1. Effluent

Effluent quality is as good as or better than predicted during facility planning. Contaminant concentrations in the effluent are low as predicted. As expected, nutrients remain the major constituent of concern because nitrogen and phosphorous are inefficiently removed (~15 percent) from the wastewater—this is why the ambient water monitoring focuses on potential nutrient effects. MWRA effluent monitoring goes beyond conventional testing; special studies responds to ongoing and emerging issues that may affect coastal water quality. Examples of special studies include factors that may potentially affect toxicity of the effluent (*i.e.* copper), characterization of endocrine disrupters in the effluent and receiving waters, characterization of stable nitrogen isotopes in the effluent and receiving waters as a means of tracing the effluent through the lower levels of the food web, examination of the effectiveness of various stages of the treatment in removal of viruses, development of viral indicators and their relationship to bacterial indicators, and development of the first ever floatables monitoring program in effluent. These studies continue to provide important information on plant performance, emerging water quality issues, and the impact of treated sewage discharge to the coastal zone. MWRA's effluent monitoring provides extensive and early information on potential changes in effluent quality, minimizing potential environmental impacts.

6.2. Modeling and physical oceanography

The physical characteristics of Massachusetts Bay play a fundamental role in the effects of the discharge. MWRA's hydrodynamic and water quality models of Massachusetts Bay are reasonably predictive, successfully modeling internal processes such as the flow reversals in currents and circulation under certain weather/wind conditions. It is clear from the physical and modeling studies that the circulation, and consequently water properties and biology of Massachusetts Bay, is largely driven by larger flow patterns in the Gulf of Maine.

Local factors such as upwelling in response to seasonal changes weather patterns or winds (persistent southerly or southwesterly winds) are superimposed on the long-term net counter clockwise circulation pattern within Massachusetts Bay, which is driven by seasonal winds and stratification. For example, during the spring freshet when northerly or northeasterly winds are prevalent, water enters Massachusetts Bay from the north near Cape Ann and follows a general path around the perimeter of Massachusetts Bay into Cape Cod Bay, then out of the system around Race Point off Provincetown. Cape Cod Bay becomes isolated from this circulation in late spring and summer when fresh water input decreases and predominant winds change to southerly or southwesterly winds. These latter winds impede the surface water inflow to Massachusetts Bay, although they may cause upwelling, which allows deep water to enter the Bay from the Gulf of Maine. Clockwise circulation in the surface waters of northern

Massachusetts Bay can occur during the summer. Wind-induced upwelling, as well as downwelling induced by winds from the northwest, causes advection of waters on- and offshore.

In the vicinity of the outfall, the long-term net (average) velocity is small; nearfield dispersion of effluent is dominated by short time scale motions in response to the tides and local winds. The result is exchange of water parcels between the outfall site and other parts of the Bay particularly southward from the diffuser towards the south shore of Massachusetts. There may also be excursions of the plume northward or eastward as the water column responds to local physical forcing.

6.3. Nutrients

Nutrient fields within Boston Harbor and Massachusetts Bay have shown striking changes since the diversion of effluent from the mouth of Boston Harbor. Nutrient concentrations in Boston Harbor, particularly ammonium, have decreased five-fold, but only doubled within the effluent plume in central Massachusetts Bay. Dissolved inorganic nitrogen, and other nutrients such as phosphate, show similar, although less dramatic, changes as a result of the diversion. Although the effluent nutrient signature is clearly observed in the vicinity of the outfall, it is diluted to background levels over a few days and tens of kilometers. As designed, the plume reaches surface waters during unstratified conditions and is trapped below the pycnocline under stratified conditions. As result, average dilution varies seasonally (higher under unstratified conditions; lower in stratified periods). As predicted by transport models, the dilution now achieved in Massachusetts Bay is far greater than that observed (and modeled) when the flow entered the Bay in the surface waters at the mouth of Boston Harbor. Moreover, the diversion has resulted in lower nutrient concentrations in Boston Harbor and the harbor water that is transported southward along the coast off Scituate and Marshfield. In contrast, there has been little change in nutrient concentrations in other areas of the system (Cape Cod Bay, areas offshore of the diffuser and at the boundary between the Gulf of Maine and the Bay). One striking result of the diversion is relatively consistent annual average nutrient levels in all areas of the bay except the nearfield, which experiences on average approximately twice the ammonia concentration observed in the other regions of the system.

The delivery of the nutrients to Massachusetts Bay by MWRA has not diminished with the diversion of the effluent into the Bay, although its point of entry significantly changes the availability to phytoplankton of nutrients added to the system via the outfall. Annually, the effluent represents ~3 percent of the total nitrogen load to Massachusetts Bay, of which 92 percent is estimated to enter the system as a result of water transported from the Gulf of Maine into the Bay across northern boundary. The design of the diffuser and increased dilution noted above results in lower nutrient concentrations available to phytoplankton resident in the photic zone, especially in the critical summer period where the effluent is confined below the pycnocline. During the unstratified period, nutrient concentrations in the plume increase only slightly above concentrations typical of unstratified conditions in the rest of Massachusetts Bay, thus do not greatly increase the potential for production in the area influenced by the plume in this period.

6.4. Dissolved oxygen

Dissolved oxygen is at its lowest at the end of the summer stratified season. The monitoring program has shown that both physical and biological factors affect the response of dissolved oxygen over the course of the year. Recent studies indicate that regional processes (*e.g.* interaction with the Gulf of Maine and surface runoff) and advection are the primary factors governing bottom water DO concentrations in Massachusetts Bay. This physical influence is clearly evident in the highly resolved temporal data from moorings located in the northern boundary of the Bay and those located to the south. Thus, an understanding of water quality conditions outside of the influence of the outfall must be known in space and time to understand the influence of the outfall on DO in this system.

6.5. Phytoplankton

Phytoplankton in the bays and harbor respond to a variety of factors including interactions between light and nutrients. Over the course of the Harbor and Outfall Monitoring Program (1992-2002), these interactions have been manifest in a general sequence of events. These events and temporal trends are evident even though the timing of the year-to-year manifestation and magnitude of the events varies. In general, but not always, a winter/spring phytoplankton bloom occurs as available light and temperatures increase, and nutrients are replete. Later in the spring, the water column transitions from well mixed to stratified conditions; this serves to cut off the supply of nutrients to the surface waters and terminates the spring bloom. The summer is generally a period of strong stratification, depleted nutrients in surface waters, and a relatively stable mixed-assemblage phytoplankton community. In the fall, stratification deteriorates and mixing supplies nutrients to surface waters resulting in a fall phytoplankton bloom. By late fall or early winter, the water column becomes well mixed and resets to winter conditions.

High spatial correlation observed within the physical parameters that characterize the bays is also observed in biological measures such as chlorophyll fluorescence and the abundance of larger phytoplankton species, such as diatoms. High resolution spatial studies have shown typical length scales (distance apart for stations to not show correlation) of 15-20 km for phytoplankton. Seasonal patterns in the phytoplankton community have been detected using multivariate statistical analyses which also indicate there are multiple sources of variance that contribute to the distribution of phytoplankton in the bays. Generally, winter community species (diatoms such as *Thalassiosira nordenskioldii, Thalassiosira anguste-lineata, Chaetoceros debilis*) are seen in months that have higher levels of silica and nitrogen. Conversely, the summer phytoplankton community (microflagellates, small centric diatoms, cryptomonads, *Heterocapsa rotundata*) is more associated with higher temperatures which reflect periods of lower nutrient availability, especially nitrogen and silica, in the photic zone (surface waters). Post diversion changes in phytoplankton species and abundance are not evident within the bays. This is as expected since changes in nutrient concentration in the bay are small and spatially limited.

Nuisance species in the system tend to occur intermittently and at low levels. The appearance of, distribution, and abundance these species, especially *Alexandrium* spp., are often affected by physical conditions and timing of wind events. The nuisance species *Phaeocystis pouchetii* has been observed intermittently within the bays at low to moderate abundance.

Chlorophyll in Massachusetts Bay following diversion has closely followed the observed baseline mean during the year, although available data suggest that chlorophyll may be higher than observed during the baseline period during the late fall to mid winter period. High chlorophyll concentrations in early February of 2001 and 2002 were coincident with elevated primary production rates and the occurrence of earlier than usual winter/spring blooms. In December 2001, mean survey chlorophyll concentration reached its annual maximum coincident with peak production. These data, if confirmed over time, suggest higher chlorophyll biomass may be occurring in the unstratified period relative to the baseline period. The factors that may contribute to this are not clear but may relate to the phytoplankton species blooming in these periods and interactions between temperature and zooplankton abundance (see below). The higher chlorophyll levels in the spring and fall also resulted in higher particulate organic carbon levels in the water column than typically observed during the baseline, indicating the transfer of carbon into non-chlorophyll biomass.

Annual average chlorophyll concentrations generally vary in this system depending on the strength of the spring and fall blooms. Annual average chlorophyll levels since the outfall diversion are higher than those typically found during the mid 1990s, lower than levels measured in the late 1990s, and comparable to averages observed in the early 1990s. Annual averages throughout the sub-regions of the bay are generally comparable following diversion. The patterns in annual mean chlorophyll observed in the monitoring data are supported by more highly resolved temporal trends determined from satellite data (SeaWiFS), which independently show the increased large annual increase from 1998 to 2000 and decrease in 2001.

Primary production within the system has shown a small to moderate spring and fall increase in the peak bloom productivity in the nearfield area in response to the outfall diversion. Productivity in the summer does not appear to have changed. Annually the post diversion productivity appears to have a slightly higher mean in comparison to the baseline period. The seasonal pattern in the productivity within Boston Harbor also changed from an eutrophication pattern with high productivity in the summer to one more typical of temperate waters (high spring and fall, low summer productivity). The changes are primarily related to altered nutrient fields within the two systems.

6.6. Zooplankton

Zooplankton communities in Massachusetts and Cape Cod Bays are dominated by numerous species of copepods, all of which have widespread distributions in the Gulf of Maine, and some of which are found throughout the east coast of the US. MWRA's zooplankton data are dominated by smaller zooplankters such as unidentifiable copepod nauplii and small copepodites, and adults of the small copepod *Oithona similis*, which are not captured at all or are under-reported in other studies due to the use of larger mesh nets than employed under the MWRA monitoring program. The larger taxa in the MWRA monitoring data and in other studies in the Bays include the estuarine species *Acartia tonsa, Acartia hudsonica*, and *Eurytemora herdmani,* as well as oceanic species *Calanus finmarchicus*, *Paracalanus parvus,* and species in the genera *Centropages* and *Pseudocalanus*. The estuarine species tend to be more prevalent in Boston Harbor and contiguous areas just offshore. The total zooplankton abundance data tends to follow a predictable temporal pattern across the monitoring period, with abundance peaking in mid-summer and abundances measured in spring and fall. In contrast, the seasonal timing for the peak abundance in individual species varies. For example, *Calanus finmarchicus* tends to peak in the nearfield in April and May, while peak abundances of *Oithona similis* occur in mid-late summer.

Spatially, high resolution sampling (meters) in the Massachusetts Bay and Cape Cod Bays system suggest large zooplankton correlate over length scales of about 10 km, indicating that samples collected more than 10 km apart are likely to be independent of each other. Moreover, the long term temporal data set from the MWRA monitoring indicate that peak abundances of individual zooplankton species are often coincident throughout Bays, although the magnitude of these peak abundances may vary across system. For example, *C. finmarchicus* peak abundances tend to be coincident in the north and central regions of Massachusetts Bay and in Cape Cod Bay, although abundances in the southern parts of the system are often observed to occur earlier than in the northern areas. A consistent north-south sequence in peak abundances for the numerically dominate species *O. similis,* adults of *Paracalanus parvus, Pseudocalanus* spp., *Paracalanus/ Pseudocalanus* copepodites, and *Centropages typicus* is not evident in the monitoring data. Thus, there is little evidence for a strong "downstream" response in zooplankton abundances following large abundances observed at the northern boundary of the system. Rather, the monitoring data suggest zooplankton species reach peak abundances at the same time in the system. Applications of multivariate statistical techniques to zooplankton species abundance and “abiotic” factors (temperature, salinity, chlorophyll fluorescence, dissolved oxygen, and transmissivity) that may influence the species composition also demonstrate the temporal response in the zooplankton community. The analysis shows that cold water species tend to be abundant early in the year, while *O. similes* is more related to warmer temperatures. The statistical analysis also identifies the observed estuarine/offshore species gradient, but found no clear correspondence in the abundances to chlorophyll biomass. The latter finding suggests zooplankton responses in may be more related to species-species interactions than to changes in biomass.

Because post-diversion change in phytoplankton species and abundance in Massachusetts Bay is not evident in the monitoring data, outfall-driven changes in the zooplankton abundances or species composition are not expected nor have they been observed. For significant changes in the zooplankton community to occur as result of the outfall diversion, the phytoplankton species or biomass within the effluent plume would need to change substantially. Such changes have not been observed in the phytoplankton data, even though small increases in nutrient concentrations are found within the water column.

6.7. Conclusion

Although the nutrient loading to the Bays by the outfall is relatively constant through time, changing the entry point to the bays has caused substantial improvement in the water quality of Boston Harbor without causing adverse alteration of the basic ecology and species comprising the base of the food web and associated primary consumers in Massachusetts Bay. The response in Massachusetts and Cape Cod Bays to the diversion is clearly restricted to the area around the outfall, possibly extending southward from the diffuser approximately 20 km (12 miles) but not eastwards towards the Stellwagen Bank area. Small observed increases in nutrient concentration in and near the nearfield area are not evident in the phytoplankton and zooplankton data in part due to the isolation of the nutrients from interaction with these species in the summer and generally small increases in total available nutrients in the remainder of the year. An increase in phytoplankton biomass appears to be present in the nearfield following the diversion, but factors other than the outfall may explain the increase. Specifically, the magnitude of the winter spring blooms since 2000 appear to be influenced by the presence of *Phaeocystis pouchetii,* which does not provide high quality food for zooplankton. Thus, zooplankton grazing may not exert significant influence on the biomass that developed in these years. Moreover, the data suggest in the absence of *Phaeocystis*, warmer years tend to have more abundant zooplankton which can graze down phytoplankton biomass and contribute to lower apparent chlorophyll biomass as observed in the strong negative correspondence between the peak chlorophyll in 1995, 1996, 1998, and 1999 and zooplankton abundance. Failure to understanding these ecological interactions could result in inappropriate attribution of cause for the apparent significant increase in annual chlorophyll levels since the outfall diversion. The latter coupled with increased ammonia in the nearfield are the only detectable changes in Massachusetts Bay after the outfall diversion, although the associations may not be causative.

MWRA's extensive receiving water monitoring program has confirmed that there has been no short-term, acute adverse response in the ecology of Massachusetts Bay. This program has contributed key insights into the bays ecosystem, including information on the scales of variability, and responses to local, regional, and hemispheric scale factors that influence the physics of the system and concomitant biological responses. The effects of Gulf of Maine circulation are seen in hydrographic characteristics such as temperature, salinity, and oxygen and plankton. Regional events (*i.e.*, phytoplankton blooms; red tide organisms in the Gulf of Maine) and seasonal winds and runoff may or may not be transmitted into Massachusetts Bay depending on local conditions and events (winds, storms, *etc.*) Interannual, regional variations contribute to spatial and temporal variability in the biological responses that have been observed by Harbor and Outfall Monitoring program over the past 15 years.

7. DEVELOPMENT OF PROPOSED SAMPLING DESIGN FOR THE NEARFIELD

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7.1. Introduction to analytical approaches

As described in Section 3 of this briefing (entitled "Water column concerns and sampling program"), and detailed in the Ambient Monitoring Plan (MWRA 1997), existing water column monitoring includes 21 nearfield stations (Table 7-1) sampled 17 times annually (Table 7-2) at five depths. (Not all parameters are measured at every station or depth.) There are eight years of baseline data and two years of discharge data available for most parameters. This large data set enabled us to carry out analyses to measure how changes in study design affect the ability to detect change in monitoring parameters.

The first step was to select key metrics and "decisions" to evaluate changes in sampling design. Most analyses were based on two key contingency plan threshold parameters which we identified as key indicators of the effects of most concern: overgrowth of algae and oxygen depletion:

- areal chlorophyll and
- bottom water dissolved oxygen.

In addition, we evaluated the effect of changing the sampling design on parameters with a clear outfall-related signal:

- ammonium
- nitrate+nitrite.

We also evaluated how plankton monitoring would be affected, because these are important indicators of potential ecosystem effects:

- phytoplankton
- zooplankton

Different study designs were evaluated using two methods. First, a linear mixed model and analysis of residual variance was used to measure the degree of redundancy of the current sampling design, both spatially and temporally. This approach allowed us to quantify how well correlated alternative sampling designs would be with the current design. Second, a series of graphical and statistical analyses were carried out on key parameters to determine the extent to which alternative sampling designs would give different results from the present designs. This empirical approach examined changes in the number and location of nearfield sampling stations, and changes in the number of surveys, in combination with reducing the number of hydrocast/dissolved nutrient stations.

7.1.1. Proposal

Based on these evaluations, MWRA proposes the following modifications to the nearfield water column monitoring:

- Drop 14 of the 21 nearfield stations (Table 7-1) at which only hydrocast and dissolved inorganic nutrients are measured.
- Retain the 7 remaining nearfield stations (Table 7-1) at which hydrocast, dissolved inorganic nutrients , and organic nutrients are measured. Plankton and primary productivity are measured at two of those stations.
- Drop 5 of the 17 surveys / year (Table 7-2)
  - Survey 5, March/April.
  - Survey 8, early July
  - Survey 10, early August
  - Survey 16, Late November
  - Survey 17, mid-December.
- Retain the remaining 12 nearfield surveys/year, including all combined nearfield/farfield surveys (Table 7-2).
- MWRA currently proposes no modifications to farfield surveys, stations, or measurements. We anticipate returning to OMSAP next year with a further evaluation of farfield study design when another year of monitoring data are available

Table 7-1 Types of samples collected at the 21 nearfield station in the existing program. Shaded rows indicate the 14 stations deleted in MWRA's proposal.

Station	hydrocast [1]	dissolved inorganic nutrients [2]	Other nutrients [3]
N01	**Y**	**Y**	**Y**
N02	Y	Y	
N03	Y	Y	
N04	**Y**	**Y**	**Y**
N05	Y	Y	
N06	Y	Y	
N07	**Y**	**Y**	**Y**
N08	Y	Y	
N09	Y	Y	
N10	**Y**	**Y**	**Y**
N11	Y	Y	
N12	Y	Y	
N13	Y	Y	
N14	Y	Y	
N15	Y	Y	
N16	**Y**	**Y**	**Y**
N17	Y	Y	
N18	**Y**	**Y**	**Y**
N19	Y	Y	
N20	**Y**	**Y**	**Y**
N21	Y	Y	

1. Includes temperature, salinity, depth, dissolved oxygen (DO) and chlorophyll fluorescence sensors, etc.
2. dissolved inorganic nutrients = nitrate, nitrite, ammonium, orthophosphate, silicate.
3. Other nutrients = particulate and dissolved organic nutrients, total suspended solids, and lab analyses for DO and Chlorophyll. Also plankton, respiration, and primary productivity samples are collected at N04 and N18

Table 7-2 Existing 17 nearfield water quality surveys. Asterisks indicate the 6 combined nearfield/farfield surveys. Shading indicates the 5 surveys deleted in MWRA's proposal.

Survey num	Month	Season (Threshold)
1*	**February**	**Spring**
2*	**February/Mar**	**Spring**
3	**March**	**Spring**
4*	**April**	**Spring**
5	April/May	Spring/Summer
6	**May**	**Summer**
7*	**June**	**Summer**
8	July	Summer
9	**July**	**Summer**
10	August	Summer
11*	**August**	**Summer**
12	**September**	**Fall**
13	**September**	**Fall**
14*	**October**	**Fall**
15	**October**	**Fall**
16	November	Fall
17	December	Fall

7.2. Statistical model approach - spatial and temporal analysis.

7.2.1. Introduction

On September 6, 2000, the Massachusetts Water Resource Authority (MWRA) ceased discharge of sewage effluent into Boston Harbor and began operation of a new outfall in Massachusetts Bay. A baseline monitoring program at 21 sampling stations that surround the new outfall was initiated approximately 8.5 years before outfall diversion and has continued through the 2.75 years since outfall diversion. MWRA and its Outfall Monitoring Science Advisory Panel (OMSAP) are currently considering the possibility of reducing the magnitude of the monitoring program in the future. The objective of this report is to provide, through the statistical analysis of chlorophyll and dissolved oxygen data from the monitoring program, an assessment of the impact of reduced levels of monitoring on the ability to make water quality decisions.

7.2.2. Methods

The correlation structure of the monitoring data determines the amount of information loss associated with a reduced monitoring strategy. Very strong temporal correlation means that little information is lost when the number of surveys per year is reduced. On the other hand, very strong spatial correlation means that little information is lost when the number of sampling stations is reduced. In order to characterize the expected information loss associated with reduced monitoring strategies for chlorophyll and dissolved oxygen, the following four-step analysis protocol was carried out.

- Model survey average readings to identify temporal fixed effects (see Section 7.2.2.1)
- Model survey-average-corrected individual station readings to identify spatial fixed effects (see Section 7.2.2.2)
- Correct the individual station readings for temporal and spatial fixed effects and derive a correlation model for the corrected data (see Section 7.2.2.3)
- Apply the correlation model to characterize the correlation of annual average readings from reduced monitoring programs with true parameter levels (see Section 7.2.2.4)

Because the distributions of chlorophyll and dissolved oxygen readings are closer to lognormal than normal distributions, all analyses were performed after taking the natural logarithm of the readings. Thus, all averages reported are geometric as opposed to arithmetic averages.

7.2.2.1. Modeling Survey Averages

Temporal fixed effects were assessed by first taking geometric averages of the parameter readings across the 21 individual sampling stations and then fitting models to the natural logarithm of the average. Different statistical models were employed for the survey averages depending on whether or not there was evidence of a seasonal pattern in the data. The presence or absence of a seasonal pattern was determined by fitting the model described in Section

7.2.2.1.1 (Equation 7-1) to the survey average data and testing the statistical significance of effects associated with the cruise number associated with a survey. Nominally, 17 surveys are performed each year at approximately the same times of year. As such, each survey represented in the monitoring data has a cruise number in the range 1-17 associated with it. Allowing each cruise number to have its own effect is essentially the same as fitting a nonparametric seasonality model to the survey average data.

If there was evidence of a seasonal pattern in the data, the model described in Section 7.2.2.1.2 (Equation 7-2) was employed to characterize the seasonal pattern as well as assess the significance of other fixed temporal effects. If no evidence of a seasonal pattern existed, then the model described in Section 7.2.2.1.3 (Equation 7-3) was employed to assess the significance of other fixed temporal effects. The manner in which insignificant effects were removed from the full models in order to obtain parsimonious models is described in Section 7.2.2.1.4 .

7.2.2.1.1. *Initial Full Model for Survey Averages*

The following full model was fitted to the survey averages in order to determine if detailed modeling of seasonality was warranted.

$$Y_t = \beta_0 + \beta_1 t + B_{n(t)} + \delta_0 I(t) + \delta_1 t I(t) + \Delta_{n(t)} + \varepsilon_t$$

Equation 7-1

where

Y_t	=	average at time t of the natural logarithm of parameter (chlorophyll or dissolved oxygen) readings across stations
β_0	=	average seasonally-adjusted Y-value just before outfall diversion
β_1	=	linear time effect before outfall diversion
t	=	time in years since outfall diversion
n(t)	=	cruise number from 1 to 17 associated with the survey at time t
$B_{n(t)}$	=	effect of cruise number n(t); essentially a nonparametric seasonality effect
δ_0	=	change in average seasonally-adjusted Y-value at outfall diversion
I(t)	=	1 after outfall diversion; 0 before outfall diversion
δ_1	=	change at outfall diversion in linear time effect
Δ_j	=	change at outfall diversion in effect of cruise number j; captures change in nonparametric seasonality effect
ε_t	=	random error term at time t with mean zero and variance σ^2 where the correlation between two error terms is assumed to be $\rho^{d/22}$ where d is the number of days between surveys. (17 surveys, if evenly spaced over the year, would be about 22 days apart.)

If the ρ parameter associated with the random error term is positive, then the survey averages represent an autocorrelated time series.

First, the Δ-parameters were tested as a group for statistical significance at the 0.05 level. If Δ was found to be statistically insignificant, then the B-parameters were tested as a group for statistical significance at the 0.05 level. If either the Δ-parameters or the B-parameters were found to be statistically significant, then the full model of Section 7.2.2.1.2 (Equation 7-2) was employed to analyze the survey averages. If neither the Δ-parameters nor the B-parameters were found to be statistically significant, then the full model of Section 7.2.2.1.3 (Equation 7-3) was employed to analyze the survey averages.

7.2.2.1.2. Full Model for Survey Averages Including Seasonality Terms

If the nonparametric seasonality effect was found to be statistically significant, the following full model was fitted to the survey averages.

$$\begin{aligned} Y_t = {} & \beta_0 + \beta_1 t + \beta_2 \sin(2\pi t) + \beta_3 \cos(2\pi t) + \beta_4 \sin(2\pi 2t) + \beta_5 \cos(2\pi 2t) \\ & + \delta_0 I(t) + \delta_1 t I(t) + \delta_2 \sin(2\pi t) I(t) + \delta_3 \cos(2\pi t) I(t) \\ & + \delta_4 \sin(2\pi 2t) I(t) + \delta_5 \cos(2\pi 2t) I(t) + \varepsilon_t \end{aligned}$$

Equation 7-2

where

Y_t	=	average at time t of the natural logarithm of parameter (chlorophyll or dissolved oxygen) readings across stations
β_0	=	average seasonally-adjusted Y-value just before outfall diversion
β_1	=	linear time effect before outfall diversion
t	=	time in years since outfall diversion
β_2	=	coefficient on annual sine-wave effect in time; combine with b_3 for annual seasonality effect
β_3	=	coefficient on annual cosine-wave effect in time; combine with b_2 for annual seasonality effect
β_4	=	coefficient on semi-annual sine-wave effect in time; combine with b_5 for semi-annual seasonality effect
β_5	=	coefficient on semi-annual cosine-wave effect in time; combine with b_4 for semi-annual seasonality effect
δ_0	=	change in average seasonally-adjusted Y-value at outfall diversion
I(t)	=	1 after outfall diversion; 0 before outfall diversion
δ_1	=	change at outfall diversion in linear time effect
δ_2	=	change at outfall diversion in coefficient on annual sine-wave effect in time; combine with δ_3 for change in annual seasonality effect
δ_3	=	change at outfall diversion in coefficient on annual cosine-wave effect in time; combine with δ_2 for change in annual seasonality effect
δ_4	=	change at outfall diversion in coefficient on semi-annual sine-wave effect in time; combine with δ_5 for change in semi-annual seasonality effect
δ_5	=	change at outfall diversion in coefficient on semi-annual cosine-wave effect in time; combine with δ_4 for change in semi-annual seasonality effect
ε_t	=	random error term at time t with mean zero and variance σ^2 where the correlation between two error terms is assumed to be $\rho^{d/22}$ where d is the number of days between surveys

The difference between this model and the model of Section 7.2.2.1.1 (Equation 7-1) is that the nonparametric seasonality component of the former model has been replaced by a parametric seasonality model represented by sine and cosine terms. Simultaneously fitting sine- and cosine-waves with individual amplitude parameters to data is equivalent to fitting a single sine-wave with an amplitude parameter and a parameter for the time at which the maximum value occurs. Thus, the above model fits sine-waves with annual and semi-annual periods to the data allowing for changes in both sine-waves at outfall diversion.

7.2.2.1.3. Full Model for Survey Averages Excluding Seasonality Terms

If the nonparametric seasonality effect was found to be statistically insignificant, the following full model was fitted to the survey averages.

$$Y_t = \beta_0 + \beta_1 t + \delta_0 I(t) + \delta_1 t I(t) + \varepsilon_t \qquad \text{Equation 7-3}$$

where

Y_t	=	average at time t of the natural logarithm of parameter (chlorophyll or dissolved oxygen) readings across stations
β_0	=	average seasonally-adjusted Y-value just before outfall diversion
β_1	=	linear time effect before outfall diversion
t	=	time in years since outfall diversion
δ_0	=	change in average seasonally-adjusted Y-value at outfall diversion
I(t)	=	1 after outfall diversion; 0 before outfall diversion
δ_1	=	change at outfall diversion in linear time effect
ε_t	=	random error term at time t with mean zero and variance σ^2 where the correlation between two error terms is assumed to be $\rho^{d/22}$ where d is the number of days between surveys

7.2.2.1.4. Assessing Fixed Effects for Survey Averages

Whether the model of Section 7.2.2.1.2 (Equation 7-2) or the model of Section 7.2.2.1.3 (Equation 7-3) were employed, fixed effects were eliminated from the full model in a backward fashion to obtain a parsimonious model. Fixed effects were eliminated in the following order:

- Effects associated with changes in seasonality or linear time trends (δ_1, δ_2, δ_3, δ_4, δ_5)
- Effects associated with seasonality or linear time trends (β_1, β_2, β_3, β_4, β_5)
- Effect associated with a change in average levels at outfall diversion (δ_0)

7.2.2.2. Modeling Individual Station Readings

Fixed spatial effects were assessed by first subtracting the survey average from each of the individual station readings and then fitting models to the resulting survey-average-corrected readings. The model employed contained parameters for a quadratic response surface in latitude and longitude as well as a random effect for sampling station. The manner in which insignificant effects were removed from the full models in order to obtain parsimonious models is described in Section 7.2.2.2.2 .

7.2.2.2.1. <u>Full Model for Station Readings</u>

The full model fitted to the survey-average-corrected readings is:

$$R_{it} = \alpha_{00} + \alpha_{10}\, x_i + \alpha_{01}\, y_i + \alpha_{20}\, x_i^2 + \alpha_{02}\, y_i^2 + \alpha_{11}\, x_i y_i + S_i + \varepsilon_{it}$$

Equation 7-4

where

R_{it}	=	survey-average-corrected log-parameter (chlorophyll or dissolved oxygen) value for the ith station at time t
x_i	=	longitudinal location of ith station in kilometers
y_i	=	latitudinal location of ith station in kilometers
α_{00}	=	average reading at location with x=0 and y=0 where the most western station has x=0 and the most southern station has y=0
α_{10}	=	linear longitudinal effect
α_{01}	=	linear latitudinal effect
α_{20}	=	quadratic longitudinal effect
α_{02}	=	quadratic latitudinal effect
α_{11}	=	interaction effect between longitude and latitude
S_i	=	random effect of ith station
ε_{it}	=	random error term for ith station at time t with mean zero and variance θ^2; each ε_{it} is assumed to be independent of all other ε terms

7.2.2.2.2. <u>Assessing Fixed Effects for Station Readings</u>

The non-planar model parameters (α_{20}, α_{02}, and α_{11}) were first tested as a group for statistical significance at the 0.05 level. If the non-planar parameters were statistically significant, no further testing of fixed effects was performed. If the non-planar parameters lack statistical significance, they were removed from the model, the model was refitted, and the statistical significance of the planar parameters (α_{10} and α_{01}) as a pair was tested at the 0.05 level.

7.2.2.3. Fitting a Combined Temporal-Spatial Covariance Model

This report addresses the consequences of reduced sampling plans on the ability to make annual decisions. The primary driver for assessing the consequences of reduced sampling plans is the correlation structure among the measured readings. In order to simultaneously capture both temporal and spatial correlation in the survey data, the following correlation model was fitted to the log-transformed data after correction for all significant fixed effects.

$$Corr(R_{ij},R_{km}) = \rho^{[365*t(i,k)/22]} [\gamma_0 - \gamma_1 s(j,m)] \text{ for } s(j,m) < \gamma_0/\gamma_1$$

Equation 7-5

where

R_{ij}	=	natural logarithm of the reading for the ith survey and jth station after correction for all significant fixed effects
ρ	=	parameter characterizing temporal correlation
γ_0	=	parameter characterizing nugget effect for spatial correlation
γ_1	=	parameter characterizing effect of distance on spatial correlation
t(i,k)	=	number of years between the ith and kth surveys
s(j,m)	=	distance in kilometers between the jth and mth stations.

If the environmental readings exhibited significant seasonality based on the analysis of survey averages, the correlation model parameter ρ was further parameterized as:

$$\rho = \rho_0 + \rho_1 \sin(2\pi\, t(i,k)) + \rho_2 \cos(2\pi\, t(i,k)) + \rho_3 \sin(2\pi\, 2t(i,k)) + \rho_4 \cos(2\pi\, 2t(i,k))$$

Equation 7-6

In either case, the combined temporal-spatial correlation model was fitted to semivariogram values calculated for all pairs of surveys such that t(i,k) was less than 1 year.

7.2.2.4. Evaluating Reduced Sampling Strategies

It is assumed that annual decisions are based on the annual average of all readings. The ideal parameter value for making annual decisions would be the true average reading for daily surveys conducted at each of the 21 currently sampled nearfield stations during an appropriate reference period. The value of the current sampling program and alternative programs under consideration can be characterized in terms of the degree to which each program produces an average annual reading that correlates with this true parameter value. Three reference periods are examined:

- RP365: Daily surveys conducted from 1/1 to 12/31
- RP335: Daily surveys conducted from 1/27 to 12/27
- RP306: Daily surveys conducted from 1/24 to 11/25

RP365 corresponds to the true parameter value being the average across all days of the year. RP335 de-emphasizes the winter storm period and RP306 further de-emphasizes the winter storm period.

For the majority of the calculations performed here, it is assumed that the surveys are equally spaced throughout the reference period. Hypothetical programs involving from one (1) to 17 surveys per year are examined. Further, we consider the full program of sampling at all 21 nearfield stations as well as the following five alternative station sets:

Station Set 1: N01 N04 N07 N10 N16 N18 N20
Station Set 2: N14 N16 N18 N20
Station Set 3: N02 N09 N16 N20
Station 21: N21
Station 01: N01

N01		N02		N03		**N04**
	N13		N14		N15	
N12						N05
	N20		N21		**N16**	
N11						N06
	N19		**N18**		N17	
N10		N09		N08		**N07**

While the last two individual stations are not viable alternative sampling plans, they are included as examples of central (N21) and extreme (N01) stations to increase the intuitive appeal of the results.

In addition to the correlations for equally-spaced surveys, correlations are also calculated for two specific survey-date scenarios:

```
17 Current Survey Dates:
2/5 2/26 3/20 4/3 4/24 5/15 6/19 7/3 7/24 8/7 8/21 9/4 9/25 10/9 10/30 11/27 12/18

12 Proposed Survey Dates:
2/5 2/26 3/20   4/10   5/15 6/19     7/24     8/21 9/4   10/2 10/23 11/13
```

All correlations are presented in the form of a plot of correlation versus number of surveys per year with different plotting symbols for different station sets. The correlations for equally-spaced surveys are presented as curves and the correlations for the specific survey-date scenarios are presented as individual points.

7.2.3. Chlorophyll results

Analysis results for log-chlorophyll readings are presented in this section. Fixed temporal and spatial effects are addressed in Sections 7.2.3.1 and 7.2.3.2, respectively. The combined temporal-spatial correlation model for log-chlorophyll is presented in Section 7.2.3.3 and the information loss associated with reduced sampling strategies for log-chlorophyll is characterized in Section 7.2.3.4.

7.2.3.1. Fixed Temporal Effects for Log-Chlorophyll

When the model of Section 7.2.2.1.1 (Equation 7-1) was fitted, the terms related to a nonparametric seasonality effect were found to be statistically insignificant. Subsequently, the model of Section 7.2.2.1.3 (Equation 7-3) was fitted to the data to assess average log-chlorophyll levels, linear time trends in log-chlorophyll levels, and whether or not these effects changed at the time of outfall diversion. None of the fixed model effects were found to be statistically significant at the 0.05 level. The modeling exercise was repeated using a statistical significance level of 0.10 to identify any marginally significant fixed effects. Only the effect related to a change in log-chlorophyll level at the time of outfall diversion (δ_0) was marginally significant (p=0.0897). The resulting fitted model is

$$Y_t = 3.8604 + 0.4150\ I(t)$$

Equation 7-7

where the estimated variance associated with the fitted model is σ^2=0.7084 and the correlation coefficient of error terms for two surveys separated by 22 days is estimated to be ρ=0.4343.

The fixed effect parameter estimates imply that geometric mean chlorophyll measurements were approximately 47.5 before outfall diversion and 71.9 after outfall diversion, with 95% confidence intervals (38.2, 59.1) and (47.6, 108.7), respectively. The estimated variance implies that the ratio of the 97.5 percentile of chlorophyll measurements to the 2.5 percentile is approximately 27.

It happens to be very important to model this data as a correlated time series. If the correlation between time points is ignored, many fixed effects in the full model are found to be statistically significant. However, the apparent statistical significance of most of the model terms is brought about only by falsely assuming that measurements from different surveys are statistically independent.

Figure 7-1 is a time-series plot of the geometric average chlorophyll values (dotted curve) versus survey date with the fitted model superimposed as a solid curve. The vertical dotted lines divide calendar years. Visual examination of Figure 7-1 reveals that chlorophyll levels appear to have increased in late 1998, remained elevated through early 2001, and perhaps have decreased since early 2001. Thus, the marginally significant increase in chlorophyll levels post-diversion may not be related to outfall diversion at all but to other processes that began years before outfall diversion.

7.2.3.2. Fixed Spatial Effects for Log-Chlorophyll

When the model of Section 7.2.2.2.1 (Equation 7-4) was fitted to the survey-average-corrected log-chlorophyll values (see introduction to Section 7.2.2.2), no statistically significant fixed effects related to station location were found.

7.2.3.3. Combined Temporal-Spatial Correlation Model for Log-Chlorophyll

Because no nonparametric seasonality effects were identified in the chlorophyll data, the combined temporal-spatial correlation model of Section 7.2.2.3 (Equation 7-5) was fitted to the data with a single ρ parameter. Further, when the model for chlorophyll was fitted, the γ_0 parameter was set equal to one and not estimated from the data. Parameter values for the log-chlorophyll correlation model are:

$\rho = 0.4323$
$\gamma_0 = 1$
$\gamma_1 = 0.02698$.

7.2.3.4. Evaluation of Reduced Sampling Strategies for Log-Chlorophyll

Figure 7-2 to Figure 7-4 contain plots of correlation coefficients versus number of surveys performed per year. Plots for reference periods RP365, RP335, and RP306 are presented as Figure 7-2 Figure 7-3 and Figure 7-4, respectively. For each plot, there is a curve for the full set of all 21 stations as well as for each of the alternative station sets. The highest point in Figure 7-2 indicates that 17 surveys equally spaced throughout the year at all 21 stations produces an annual average chlorophyll value that has a 0.97 correlation coefficient with the true chlorophyll value obtained from all 365 daily chlorophyll surveys at all 21 stations.

The closeness of the curves for Station Sets 1, 2, and 3 to the curve for All Stations indicates that the chlorophyll data contains a high degree of spatial redundancy. If the stations were producing independent chlorophyll data, one would expect a reduction from 21 to just 4 sampling stations (Station Sets 2 or 3) to decrease the correlation coefficient by more than a factor of two [$(21/4)^{1/2}$]. High correlation coefficients are maintained for these station sets because of the high spatial correlation between readings at the eliminated stations and readings at the included stations.

Temporal redundancy would exhibit itself in the plots in the form of flat curves, and there is some evidence of such redundancy in the chlorophyll data. For example, if the individual surveys produced independent data, then a switch from 17 to four (4) surveys per year would cause the correlation coefficient to decrease by more than a factor of two [$(17/4)^{1/2}$]. For the chlorophyll data, the correlation decreases by less than a factor of 1.4. While present, the temporal redundancy is not as strong in the chlorophyll data as is the spatial redundancy. More modest reductions in the number of surveys per year must be considered if high correlation coefficients are to be maintained.

Contrasting the lower two curves gives an indication of the degree to which individual stations correlate with the true chlorophyll parameter value. Chlorophyll values from Station 21 correlate much better with the true value than do values from Station 01. This is because Station 21 is in the center of the region of interest and, therefore, somewhat better correlated with all the sampling stations in the nearfield. In contrast, Station 01 is at the northwest extreme of the nearfield and is much less correlated with the southern and eastern sampling stations.

The correlation plot can be used to relate the effects of reductions in the number of stations and surveys per year. For example, a spatial reduction to the four stations in Set 2 with 17 surveys per year would produce similar results as a temporal reduction to 14 surveys per year at all 21 stations. In a similar fashion, an extreme spatial reduction to Station 21 surveyed 17 times per year would produce similar results as 11 surveys per year performed at the four stations in Set 3.

The individual points plotted in Figure 7-2 to Figure 7-4 illustrate the correlations for 17 and 12 surveys conducted under the current plan for 17 surveys in 2004 and under the proposed plan for conducting 12 surveys in 2004. Specific survey dates are used for these correlation calculations. Since reference period RP335 is specifically tailored to the 17-survey plan for 2004 and RP306 is specifically tailored to the 12-survey plan for 2004, the 17-survey plan performs best in Figure 7-3 and the 12-survey plan performs best in Figure 7-4.

In conclusion, reductions in the number of sampling stations are less detrimental to the quality of the data for annual decision-making than are reductions in the number of surveys per year. Some stations are more predictive of the ideal nearfield chlorophyll value than other stations and, therefore, some station sets are more predictive than others of the same size. When assessing the merits of the 17-survey plan and the 12-survey plan for 2004, one must consider the appropriate reference period of interest.

7.2.4. Dissolved oxygen results

Analysis results for log-DO readings are presented in this section. Fixed temporal and spatial effects are addressed in Sections 7.2.4.1 and 7.2.4.2, respectively. The combined temporal-spatial correlation model for log-DO is presented in Section 7.2.4.3 and the information loss associated with reduced sampling strategies for log-DO is characterized in Section 7.2.4.4.

7.2.4.1. Fixed Temporal Effects for Log-DO

When the model of Section 7.2.2.1.1 was fitted, the terms related to a change in nonparametric seasonality effect at outfall diversion were found to be statistically insignificant, but the terms related to a nonparametric seasonality effect were strongly significant ($p<0.0001$). Subsequently, the model of Section 7.2.2.1.2 was fitted to the data to assess average log-DO levels, linear time trends in log-DO levels, and whether or not these effects changed at the time of outfall diversion. None of the fixed model effects related to change at outfall diversion were statistically significant. Further, only the fixed model effects related a parametric seasonality effect were found to be statistically significant. The resulting fitted model is

$$Y_t = 2.2123 - 0.00875 \sin(2\pi t) - 0.17750 \cos(2\pi t) - 0.05201 \sin(2\pi 2t) - 0.03063 \cos(2\pi 2t)$$

Equation 7-8

where the estimated variance associated with the fitted model is $\sigma^2=0.005662$ and the correlation coefficient of error terms for two surveys separated by 22 days is estimated to be $\rho=0.6326$.

The fixed effect parameter estimates imply that geometric average DO measurements consistently (from year to year) reach a maximum value of approximately 10.93 on a date near February 3 and a minimum value of approximately 7.28 on a date near September 24. The estimated variance implies that the ratio of the 97.5 percentile of DO measurements to the 2.5 percentile is approximately 1.34.

Figure 7-5 is a time-series plot of the geometric average dissolved oxygen values (dotted curve) versus survey date with the fitted model superimposed as a solid curve. The vertical dotted lines divide calendar years.

7.2.4.2. Fixed Spatial Effects for Log-DO

When the model of Section 7.2.2.2 was fitted to the survey-average-corrected log-DO values, the non-planar fixed effects were statistically insignificant, but the planar effects were found to be statistically significant ($p=0.05$). The resulting model for spatial fixed effects is

$$R_{it} = 0.01945 - 0.001432\, x_i - 0.001624\, y_i$$

Equation 7-9

Since the aerial extent of the nearfield sampling area is smaller than 11 km by 10 km (x-direction by y-direction), these parameter estimates imply that the above spatial fixed effect model accounts for less than a 3.3% change in DO values across the entire nearfield sampling area. Thus, while statistically significant, the above parameters may not be practically significant. Nevertheless, there appears to be a spatial fixed effect trend that produces maximum values in the southwest and minimum values in the northeast.

7.2.4.3. Combined Temporal-Spatial Correlation Model for Log-DO

Because statistically significant seasonality effects were identified in the dissolved oxygen data, the combined temporal-spatial correlation model of Section 7.2.2.3 (Equation 7-6) was fitted to the data with the temporal correlation parameter ρ being further parameterized to contain seasonality. Estimated parameter values for the log-DO correlation model are:

$\rho_0 = 0.7191$
$\rho_1 = -0.1064$
$\rho_2 = 0.0020$
$\rho_3 = -0.0649$
$\rho_4 = -0.0094$
$\gamma_0 = 0.8733$
$\gamma_1 = 0.02499$.

7.2.4.4. Evaluation of Reduced Sampling Strategies for Log-DO

Figure 7-6 to Figure 7-8 contain plots of correlation coefficients versus number of surveys performed per year. Plots for reference periods RP365, RP335, and RP306 are presented as Figure 7-6, Figure 7-7, and Figure 7-8, respectively. For each plot, there is a curve for the full set of all 21 stations as well as for each of the alternative station sets. The highest point in Figure 7-6 indicates that 17 surveys equally spaced throughout the year at all 21 stations produces an annual average DO value that has a 0.99 correlation coefficient with the true DO value obtained from all 365 daily DO surveys at all 21 stations.

The closeness of the curves for Station Sets 1, 2, and 3 to the curve for All Stations indicates that the DO data contains a high degree of spatial redundancy. If the stations were producing independent DO data, one would expect a reduction from 21 to just 4 sampling stations (Station Sets 2 or 3) to decrease the correlation coefficient by more than a factor of two $[(21/4)^{1/2}]$. High correlation coefficients are maintained for these station sets because of the high spatial correlation between readings at the eliminated stations and readings at the included stations. Note that the DO data, while having a high degree of spatial redundancy, does not exhibit quite as much spatial redundancy as does the chlorophyll data.

Temporal redundancy would exhibit itself in the plots in the form of flat curves, and there is strong evidence of such redundancy in the DO data. For example, if the individual surveys produced independent data, then a switch from 17 to four (4) surveys per year would cause the correlation coefficient to decrease by more than a factor of two $[(17/4)^{1/2}]$. For the DO data, the correlation decreases by less than a factor of 1.2. The temporal redundancy is stronger in the DO data than it is in the chlorophyll data, but still is not as strong as the spatial redundancy. Thus again, slightly more modest reductions in the number of surveys per year must be considered if high correlation coefficients are to be maintained.

As with the chlorophyll data, contrasting the lower two curves gives an indication of the degree to which individual stations correlate with the true DO parameter value. DO values from Station 21 correlate much better with the true value than do values from Station 01. This is because Station 21 is in the center of the region of interest and, therefore, somewhat better correlated with all the sampling stations in the nearfield. In contrast, Station 01 is at the northwest extreme of the nearfield and is much less correlated with the southern and eastern sampling stations.

The correlation plot can be used to relate the effects of reductions in the number of stations and surveys per year. For example, a spatial reduction to the four stations in Set 2 with 17 surveys per year would produce similar results as a temporal reduction to 8 surveys per year at all 21 stations. In a similar fashion, an extreme spatial reduction to Station 21 surveyed 17 times per year would produce similar results as 5 surveys per year performed at the four stations in Set 3.

The individual points plotted in Figure 7-6 to Figure 7-8 illustrate the correlations for 17 and 12 surveys conducted under the current plan for 17 surveys in 2004 and under the proposed plan for conducting 12 surveys in 2004. Specific survey dates are used for these correlation calculations. Since reference period RP335 is specifically tailored to the 17-survey plan for 2004 and RP306 is specifically tailored to the 12-survey plan for 2004, the 17-survey plan performs best in Figure 7-7 and the 12-survey plan performs best in Figure 7-8.

In conclusion, reductions in the number of sampling stations are less detrimental to the quality of the data for annual decision-making than are reductions in the number of surveys per year, although there is less of a difference in this regard for DO than there is for chlorophyll. As with chlorophyll, some stations are more predictive of the ideal nearfield DO value than other stations and, therefore, some station sets are more predictive than others of the same size. This station set effect is larger for DO than it is for chlorophyll. Again, as with chlorophyll, when assessing the merits of the 17-survey plan and the 12-survey plan for 2004, one must consider the appropriate reference period of interest.

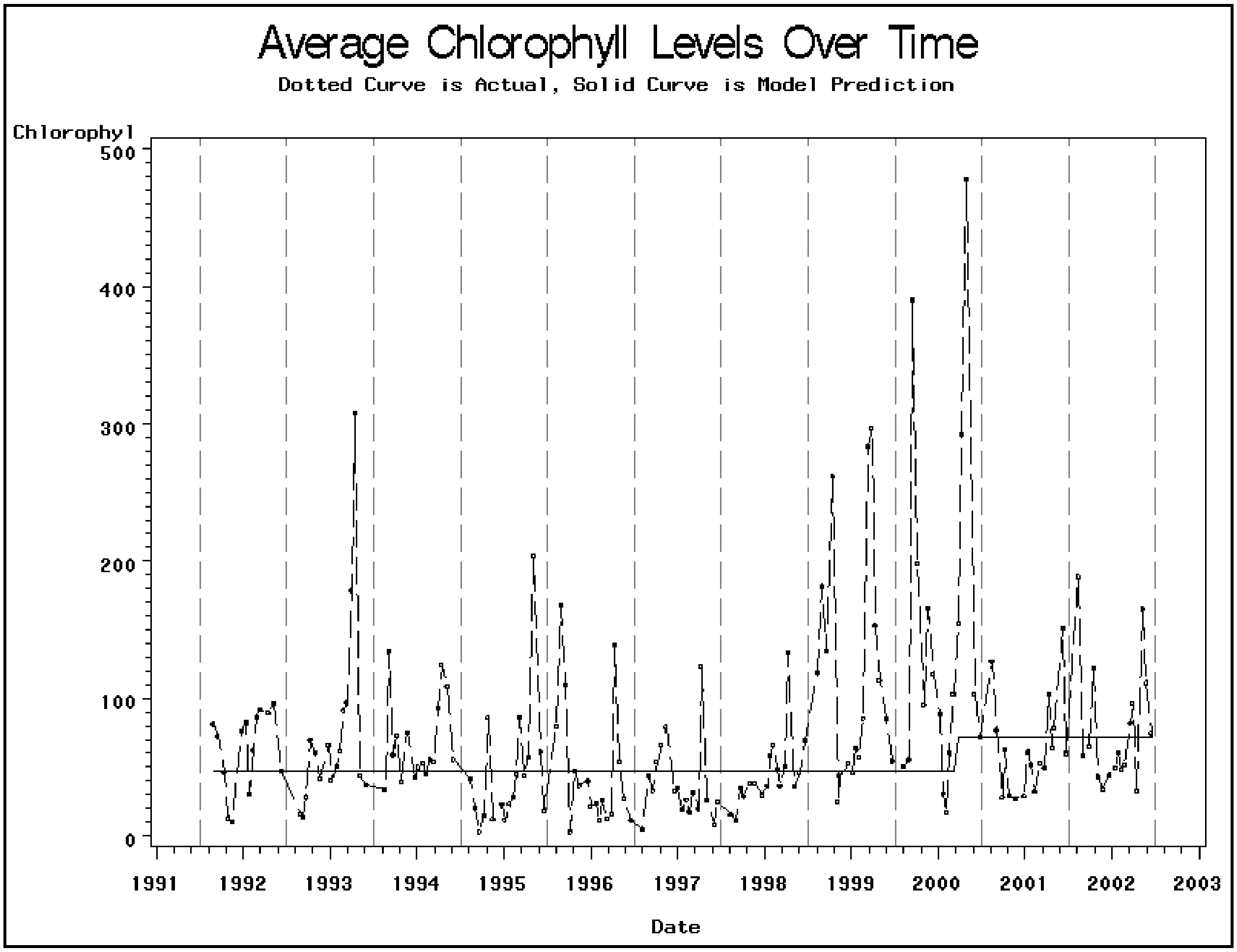


Figure 7-1 Average Chlorophyll Levels Over Time with Model Predictions

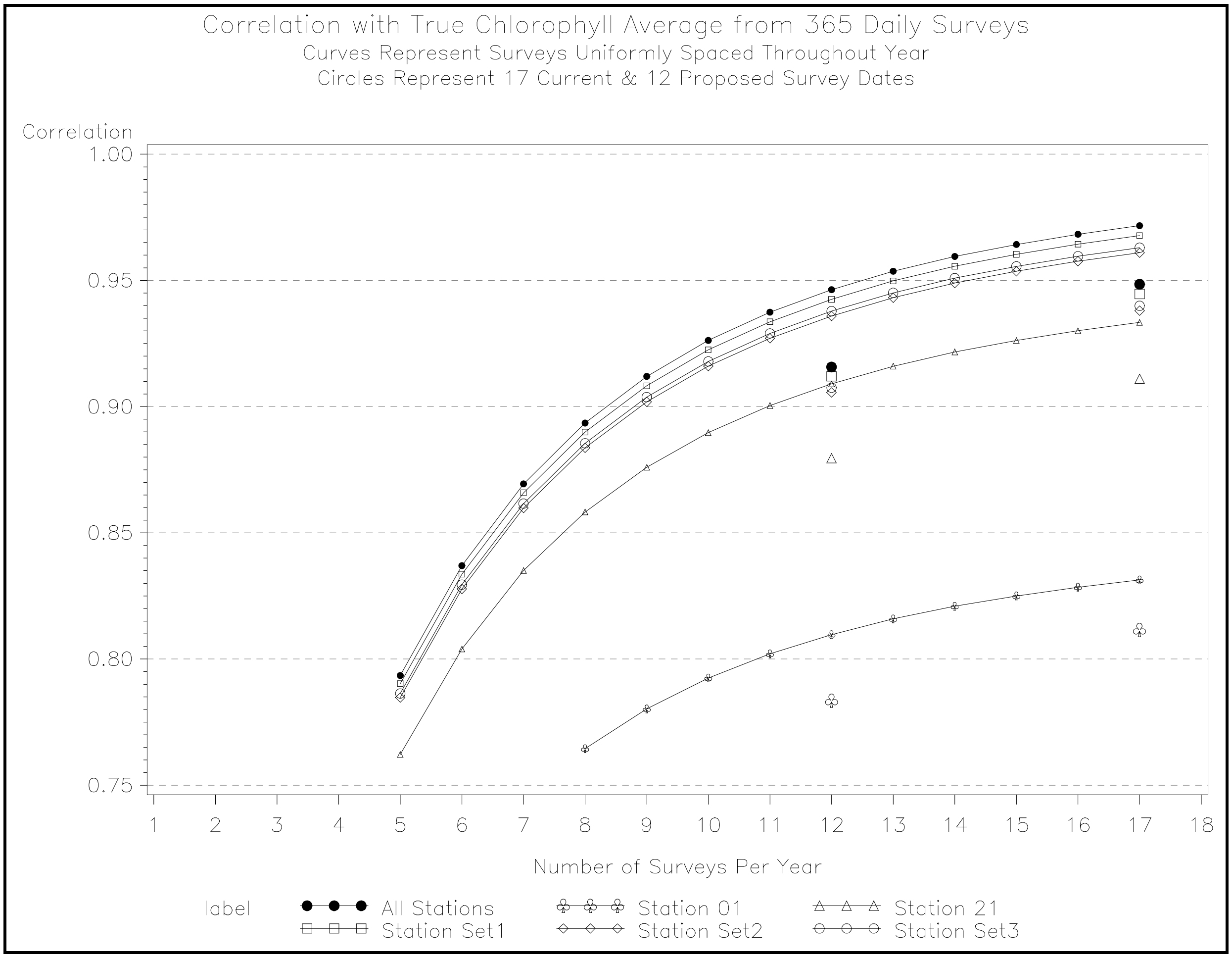


Figure 7-2 Correlation with Annual Chlorophyll Average from Daily Surveys in Reference Period RP365

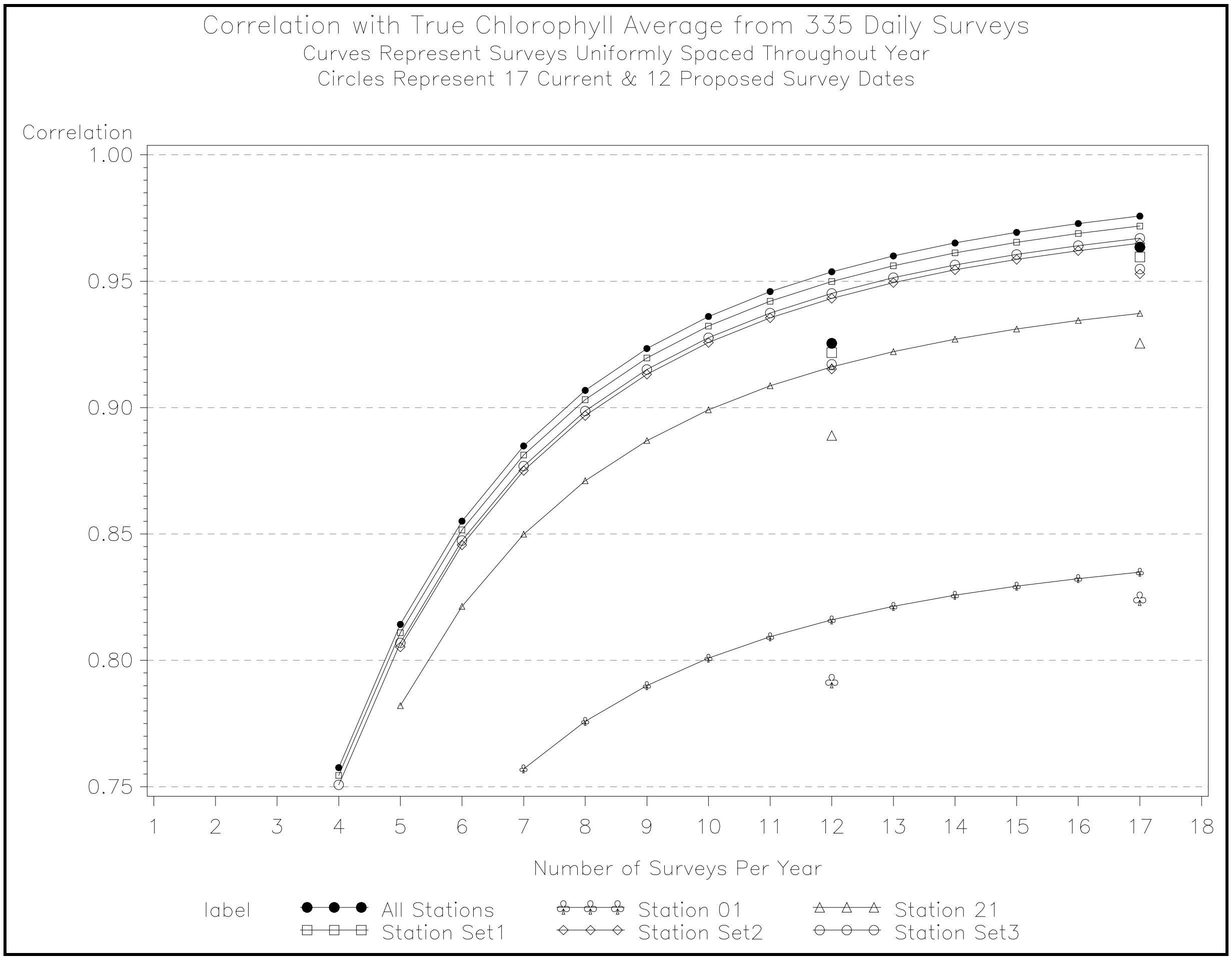


Figure 7-3 Correlation with Annual Chlorophyll Average from Daily Surveys in Reference Period RP335

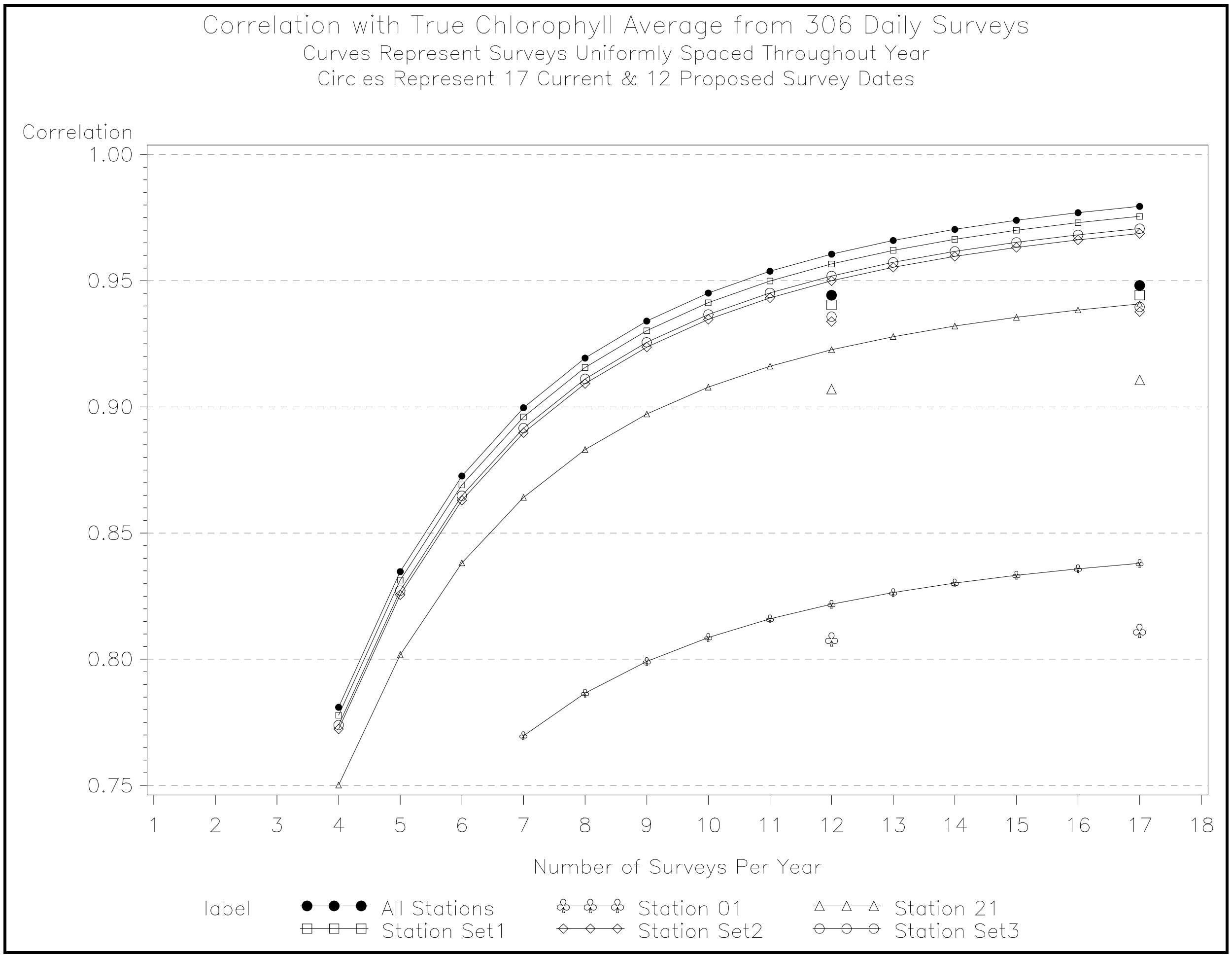


Figure 7-4 Correlation with Annual Chlorophyll Average from Daily Surveys in Reference Period RP306

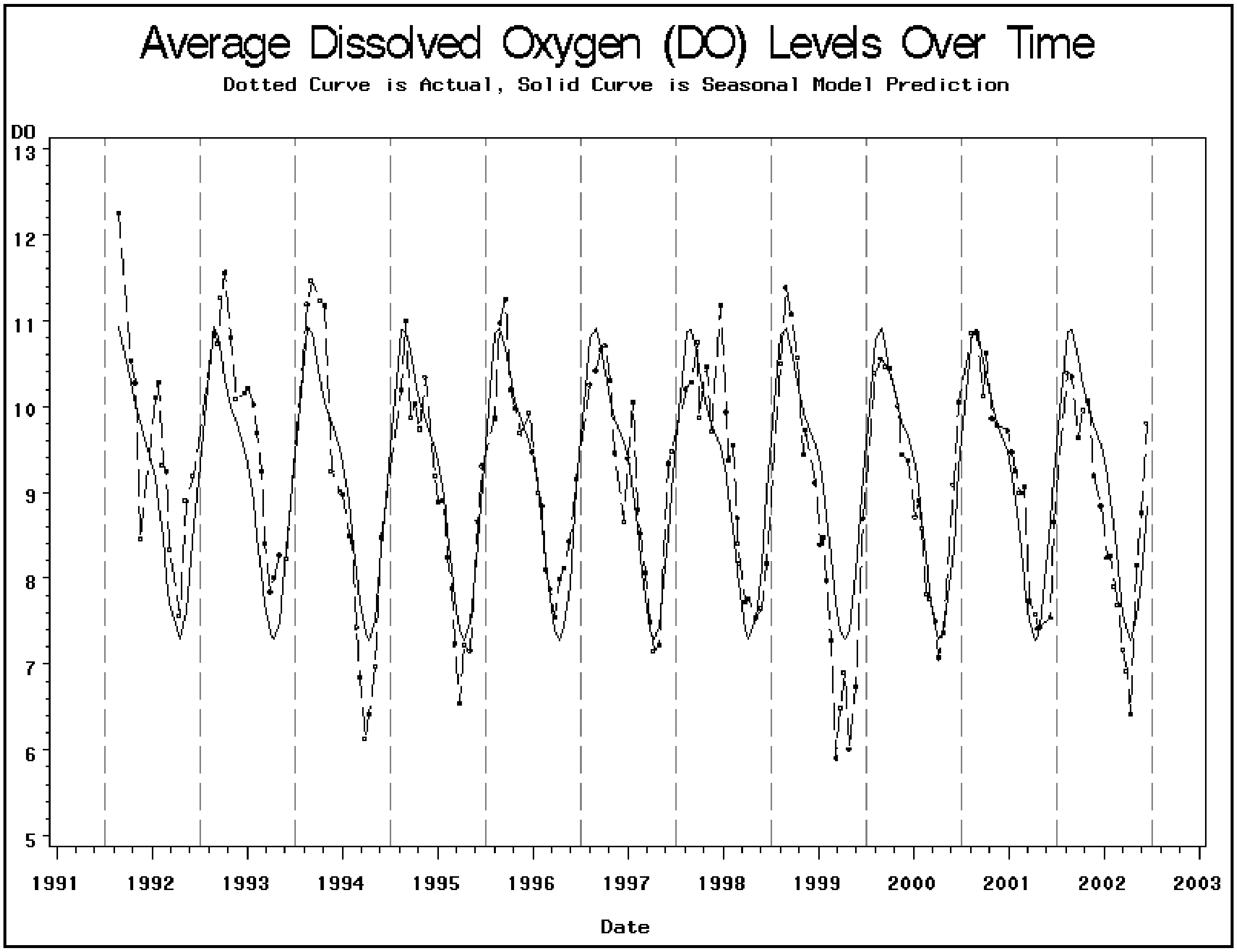


Figure 7-5 Average Dissolved Oxygen Levels Over Time with Model Predictions

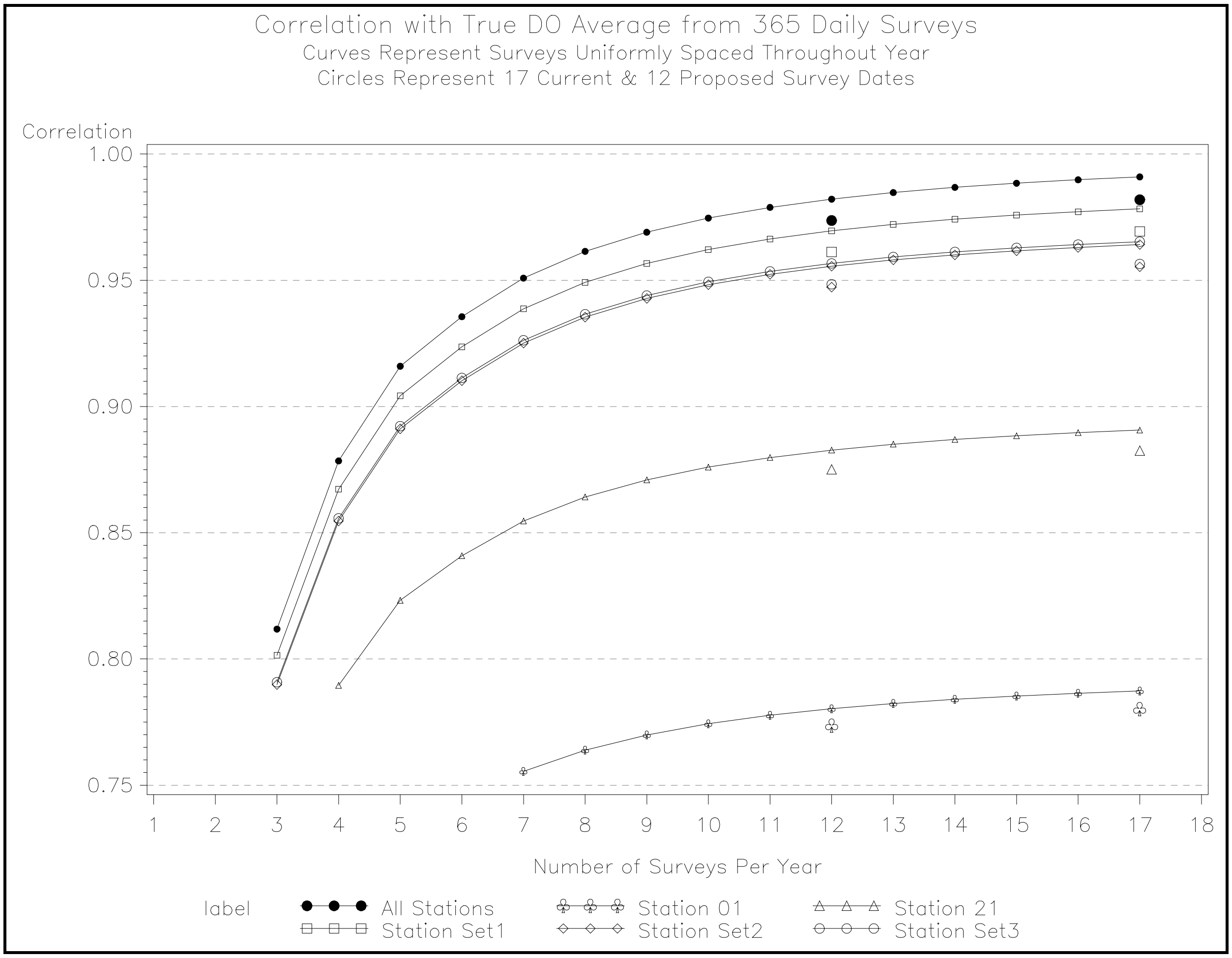


Figure 7-6 Correlation with Annual DO Average from Daily Surveys in Reference Period RP365.

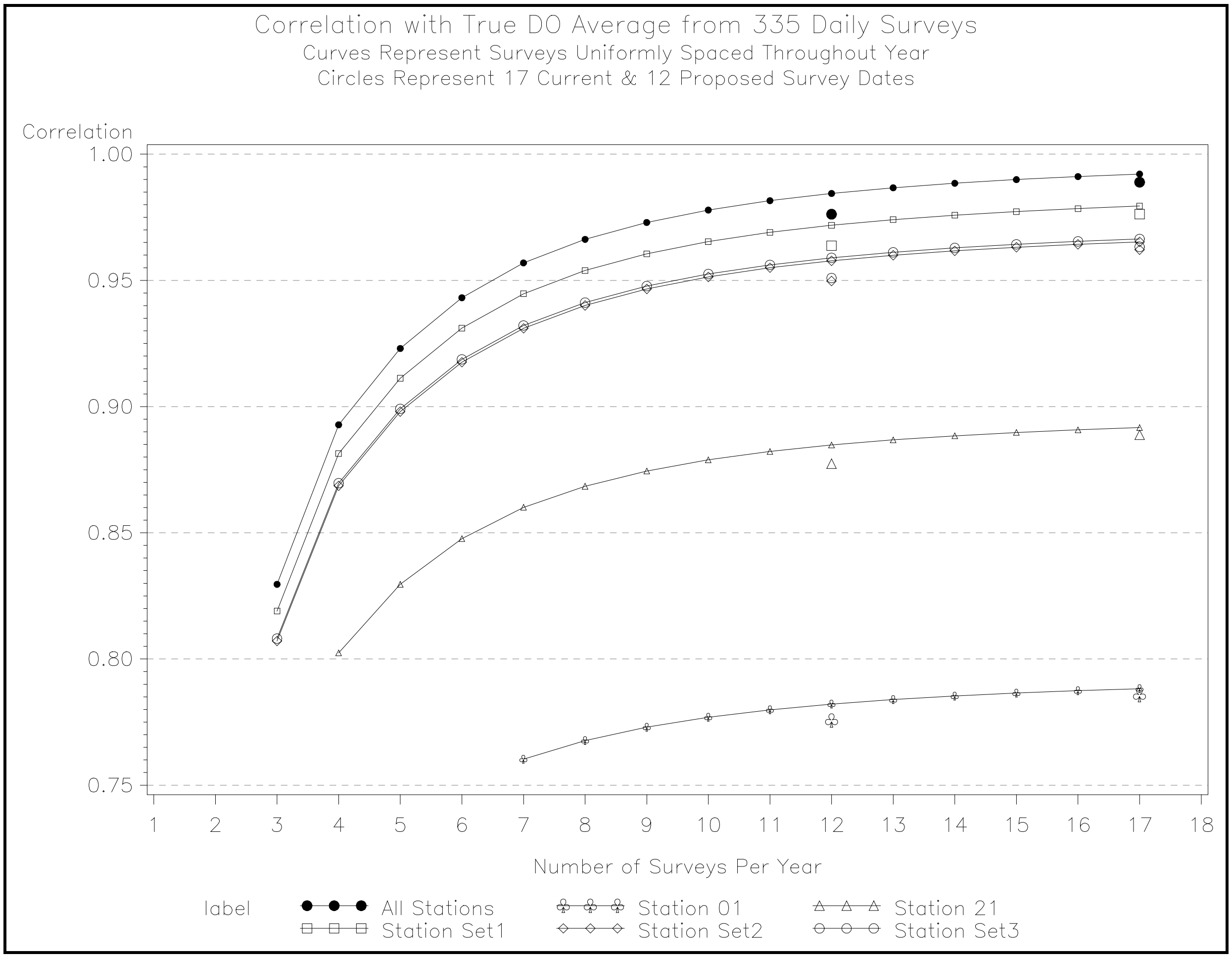


Figure 7-7 Correlation with Annual DO Average from Daily Surveys in Reference Period RP335

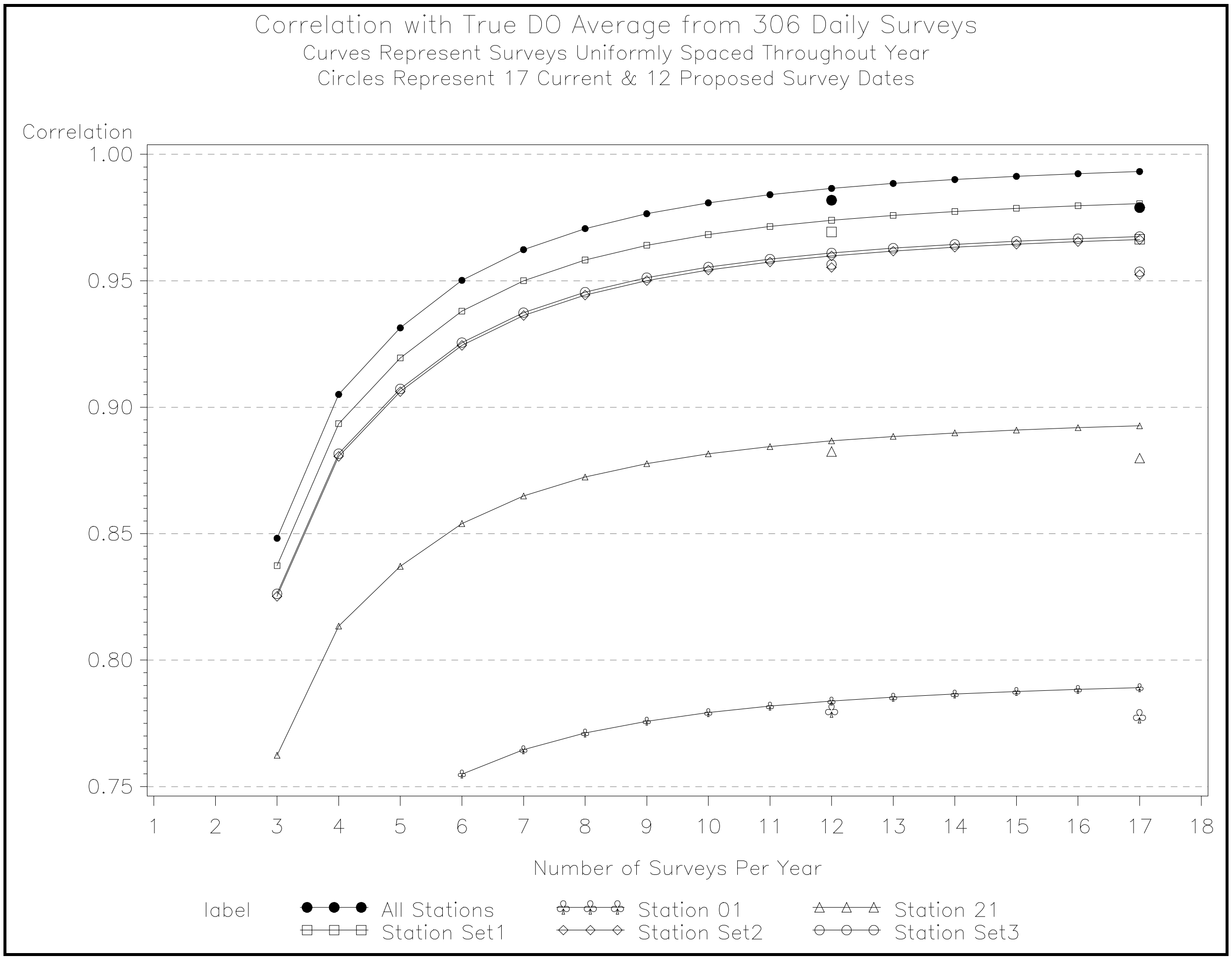


Figure 7-8 Correlation with Annual DO Average from Daily Surveys in Reference Period RP306

7.3. Empirical approach - spatial analysis: effect of reducing numbers of nearfield stations on the survey means of four key parameters

While the mixed model regression approach detailed in Section 7.2 was in planning and underway, we carried out a series of complementary evaluations. We tested the effects of three scenarios of station reduction in the nearfield on survey means for areal chlorophyll, bottom dissolved oxygen, ammonium, and nitrate+nitrite. For chlorophyll and DO, these evaluations were intended to be redundant with the regression modeling, both as a semi-independent check (seeing if we got equivalent results using a simpler approach) and as backup in the event the regression modeling was unsuccessful. Additionally, these analyses supplement those in Section 7.2 by evaluating the impact of station reductions on parameters (ammonium and nitrate/nitrite) not modeled there.

In the evaluations in this Section 7.3 we focused on the ability of reductions in the number of nearfield stations to reproduce the survey means determined from the full 21-station nearfield design. The survey mean is the major statistic used for calculating contingency plan thresholds and identifying trends. If the current nearfield station array is heavily over-sampled and/or the data contain significant spatial autocorrelation, reducing the numbers of stations should not change the survey means very much. If there is neither over-sampling nor spatial autocorrelation, reducing the number of stations used to calculate a survey mean would cause those means to vary from the 21-station nearfield means.

Preliminary work in January indicated that chlorophyll survey means for the subset of 7 "other nutrient" stations compared very well to the full station set, so we did not evaluate any larger station subsets.

We compared three subsets of stations to the full set of 21 stations, which are marked on Figure 7-9 as solid circles:

(1) Seven stations. This subset drops all "hydrocast and inorganic nutrients only" stations and retains all stations at which organic nutrient and other analyses are currently carried out. It includes four stations at the four corners of the nearfield and three stations at the center of the nearfield (blue empty circles on Figure 7-9)
(2) Three stations. This subset includes N01 and N07 at the northwest and southeast corners of the nearfield, and N20 just west of the outfall (red squares on Figure 7-9).
(3) One station. This subset included only N20 (purple hexagon on Figure 7-9).

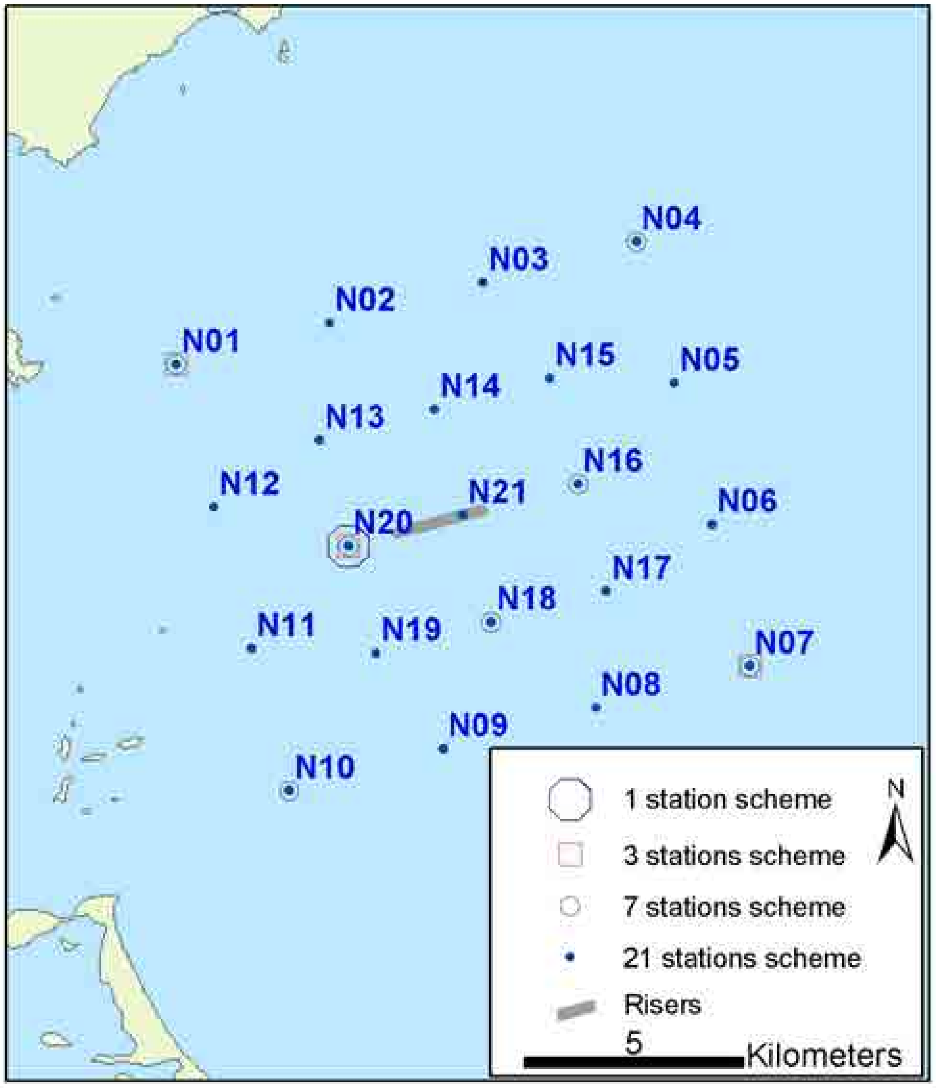


Figure 7-9 Map of nearfield with some reduced station scenarios evaluated in Section 7.3, including the 7-station subset proposed by MWRA.

Table 7-3 Types of samples collected at each station in existing program and in station subsets evaluated. Shaded cells = no measurements.

Station	Existing program (21 stations)		7 station subset		3 station subset		1 station subset	
	Hydro-cast and dissolved inorganic nutrients	Other nutrients	Hydro-cast and dissolved inorganic nutrients	Other nutrients	Hydro-cast and dissolved inorganic nutrients	Other nutrients	Hydro-cast and dissolved inorganic nutrients	Other nutrients
N01	Y	Y	Y	Y	Y	Y		
N02	Y							
N03	Y							
N04	Y	Y	Y	Y				
N05	Y							
N06	Y							
N07	Y	Y	Y	Y	Y	Y		
N08	Y							
N09	Y							
N10	Y	Y	Y	Y				
N11	Y							
N12	Y							
N13	Y							
N14	Y							
N15	Y							
N16	Y	Y	Y	Y				
N17	Y							
N18	Y	Y	Y	Y				
N19	Y							
N20	Y	Y	Y	Y	Y	Y	Y	Y
N21	Y							

For each station subset and for the full dataset, we calculated the survey means for all nearfield surveys to date (February 1992 to December 2002). The effect of station reduction on the means was evaluated qualitatively and quantitatively using graphical comparisons and statistics. Depth was treated differently for different parameters. Areal chlorophyll is based on a depth-integrated average; there is only one mean per survey. Bottom water dissolved oxygen is calculated at one depth. Survey means for ammonium and nitrate+nitrite were calculated and evaluated separately for each of the five depths at which those samples are collected (bottom, near-bottom, midwater, near-surface and surface).

7.3.1. Areal chlorophyll

The distributions of the survey means from the four scenarios of sampling stations for the four parameters are compared using box plots. Figure 7-10 shows that the distributions of the survey means of areal chlorophyll, including the median (the line inside the box), the range of the middle half of the data, and the length of whiskers, and the outliers, are similar across the four scenarios of sampling stations The deviations of the survey means of reduced stations from N=21 stations are shown in bivariate plots. The Kolmogorov-Smirnov Goodness-of-Fit test shows that the survey means from all 3 subsets have the same distribution as means from the all stations. Figure 7-11 shows that survey means of area chlorophyll from N= 21 stations correspond to the means from the subsets of 7, 3, and 1 stations. The reference line is one-to-one ratio of survey means from N=21 stations. While the correspondence is close for all subsets, as the number of stations in a subset decreases the deviation of survey means from those for the full dataset increases. For example, the percentages of subset survey means that differ by more than 20% from those of the current survey means (N= 21) increases from 4% for N=7, to 14% for N=3, to 44% for N=1. [Appendix D breaks this analysis into two time periods - before and after diversion of flow to the new outfall.]

7.3.2. Dissolved oxygen

Both box and bivariate plots of the survey means of bottom dissolved oxygen show a close agreement of survey means between current and reduced sampling stations (Figure 7-12 and Figure 7-13). The data distributions from the four scenarios of sampling stations are the same, according to the Kolmogorov-Smirnov test. A frequency distribution analysis of the deviation of survey means (see Appendix C) shows that 98% or more of survey means for all subsets differ by less than 10% of current means.

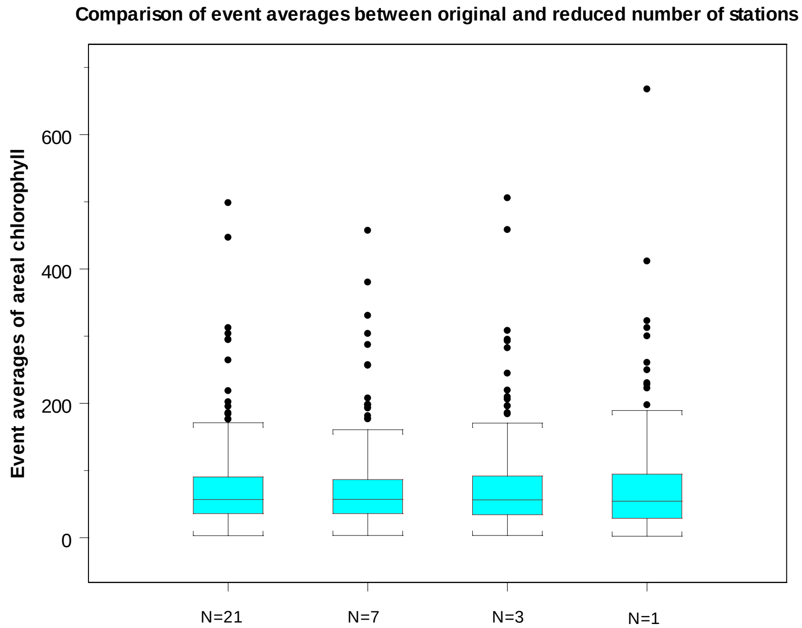


Figure 7-10 Distributions of survey means of areal chlorophyll (mg/m2) for all nearfield stations and the three subsets evaluated.

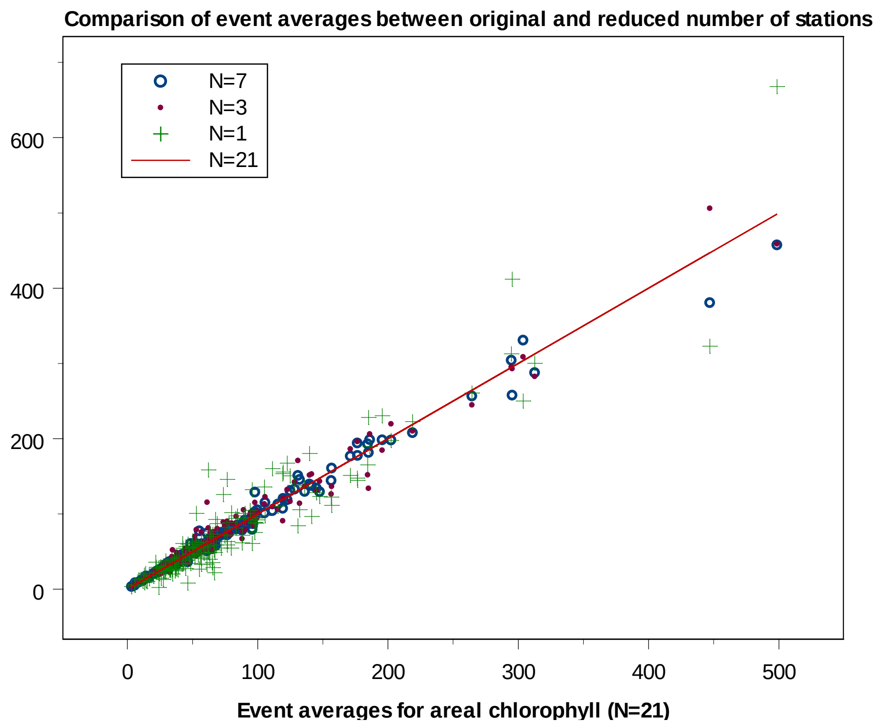


Figure 7-11 Scatterplot of subset survey means of areal chlorophyll compared to those from all nearfield stations.

The red line is one-to-one ratio of the survey means from all nearfield stations (N=21).

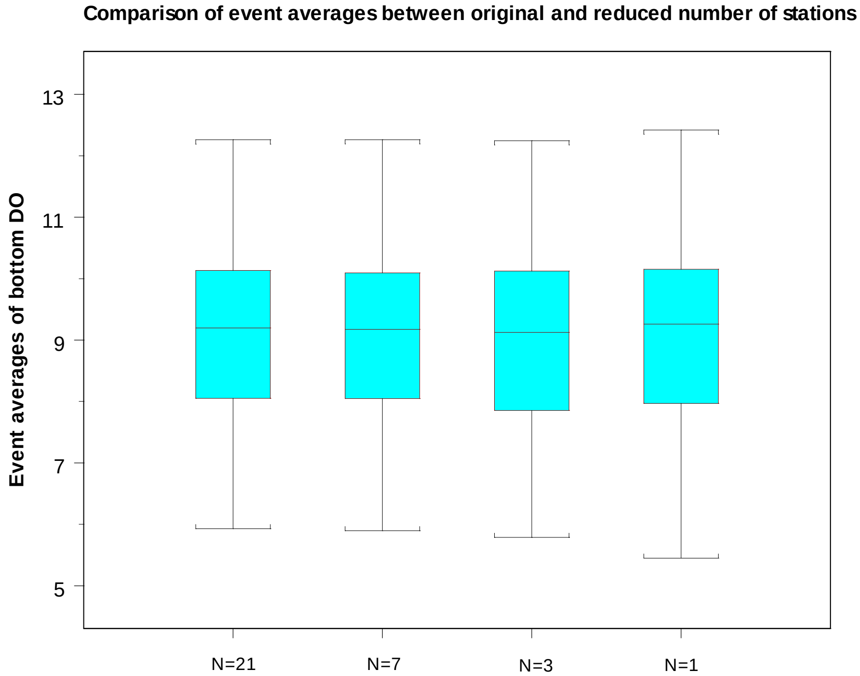


Figure 7-12 Distributions of survey means of bottom dissolved oxygen (mg/L) all nearfield stations and the three subsets.

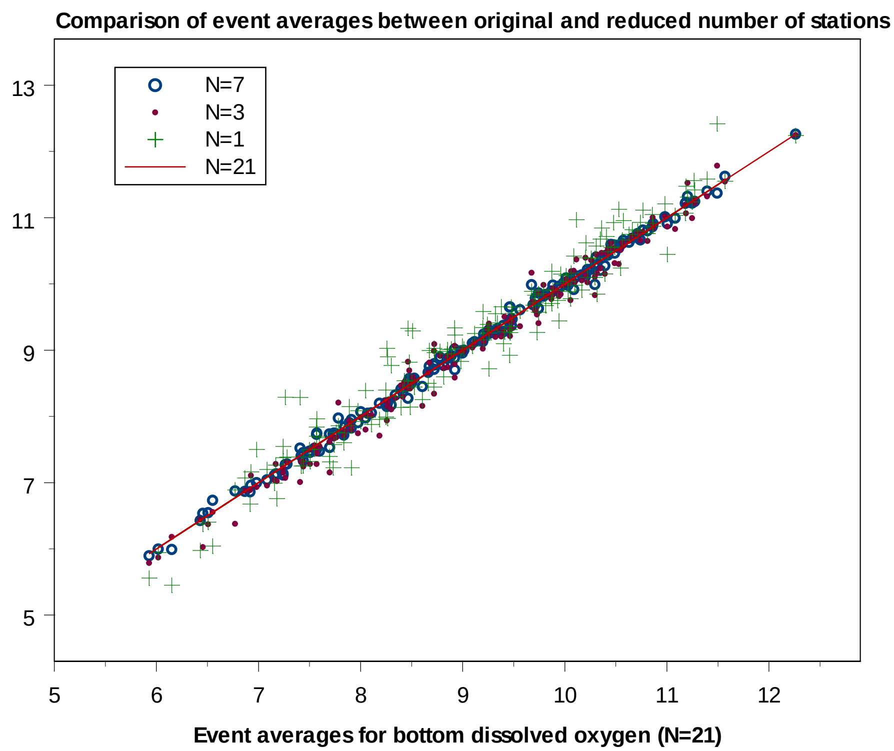


Figure 7-13 Comparison of subset bottom water dissolved oxygen survey means to those from all nearfield stations.

The red line is one-to-one ratio of the survey means from all stations (N=21).

7.3.3. Ammonium and nitrate+nitrite

We evaluated the effect of station reduction on the survey means at each of five discrete depths (surface, mid-surface, mid, mid-bottom, and bottom depth) for ammonium and nitrate plus nitrite. Deviation of the survey means from the N=21 stations increases as the number of stations decreases, as shown in the box and bivariate plots (Figure 7-14 to Figure 7-17). The data distributions from the sampling stations of N=7 for ammonium and nitrate/nitrite are the same as N=21 across all five depths, according to the Kolmogorov-Smirnov test. However, the scatter become more pronounced in all depths as the station reduction increases. The percentage of ammonium survey means differing by less than 20% from current means decreases from 49 % for N=7, 34% for N=3, and 22% for N=1 at the surface depth. The percentage of survey means for nitrate/nitrite differing less than 20% of current means decreases from 62% for N=7, 49% for N=3, and 41% for N=1 at the surface depth. The deviations in survey means decrease for all subsets as the depth increases for both ammonium and nitrate/nitrite (see Appendix C.)

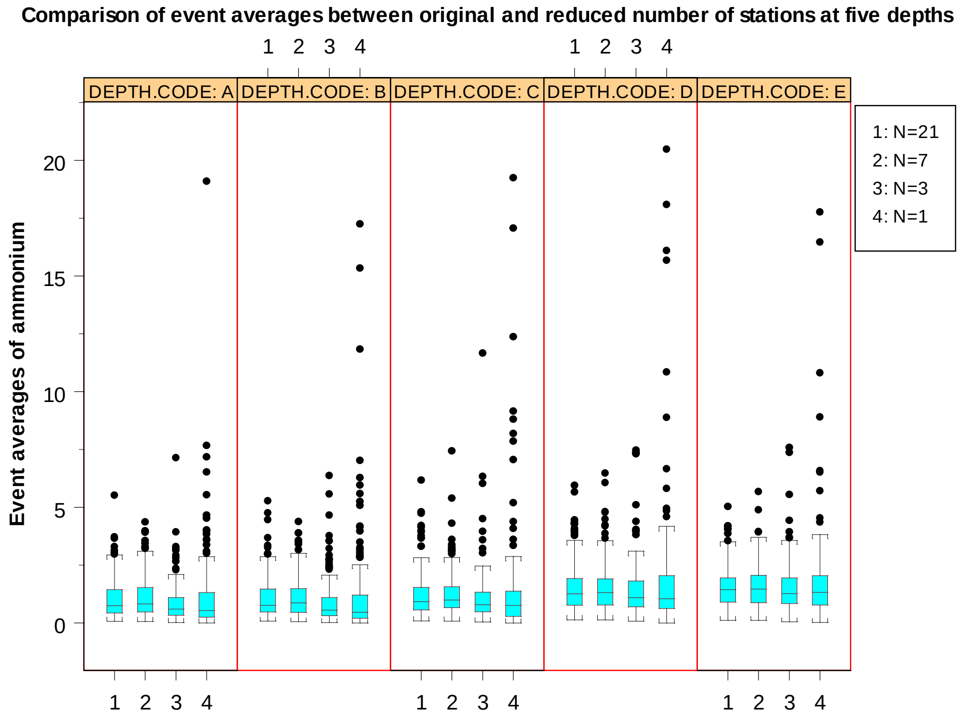


Figure 7-14 Distributions of survey means of ammonium (micromolar) for four scenarios of sampling stations.

Depth code A, B, C, D, E, denote surface, near-surface, midwater, near-bottom, and bottom depth, respectively.

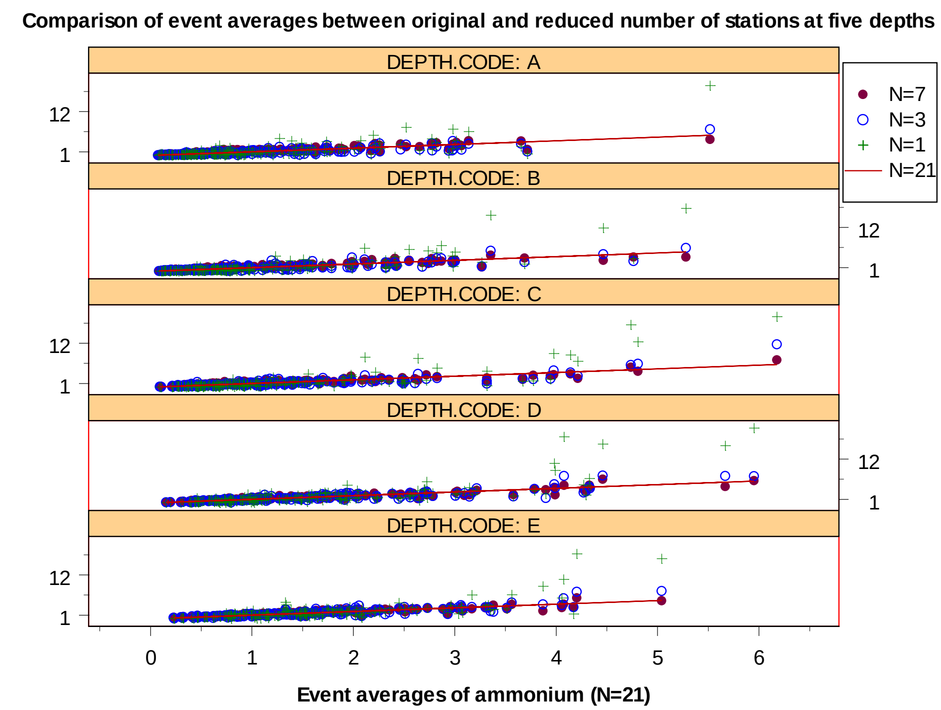


Figure 7-15 Correlation of subset ammonium survey means to those from current 21 sampling stations.

The red line is one-to-one ratio of the survey means from N=21. Depth code as above.

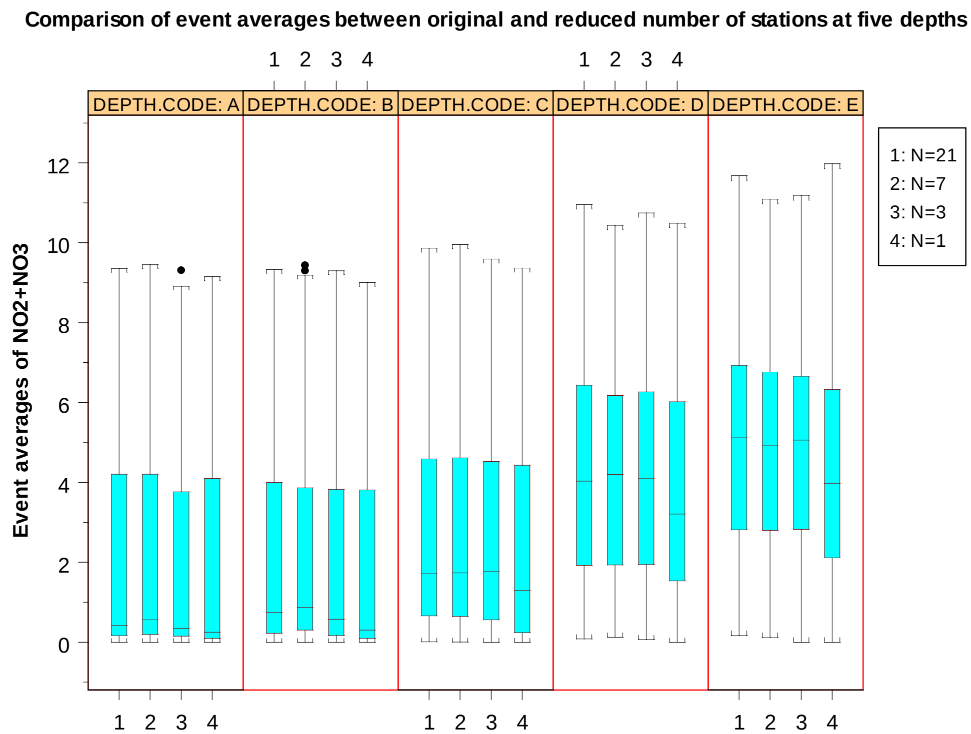


Figure 7-16 Distributions of survey means of nitrate plus nitrite (micromolar) for all stations and the 3 subsets.

Depth code A, B, C, D, E, denote surface, near-surface, midwater, near-bottom, and bottom depth, respectively.

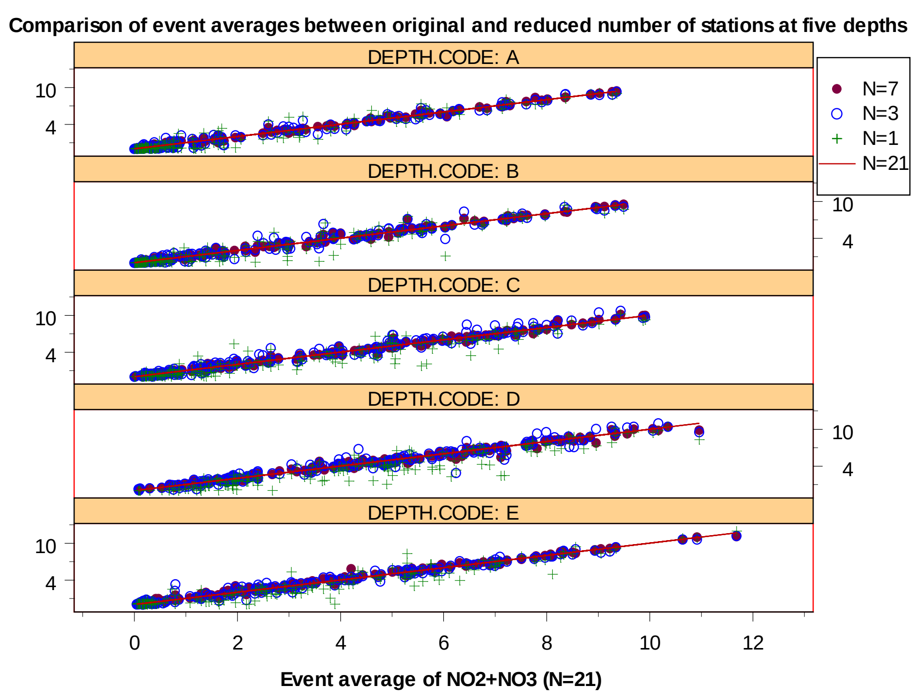


Figure 7-17 Correlation of subset nitrate+nitrite survey means to those from current 21 sampling stations.

The red line is one-to-one ratio of the survey means from N=21. Depth code as above.

As would be expected from the scatterplots, survey means for the full 21-station dataset are strongly correlated with those for the subsets evaluated in this section (Table 7-4). For all parameters and depths evaluated, Pearson's correlation coefficients between the full station set and the proposed 7-station subset are greater than 0.90 ($r > 0.99$ for all parameters except ammonia).

Summary of spatial analysis. The effect of station reduction on the distribution and deviation of survey means for areal chlorophyll, bottom dissolved oxygen, ammonium, nitrate/nitrite are similar in term of general trend. The proposed subset of 7 stations has minimal effect on the distribution and deviation of survey means. As the number of sampling station decreases, the discrepancy in data distribution and mean deviation from full station set increases. Among parameters, the survey means of areal chlorophyll and bottom dissolved oxygen are less sensitive to station reduction than are those for ammonium and nitrate+nitrite. For the nutrients, the effect of station reduction seems to be greater at the surface or mid-surface depth than the lower depth.

Table 7-4 Correlation coefficients between nearfield survey means for the current design (21 stations) and subsets of 7, 3, and 1 station

Parameter/	Station Subset		
depth	7	3	1
Areal chlorophyll	0.993	0.985	0.941
Bottom DO	0.998	0.993	0.978
Ammonium			
Surface	0.908	0.817	0.712
Near-surface	0.916	0.845	0.757
Midwater	0.915	0.833	0.785
Near-bottom	0.929	0.875	0.759
Bottom	0.914	0.864	0.710
Nitrate/Nitrite			
Surface	0.996	0.991	0.983
Near-surface	0.996	0.987	0.968
Midwater	0.993	0.976	0.941
Near-bottom	0.993	0.975	0.942
Bottom	0.990	0.975	0.919

These evaluations, and the statistical modeling results carried out in Section 7.2, document that even after reducing the numbers of nearfield stations by two-thirds (14 stations) the proposed 7-station nearfield subset retains detectable oversampling and/or spatial autocorrelation in the parameters modeled. Despite this, we believe retaining a level of spatial redundancy in the nearfield is appropriate until additional years' of discharge data are available for evaluation. The 7-station subset retains all organic nutrient, TSS, plankton, respiration, and primary productivity stations, so survey means for these parameters and parameters derived from them (like total nitrogen) would be unaffected.

7.4. Empirical approach - temporal analysis: effect of reducing numbers of surveys.

The understanding of natural processes in the bays enables us to determine the time-frames within which natural processes occur. Thus, we can prioritize nearfield surveys to ensure that we capture the important events relative to possible outfall effects. From the survey-rationale list at the end of section 3, nearfield surveys should measure at least chlorophyll, nutrient and plankton levels during the winter/spring and fall blooms and during the summer, and stratification and dissolved oxygen at the beginning and end of the summer including the fall dissolved oxygen minimum.

The analyses in Section 7.2 suggest that a nearfield monitoring design consisting of the 7-station design with 12 surveys per year should generate annual chlorophyll means that correlate with those from the full 17-survey design with $r > 0.9$ (Figure 7.2).

In this section, we describe the effects of reducing the number of surveys on two threshold parameters (areal chlorophyll seasonal means, and dissolved oxygen minimum) from seventeen to twelve times per year. All analyses assume seven nearfield stations for these measurements as described above. We evaluate the sensitivity of this proposal to the timing of the twelve surveys and to the number of nearfield stations, and examine the effects of reducing the number of surveys further. Finally, we check the effects of the proposed survey set on the results for other parameters of interest.

All the analyses assumed that the surveys would be chosen from among the seventeen presently sampled (Table 7-5). To ensure that the important events mentioned above are captured, however, our proposal shifts the target dates of a few of remaining surveys by several days. In practice, weather and other operational considerations frequently result in surveys taking place up to two weeks from their target date. Thus, the results of the analysis of twelve surveys from the existing set should apply even if the dates are shifted slightly.

7.4.1. Proposed survey schedule

The proposal drops surveys in late April, early July, early August, late November, and mid-December, but shifts the date of other surveys to better cover the gaps. Specifically, the April 1 survey is shifted later one week, and the autumn surveys are spread out to a three-week period between them to cover October – mid-November (Table 7-5)

Table 7-5 Rationale for surveys retained in MWRA's proposal

Survey number	Survey date	Rationale
1	Early February	Combined with farfield survey. Capture the winter/spring bloom - peak chlorophyll, productivity, phytoplankton abundance.
2	Late February	Combined with farfield survey. Capture the winter/spring bloom - peak chlorophyll, productivity, phytoplankton abundance.
3	Mid-March	Have observed peak of *Phaeocystis* blooms at this time.
4	Early April	Combined with farfield survey. Shifted later by one week to characterize April.
6	Mid-May	Only need one survey in late April through May because low chlorophyll, DO is still high, surface nutrients already depleted. Other studies measure *Alexandrium* better.
7	Mid-June	Combined with farfield survey. Mid-June, late July, mid-August surveys sufficient to track rate of DO decrease, low chlorophyll and surface nutrients.
9	Late July	Mid-June, late July, mid-August surveys sufficient to track rate of DO decrease, low chlorophyll and surface nutrients.
11	Mid-August	Combined with farfield survey. Mid-June, late July, mid-August surveys sufficient to track rate of DO decrease, low chlorophyll and surface nutrients.
12	Early September	Characterize the fall bloom and associated peaks in chla, POC, phytoplankton, and production and capture the DO minimum. Conduct each of the autumn surveys 3 weeks apart.
13	Late September	Characterize the fall bloom and associated peaks in chla, POC, phytoplankton, and production and capture the DO minimum. Conduct each of the autumn surveys 3 weeks apart.
14	Mid-late October	Combined with farfield survey. Characterize the fall bloom and associated peaks in chlorophyll, POC, phytoplankton, and production and capture the DO minimum. Conduct each of the autumn surveys 3 weeks apart.
15	Mid-November	Characterize well-mixed winter conditions.

Rationale for proposed survey schedule

Surveys 1, 2, and 4 characterize the winter/spring bloom, including chlorophyll, peak production, and peak phytoplankton abundance. A fourth spring survey does not appear to be critical to characterizing the spring bloom, however, having four winter/spring surveys makes it more likely that transient *Phaeocystis* blooms will be observed. Thus, our proposal keeps the mid-March survey and moves the fourth survey slightly later in April.

Chlorophyll has usually decreased sharply by late April and May; the water column is becoming more stratified, but DO is still high. Nutrients are usually depleted in surface waters due to the earlier bloom. Although this is the season when *Alexandrium* blooms have been observed, other studies (Anderson *et al.* 2002, Division of Marine Fisheries seasonal PSP monitoring) use more appropriate techniques to capture any likelihood of PSP toxicity.

Data from the three summer surveys (8, 9, and 10) are quite consistent. Although bottom water dissolved oxygen is decreasing, it demonstrates a fairly uniform rate of decline across the summer and can be adequately captured by a mid-June, late July, mid-August sequence. Chlorophyll is generally low all summer, nutrients remain depleted in surface waters. Sporadic upwelling or mixing events have been noted in the past, but the availability of mooring and satellite data should capture these better than the existing four July/August surveys.

Data from the four autumn surveys (12, 13, 14, and 15) characterize the fall bloom and associated peaks in chlorophyll, POC, phytoplankton, and production, and capture the oxygen minima. The oxygen minimum has occurred in the nearfield from as early as 9/8 (1999) and as late as 11/4 (1998). There appears to be interannual differences in the pattern of dissolved oxygen decline and rebound during the fall. The proposed schedule keeps all four surveys, but reschedules them such that they occur every three weeks, pushing the 15th survey into mid-November.

The water column in the nearfield has usually returned to well mixed conditions by November (which will be described by the 15th survey). Winter nutrient conditions in some years are not achieved until the period of most intense storm activity in late December to early February. Thus, the first survey of the year (early February) should characterize the initial conditions for the spring bloom.

Twelve surveys, seven stations – chlorophyll seasonal mean

In this section, we examine whether the 12-survey schedule reproduces the nearfield mean chlorophyll, which is used to calculate the seasonal and annual thresholds.

Figure 7-18 shows the nearfield areal averaged chlorophyll for each survey in the full data set and the proposed 12-survey subset. The 12-survey set captures most of the features in the chlorophyll data observed in 1992-2002.

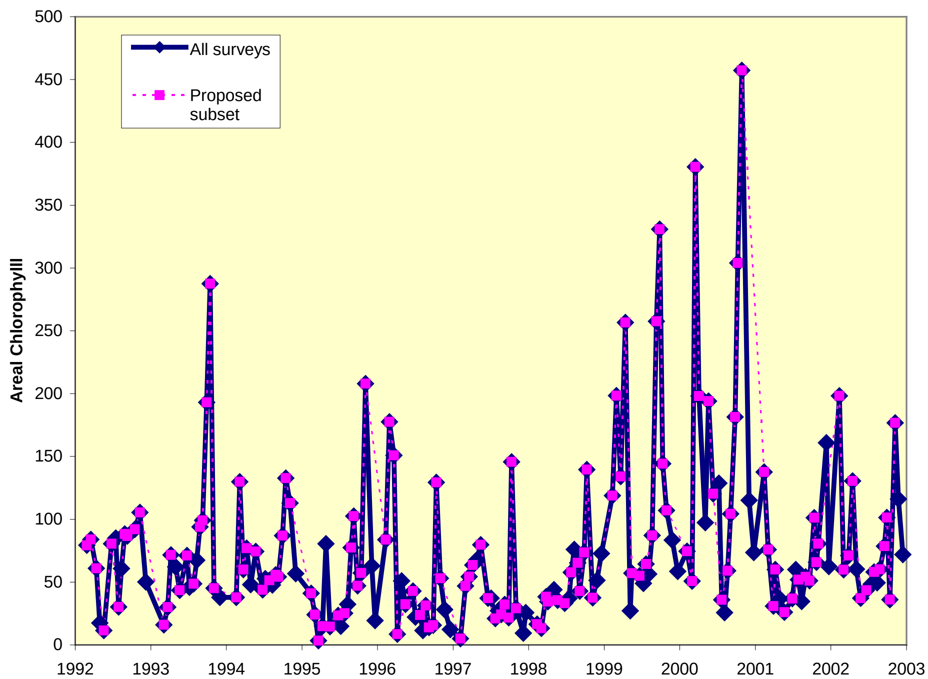


Figure 7-18 Time series of survey means for the whole dataset and for the proposed 12-survey subset (7 station means).

Figure 7-19 shows the seasonal means calculated from those survey means. Seasons are defined as for threshold testing (January-April, May-August, September-December.) Figure 7-20 is a scatterplot of seasonal means for the proposal compared to those for all surveys. The 1:1 line for seasonal means based on all surveys is also plotted.

The proposed survey subset overpredicts some of the highest seasonal means we've seen. Most of these are fall seasonal means for 1993, 1999, and 2000. By leaving off the last two surveys per year, by which time blooms have normally declined, autumn chlorophyll means for the proposal are predictably higher than those of the full 17-survey dataset. Therefore, if this reduced subset of 12 surveys/year is adopted beginning in 2004, MWRA will recalculate the baseline for autumn seasonal mean chlorophyll and the resulting threshold based on the 12-survey subset rather than the existing 17.

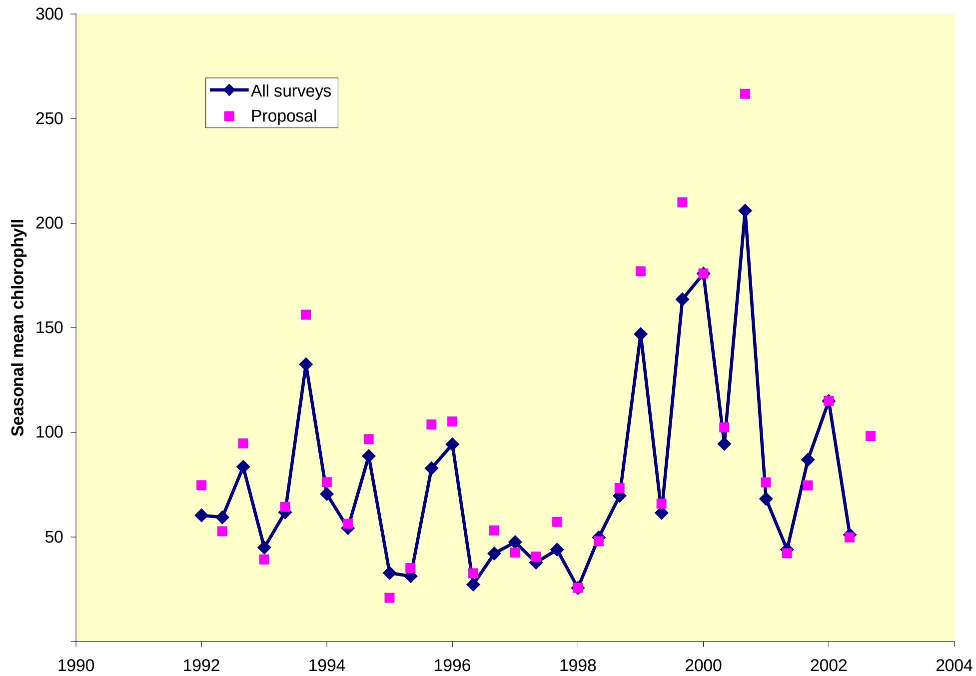


Figure 7-19 Timeline of seasonal means (threshold bins, spring, summer, fall) for the full survey set and the proposed 12-survey subset.

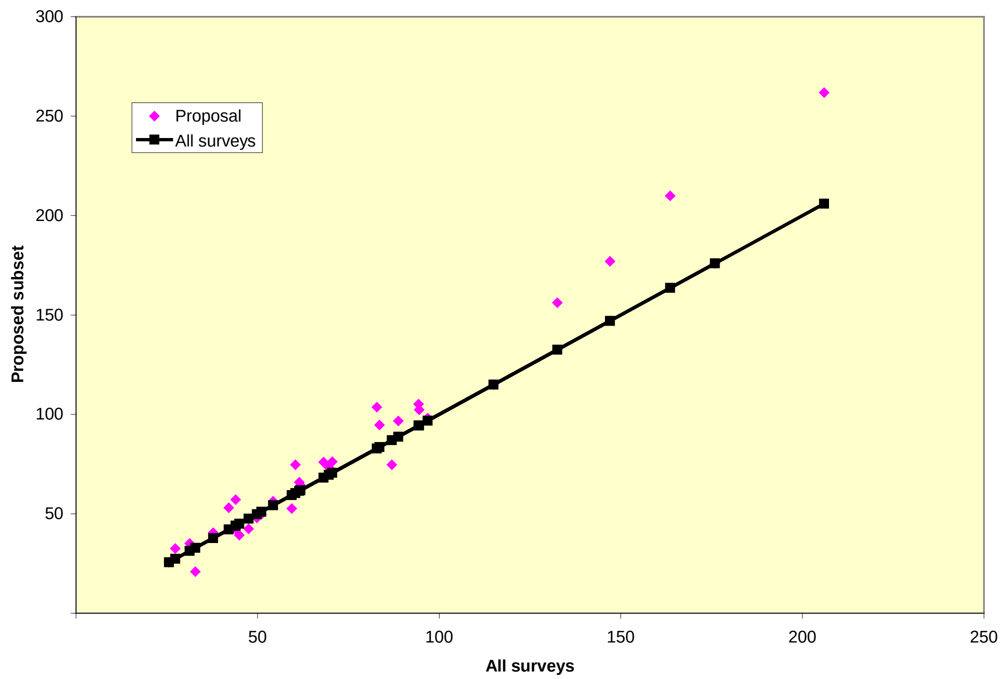


Figure 7-20 Seasonal mean chlorophyll, (spring 1992-fall 2002) for the proposed twelve-survey subset compared with those for the full data set.

A high Pearson's *r* between the seasonal means (spring, summer, and fall together) of the subset and those from the full dataset indicates that the subset of surveys fairly closely reproduces the seasonal means determined from the whole data set. Pearson's *r* between seasonal mean chlorophyll for this subset and the whole dataset (log transformed data) was 0.965.

Twelve surveys, seven stations – dissolved oxygen minimum

Both for threshold testing purposes and for evaluation in interpretive reports, MWRA focuses on bottom water dissolved oxygen on a per-survey basis, without calculating annual or seasonal means. Figure 7-21 shows that the proposed 12-survey subset reproduces most of features observed in bottom water DO since 1992.

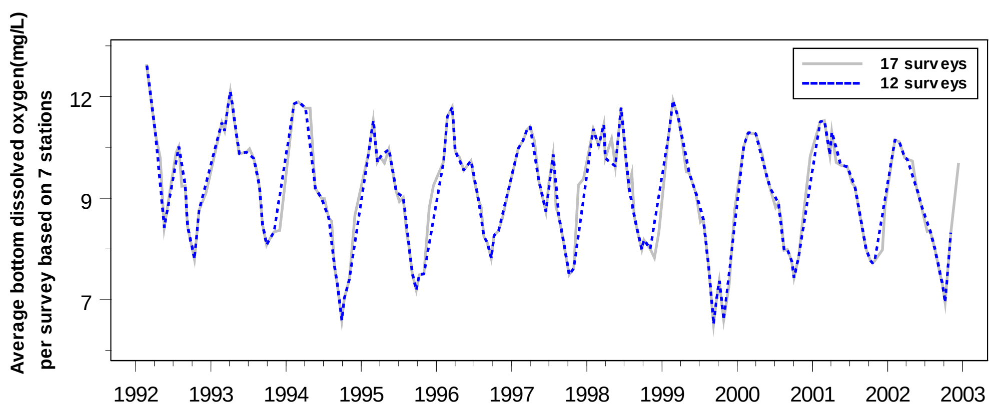


Figure 7-21 Temporal pattern of average bottom dissolved oxygen per survey based on 7 stations from all surveys (17/year) and the proposed survey subset.

Sensitivity to timing of surveys

We ultimately chose the twelve surveys proposed because of our understanding, from years of monitoring, of the timing of key ecosystem events. We also examined how well the subset chosen performed in relation to other possible subsets, by calculating the nearfield seasonal mean chlorophyll from spring 1992-fall 2002 for every one of the possible 6,188 subsets of 12 surveys.

We considered all three seasons, to ensure that a highly ranked survey subset would reproduce the major pattern of variability observed, with variable (sometimes high) levels of chlorophyll observed in the spring, relatively low chlorophyll in summer, and normally high fall chlorophyll. Input data were log-transformed survey mean chlorophyll (areal) for the seven-station design. This results in 33 seasonal means between winter/spring 1992 and autumn 2002, although for some combinations a season might have no data.

As an indicator of how well data for a survey subset reflects the whole dataset, we used Pearson's *r* between seasonal means for the entire dataset and those for each subset. Means for most of the 12-survey subsets had a correlation coefficient with the full dataset higher than 0.9 (Figure 7-22). That is, there are many combinations of twelve surveys which would well-represent the observed patterns in seasonal mean chlorophyll. The survey set proposed above (retain surveys 1,2,3,4,6,7,9,and 11-15) is one of the 50-best performing combinations of 12 surveys that retain all 6 combined nearfield/farfield surveys; as noted in the previous section, Pearson's *r* between seasonal mean chlorophyll for this subset and the whole dataset (log transformed data) was 0.965.

The 5 top-ranked subsets for n = 12 include all 5 winter-spring surveys (survey 5 is on the cusp between winter-spring and summer). The proposed survey subset performs nearly as well although it drops one winter-spring survey. In addition, we chose a subset of nearfield surveys that included the six surveys during which we currently sample the farfield as well, with minor modifications to the timing of those surveys.

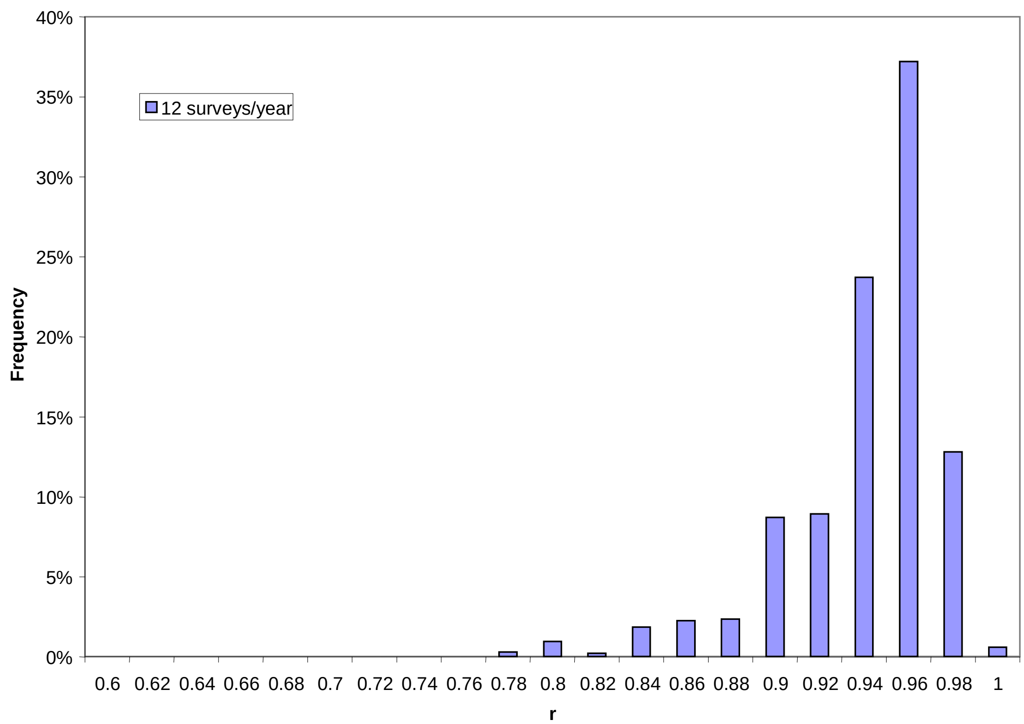


Figure 7-22 Frequency distribution of Pearson's r between seasonal means for the entire dataset and those for all possible subsets of twelve surveys subsets.

7.4.2. Sensitivity to smaller numbers of surveys

Figure 7-2 suggests that correlation between chlorophyll annual means calculated by the existing program (17 surveys/year) and those from a reduced numbers of surveys drops quickly as the numbers of surveys drops below 10. To determine how well such subsets might correlate with the seasonal means generated by the full program, we compared the distribution of seasonal mean areal chlorophyll for the seven-station design (all surveys) with all combinations of n = 6, 8, and 10 surveys per year drawn from the 17 now conducted.

There are 33 seasonal means between winter/spring 1992 and autumn 2002, although for some combinations (especially with n = 6 or 8) one or more seasons will have no data. For example, one 6-survey combination made up of surveys 12-17 (all of which are in autumn) has no data for spring and summer in any year.

As the number of surveys per year in a subset decreases, the correlations between subset seasonal means and the full dataset seasonal means are generally lower than for combinations of 12 surveys, as one would expect. Means for most of the 10-survey subsets had a correlation coefficient with the full dataset higher than 0.9 (Figure 7-23). As the size of the subset decreases, there remain some subsets whose seasonal means correlate quite well with the full dataset, but for the majority of subsets the correlation becomes weaker (Figure 7-24.)

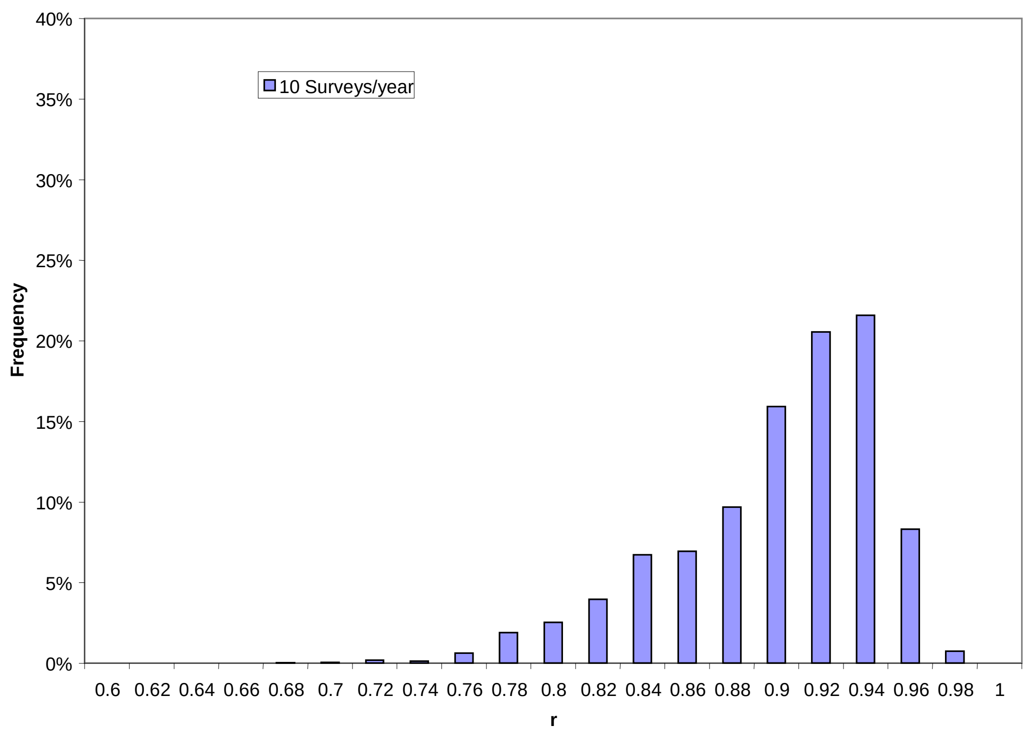
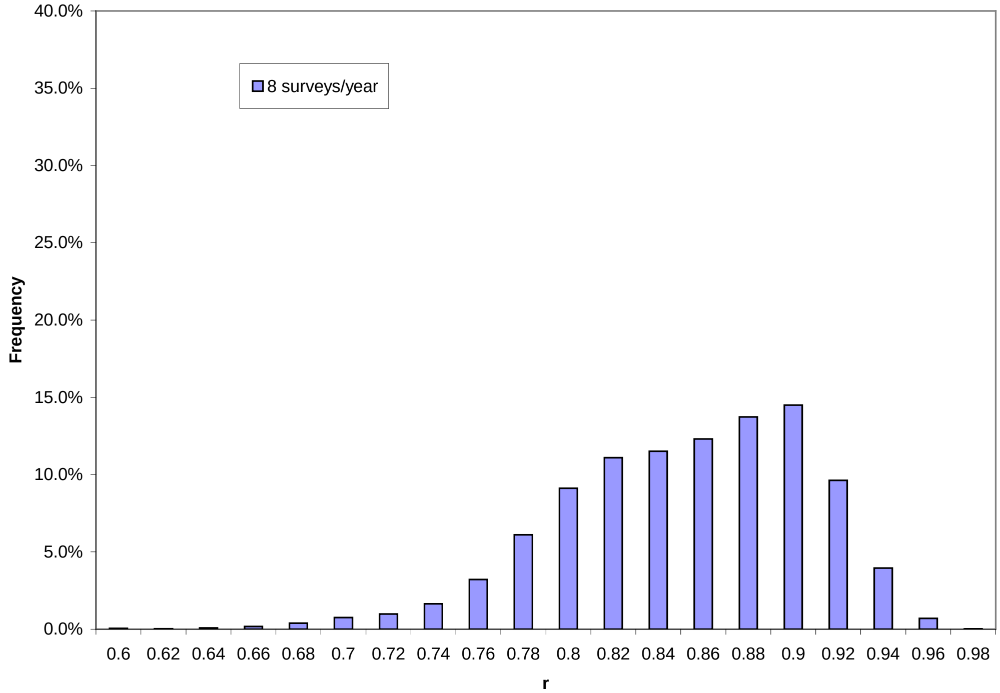


Figure 7-23 Distribution of Pearson's r between subset seasonal chlorophyll means and the entire dataset for all subsets of 10 surveys/year (bottom) containing data for all 33 seasons, Spring 1992 to Fall 2002.



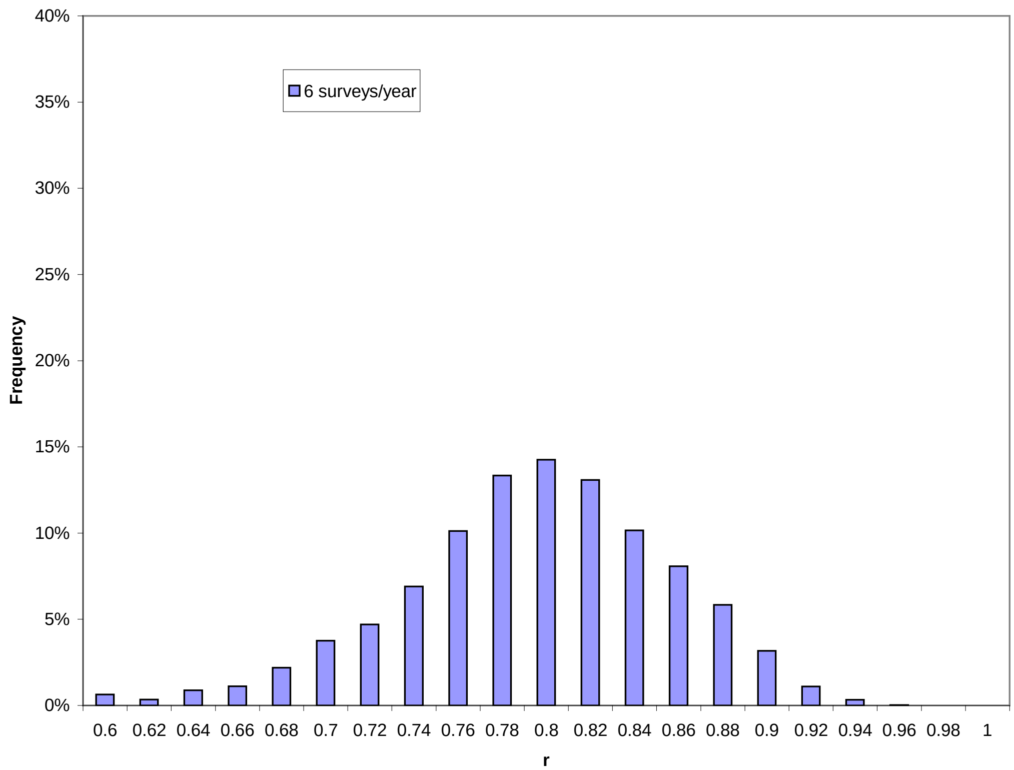


Figure 7-24 Distribution of Pearson's r between subset seasonal chlorophyll means and the entire dataset for all subsets of 8 (top) and 6 surveys/year (bottom) containing data for all 33 seasons, Spring 1992 to Fall 2002.

Figure 7-25 and Figure 7-26 document that while the seasonal means for the best performing subsets of data are very highly correlated with those for the whole dataset (with r > 0.94), as the numbers of surveys per year decreases, subset seasonal means increasingly differ from those for all surveys. As one might expect, seasonal means from the 10 and 12 survey subsets appear to match means from the whole dataset better than do those from the best performing 6 and 8 survey subsets.

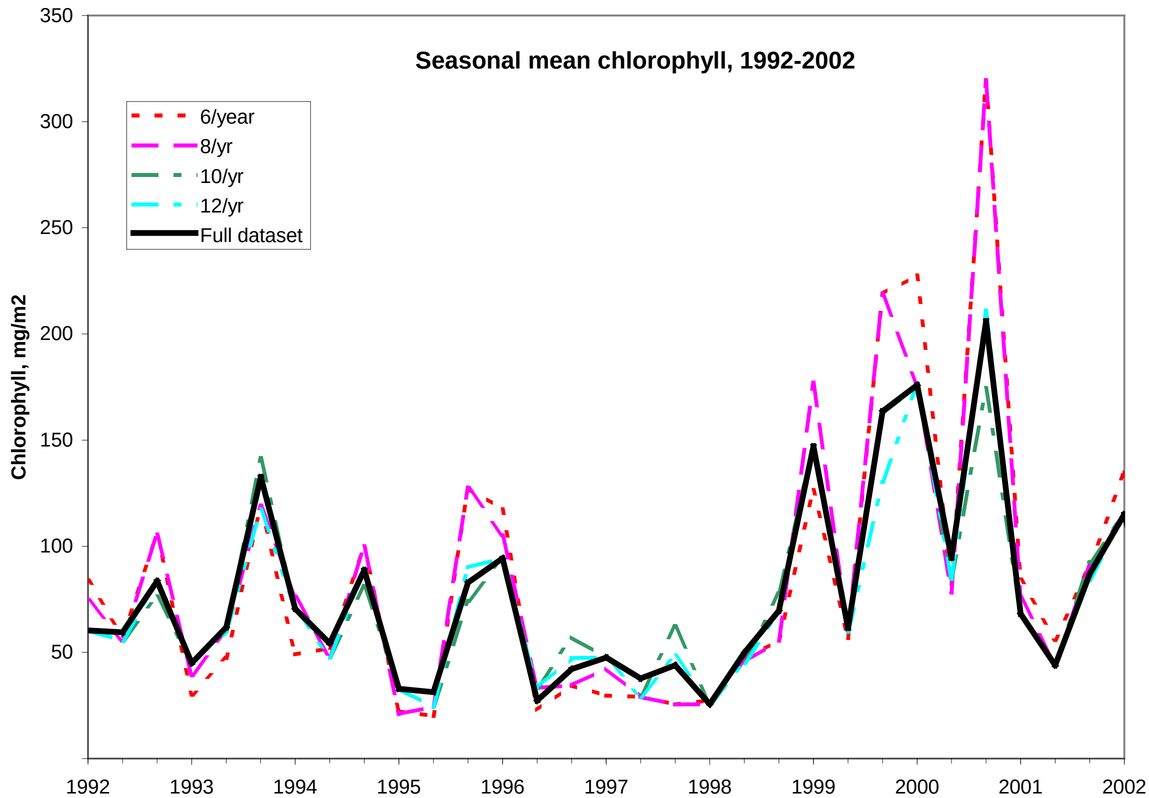


Figure 7-25 Time series of seasonal mean chlorophyll for the entire dataset as well as the best-ranked survey subsets for each of 6, 8, 10, and 12 surveys per year.

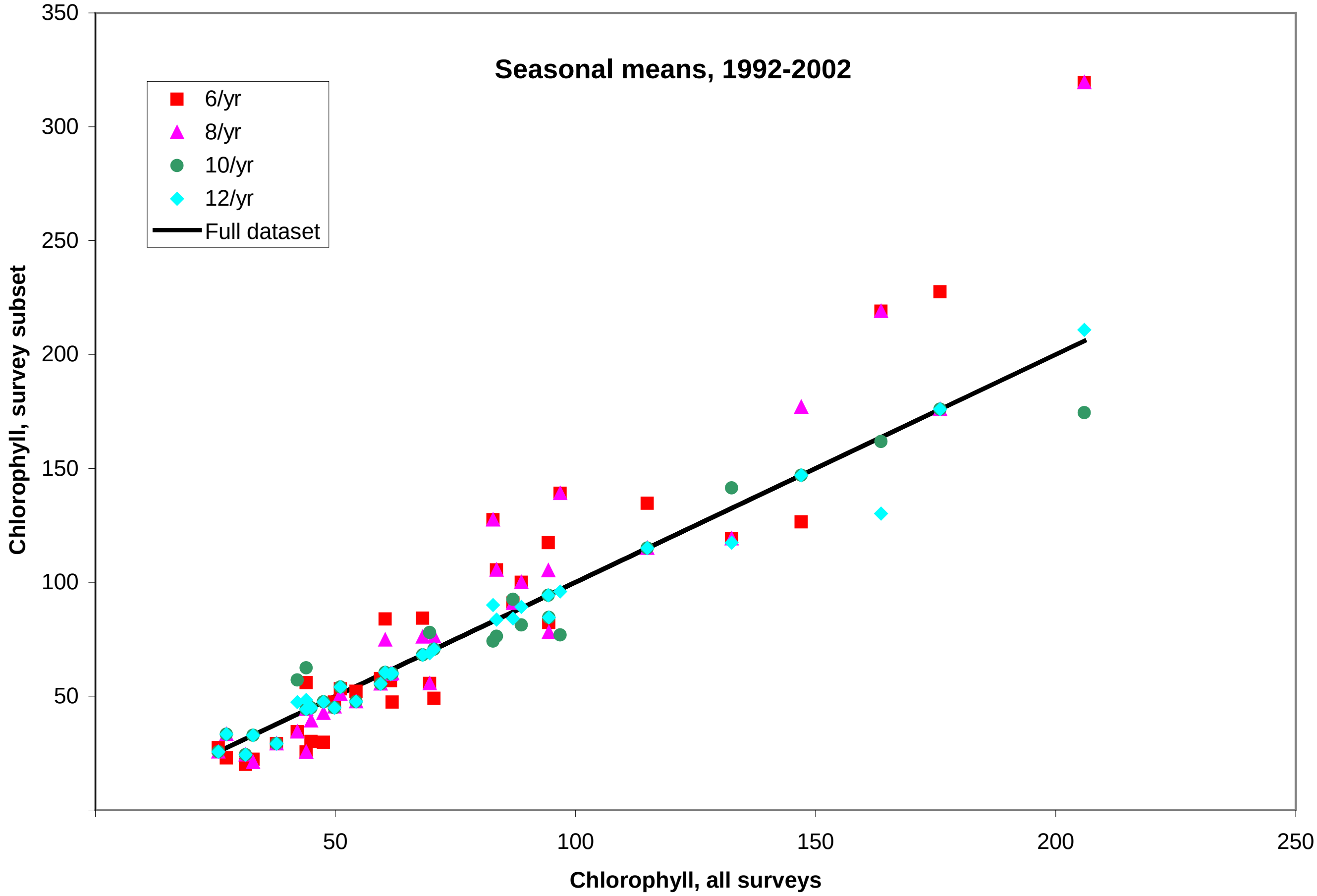


Figure 7-26 Scatterplot between seasonal chlorophyll means for the full survey dataset and the best-ranked survey subsets of 6, 8, 10, and 12 surveys/year.

Figure 7-27 shows a time series of the survey means from all surveys versus the best-performing 10-survey subset as well as a selected subset of 12 surveys per year for the 7 sampling station design. The 10 survey subset (surveys 1,2,3,4,5,7,9,12,14,16) generated seasonal means that correlate with those from all surveys at r =0.982. The 12-survey subset in this example (surveys 2,3,4,5,6,7,9,11,12,14,15,16) has a lower correlation with the seasonal means from all surveys (r = 0.954) than does the 10-survey subset or the proposed 12-survey subset (r = 0.965.) Nevertheless, the time series plot shows that the best performing 10-survey subset missed or underestimated the magnitude of the 1996, 1999, and 2000 fall blooms. Both the 12-survey subset in this figure and the 12-survey subset proposed (Figure 7-18) capture the peak of the fall blooms better than the 10-survey subset ranked highest in this evaluation.

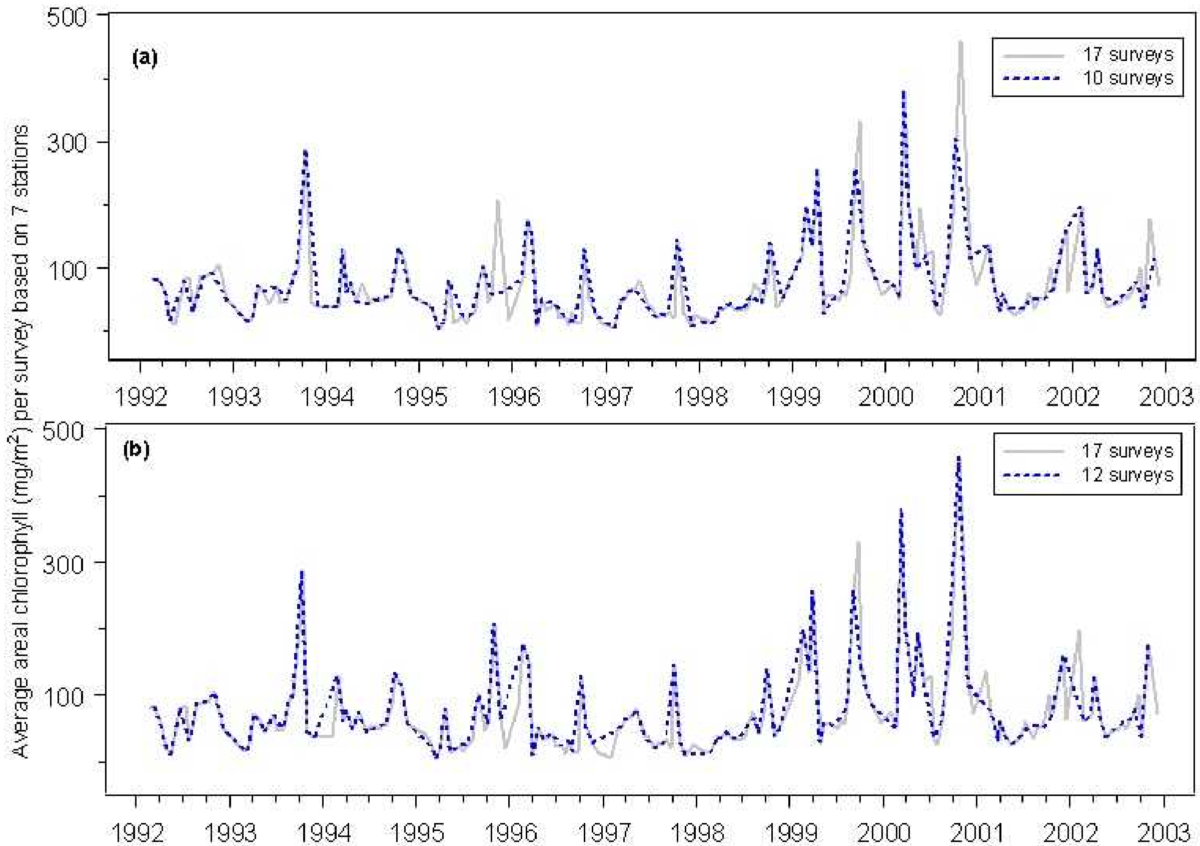


Figure 7-27 Comparison of the survey means for the best performing 10-survey subset and a randomly chosen subset of 12 surveys/year to those from all surveys.

Summary Many combinations of 10 or 12 surveys/year do a good job of reproducing the pattern (if not the absolute values) in nearfield seasonal mean chlorophyll, while many fewer 8 and 6 survey subsets do. For subsets of both 8 and 6 surveys, the top 5 ranked combinations (see appendix) seem to overestimate high chlorophyll seasons and slightly underestimate low chlorophyll seasons.

These results show that reducing the number of surveys to 10-12 surveys/year can closely reproduce the pattern of nearfield seasonal mean chlorophyll.

7.4.3. Rationale for 12 surveys instead of 10 or 8

Although the results above indicate that the distribution of annual and seasonal means for areal chlorophyll could be adequately monitored with ten surveys, we propose twelve surveys to better ensure that other features (*e.g.* peak of blooms) are captured while continuing to sample all 6 combined nearfield/farfield surveys. In the future, it may be appropriate to revisit the survey frequency as we review the farfield water column monitoring or as other techniques become more dependable, for example moored measurements of dissolved oxygen and computer model predictions of the evolution of bloom events.

7.4.4. Other parameters

The effect of reducing the number of surveys on the results for chlorophyll and bottom dissolved oxygen is examined in detail above. We also wished to know whether the proposed nearfield survey schedule would adequately characterize nutrient and plankton levels during the winter/spring and fall blooms and during the summer, and stratification at the beginning and end of the summer. We did this by plotting several parameters of interest at the five sample depths (A=surface to E=bottom), for the seven proposed stations, for all surveys 1992-2002 (Figure 7-28). Target dates for the proposed survey schedule are shown on the figures by gray vertical lines (in practice, weather frequently delays surveys by up to 2 weeks). All parameters are z-scaled [scaled by (survey mean per depth - grand mean of all survey means per depth)/ standard deviation of all survey means per depth.] The figures show that the proposed schedule would be expected to observe not only the extrema of chlorophyll and bottom dissolved oxygen, but also the seasonal variation in nutrient levels, onset and decline of stratification, occurrence of nuisance algal species, and seasonal growth and disappearance of phytoplankton and zooplankton.

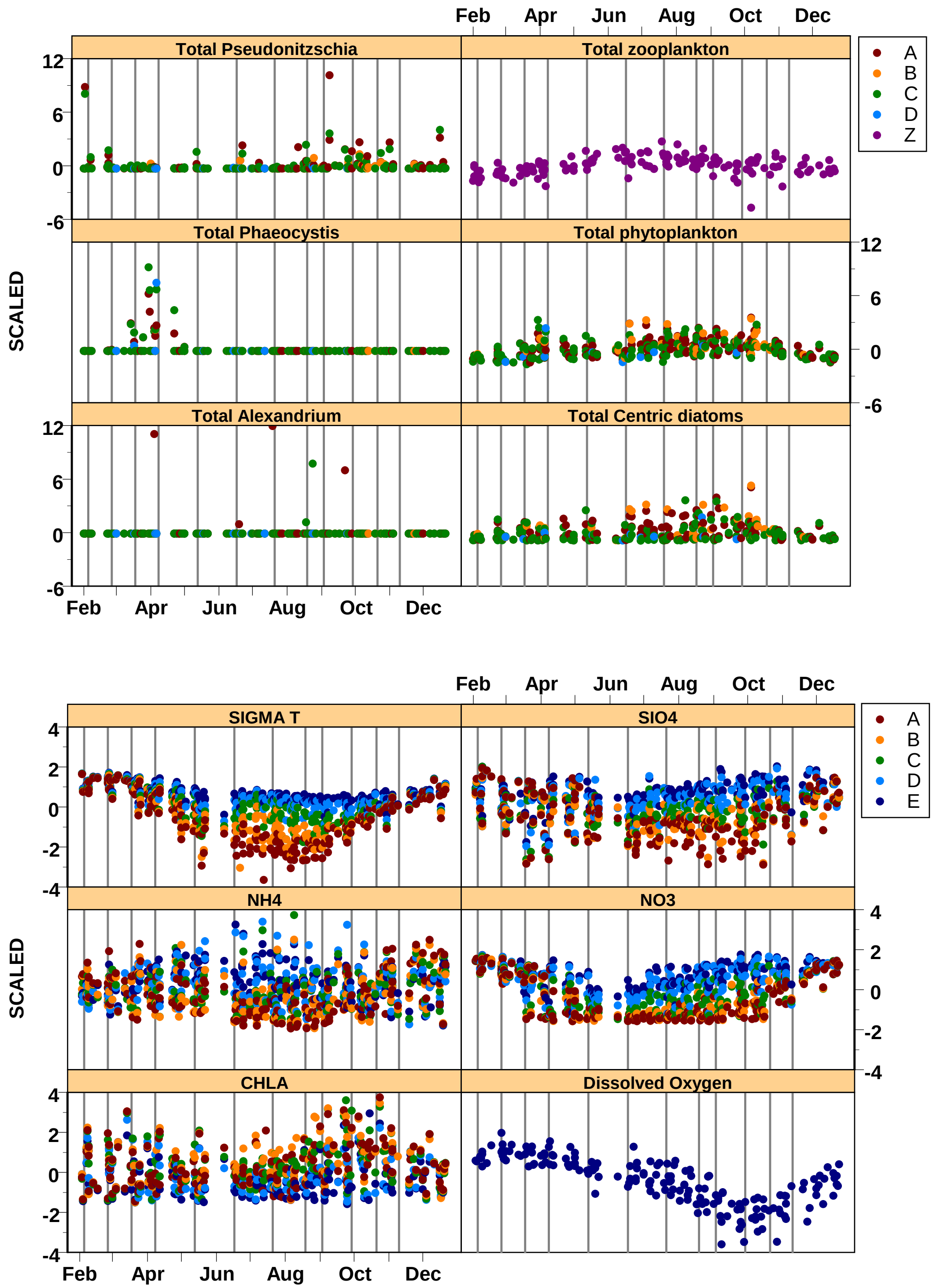


Figure 7-28 Annual distribution of water column monitoring parameters by depth, 1992-2002. All parameters are scaled (z-transform). Gray lines indicate target dates for the proposed 12-survey schedule.

7.5. Summary

Based on the evaluations detailed above, MWRA proposes to change the nearfield water column monitoring schedule to twelve surveys per year (targeting weeks number 6, 9, 12, 15, 20, 25, 30, 34, 36, 40, 43, and 46.) There will be seven stations distributed throughout the nearfield for hydrography, chlorophyll fluorescence, and dissolved and particulate nutrients, at the same depths currently sampled. We propose no changes to plankton monitoring stations (two nearfield stations, two depths for phytoplankton and net tow for zooplankton) or to primary productivity and respiration monitoring stations (two nearfield stations). The only change to farfield monitoring proposed at this time is to move the early April survey one week later and the early October survey to mid-late October.

7.5.1. References

Anderson DM, Keafer BA, Churchill J and III TCL. 2002. **Post-outfall surveys of toxic Alexandrium fundyense populations in Massachusetts Bay, 2001**. Boston: Massachusetts Water Resources Authority. Report 2002-08. 36 p.

MWRA. 1997. **Massachusetts Water Resources Authority effluent outfall monitoring plan: Phase II post discharge monitoring.** Boston: Massachusetts Water Resources Authority. Report ms-044. 61 p.

Acknowledgement The evaluation of all possible combinations of survey subsets made extensive use of SPSS syntax and macro routines posted on the website of Raynald Levesque, http://pages.infinit.net/rlevesqu/ .

APPENDIX A

A. COMPARISON OF SHIPBOARD AND MOORED MEASUREMENTS

Citation:
Dragos P and Hunt C. 2003. **Comparison of Shipboard and Moored Measurements**. Letter report June 5, 2003. Boston: Massachusetts Water Resources Authority. pp. 13.

A.1 Background

Electronic sensors are currently employed to make both shipboard and moored measurements of temperature, salinity, turbidity, dissolved oxygen, and fluorescence (chlorophyll concentration). While shipboard measurements are made at stations over a broad geographic area and from surface to bottom throughout the water column, the frequency of those measurements is currently limited to 17 nearfield and 6 farfield surveys per year. On the other hand, moored measurements provide a continuous record of observation, but at only one location and depth per sensor package. The cost of moored measurements is relatively high because an additional sensor package is required for each additional measurement location. At present there are three moorings located in Massachusetts Bay: one mooring in the nearfield (Figure A-1) and one off Scituate, both maintained by the USGS, and another at the northeast boundary of the farfield (Figure A-2), maintained by the GOMOOS program.

A.2 Data Analysis

Comparison of shipboard and moored measurements provides an opportunity to examine the effect that a reduction in the frequency of shipboard surveys might have on the ability of those surveys to observe important short-term processes or phenomena and capture potential threshold exceedances. Figure A-3 presents shipboard measurements of temperature, salinity, dissolved oxygen, and fluorescence from stations N18 and N21 along with time-series measurements from the USGS mooring located in the nearfield near those stations during summer and fall 2002. Shipboard measurements at depths greater than 25m were compared to the near-bottom moored measurements at 29m and shipboard measurements between 9 and 17 m depth were compared to the moored fluorescence measurements at 13m depth. Shipboard dissolved oxygen and fluorescence sensor data were calibrated during each survey with in situ water samples. Figure A-4 presents shipboard measurements of temperature, salinity, and dissolved oxygen from stations F22, F26, and F27 superimposed with time-series measurements from the GOMOOS "A" mooring located near those stations. Data from the GOMOOS mooring sensors and corresponding shipboard measurements were selected from comparable depths.

A.3 Results

Shipboard and moored measurements of temperature and salinity track reasonably well for the period presented in Figures 3 and 4. The linear regression analysis (shown in Figures 5 and 6) reveals high correspondence between shipboard and moored measurements of temperature (r^2 = 0.92 and r^2 = 0.93) and somewhat poorer correspondence for salinity (r^2 = 0.72 and r^2 = 0.50). The poor correspondence between shipboard and moored salinity is probably attributable to the higher variance in the salinity signal. The depth of the measurements is an important factor in the degree of correspondence between the two measurements. Geyer found much poorer correspondence between the USGS mooring and shipboard measurements in summertime surface temperature due to the large, short-term fluctuations in temperature in the surface layer. But despite the good correspondence for the deep observations of temperature and salinity, Figures 3 and 4 show how certain features are not captured by the relatively infrequent shipboard measurements. In early September 2002, for instance, a jump in near bottom water temperature of approximately 5 °C with a corresponding drop in salinity were recorded by the mooring sensors, but were missed between shipboard surveys.

Dissolved oxygen, which is a threshold parameter, shows good correspondence between the moored and shipboard observations, but with an obvious offset between the two measurements. The regression is high, with $r^2 = 0.94$ and $r^2 = 0.99$ for the USGS and GOMOOS moorings, respectively (Figures A-5 and A-6), but the moored measurements are consistently between 1.4 and 1.5 mg/L less than the shipboard measurements. This disparity would be difficult to resolve if not for some recent measurements using a new sensor technology which suggest that moored Seabird type dissolved oxygen sensors report low data despite pre-survey and post-survey calibration[1]. The data reported here for both USGS and GOMOOS moorings was measured using a Seabird dissolved oxygen sensors. Assuming that the offset between calibrated shipboard measurements and moored measurements of dissolved oxygen can be resolved in the near future, moored measurements will continue to provide temporal resolution not available in the shipboard program. As with temperature and salinity, certain features visible in the time-series from moored observations are not captured by the shipboard measurement program. Of particular interest here are low readings of dissolved oxygen which approach or exceed threshold levels. For example, during early September moored observations of dissolved oxygen reach a minimum, not captured by the shipboard measurements, which was approximately 1 mg/L lower than the nearest shipboard measurement (even after correcting for a 1.5 mg/L offset).

Fluorescence measurements made using shipboard and moored sensors (Figure A-3) show an insignificant correlation ($r^2 = 0.19$; Figure A-5). Experience with the calibration of *in situ* fluorescence sensors has shown that a high degree of variability exists between sensor readings and chlorophyll concentration over short and long time scales. This is due to many factors including phytoplankton species, colony size, instrument fouling, and status of the phytoplankton. The poor correspondence seen in Figure A-3, suggests factors other than the high frequency variability in the chlorophyll signal suggested by the time-series moored measurements.

Finally, to get a sense of the spatial scale represented by an individual mooring, data from sensors at approximately the same depth from both the USGS and GOMOOS moorings were compared. The upper panels in Figuers 7 and 8 present the temperature and salinity time-series

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[1] USGS deployed a new Aanderaa optical dissolved oxygen sensor in conjunction with the standard Seabird dissolved oxygen sensor and found that, during the 1 month period when both sensors were operating at the same depth on the nearfield mooring, the Seabird sensor recorded oxygen levels approximately 1.5 mg/L lower than the Aanderaa sensor (Marinna Martini, personal communication).

measured at both moorings. The coherence in the signal between the two moorings is apparent for the seasonal trends and long time-scale features. This is especially true for the salinity observations where the correspondence between the two mooring is high. Short term variability (time-scales of a few days), however, in one record is not so well represented in the other. The normalized cross-covariance functions are shown in the lower panels in Figures A-7 and A-8. The peak normalized covariance in temperature records is 0.63 at a lag of 3 hrs. This means that 63% of the variability in temperature can be attributed to the two mooring observing the same water mass and the same processes at work: advection, mixing, heating, and cooling. For salinity, 82% of the variability at the two stations is attributable to the same water masses and processes (in the case of salinity, advection and mixing). For salinity the peak lag is 9 hr with nearfield USGS observations leading the GOMOOS. The peak lag, however, is not so telling because the covariance function (for both temperature and salinity) is fairly flat around zero with both positive and negative lags less than 2 to 3 days represent high covariance. This suggests that the two stations are observing similar water masses and similar processes, within the degree of coherence (63% to 82%), with up and down coast advection causing 2 or 3 days or less of lag.

A.4 Mooring Reliability

Moored measurements are currently providing information that aids in interpreting processes at work on time scales shorter than can be observed by shipboard sampling. The USGS mooring currently deployed in the nearfield is configured with internally recording sensors. Sensor fouling, damage to instrumentation by storms etc., and battery failure can and in the past has caused, significant loss of data that is not discovered until the mooring is recovered. The current disagreement between moored and shipboard dissolved oxygen measurements suggests that a more comprehensive quality assurance program may be require, including at least concurrent ship board measurements during mooring deployment and recovery. If mooring sensors are to be used to monitor threshold parameters, the USGS mooring will have to be reconfigured for real-time data transmission, so that the data will be immediately available both for threshold analysis and to identify instrument failures. But real-time data telemetry only identifies instrument or sensor failures. The GOMOOS “A” mooring, for instance, is configured for real-time data transmission, but has been out of service since May 14 and is currently awaiting redeployment. Redundant systems and contingency plans (and budget) must be in place to quickly repair or replace moorings or mooring components that are damaged or malfunctioning.

A.5 Summary

Moored time-series measurements provide researchers with observations of the short-term variability of water properties but the measurements are limited by instrument reliability, calibration issues and limited spatial coverage. Shipboard surveys provide spatial coverage, *in situ* calibration and a higher degree of reliability, but lack the ability to capture information about short-term variability and may miss short-term phenomenon. Both techniques provide important information to the monitoring program. A reduction in the number of shipboard surveys must be design with attention to what time-series measurements show about changes in important parameters that may be missed by relatively infrequent shipboard surveys. A statistical model used to predict shipboard sampling frequency required to observe statistically significant system changes should also consider short-term variability in threshold parameters observed in mooring data but not captured by the shipboard surveys.

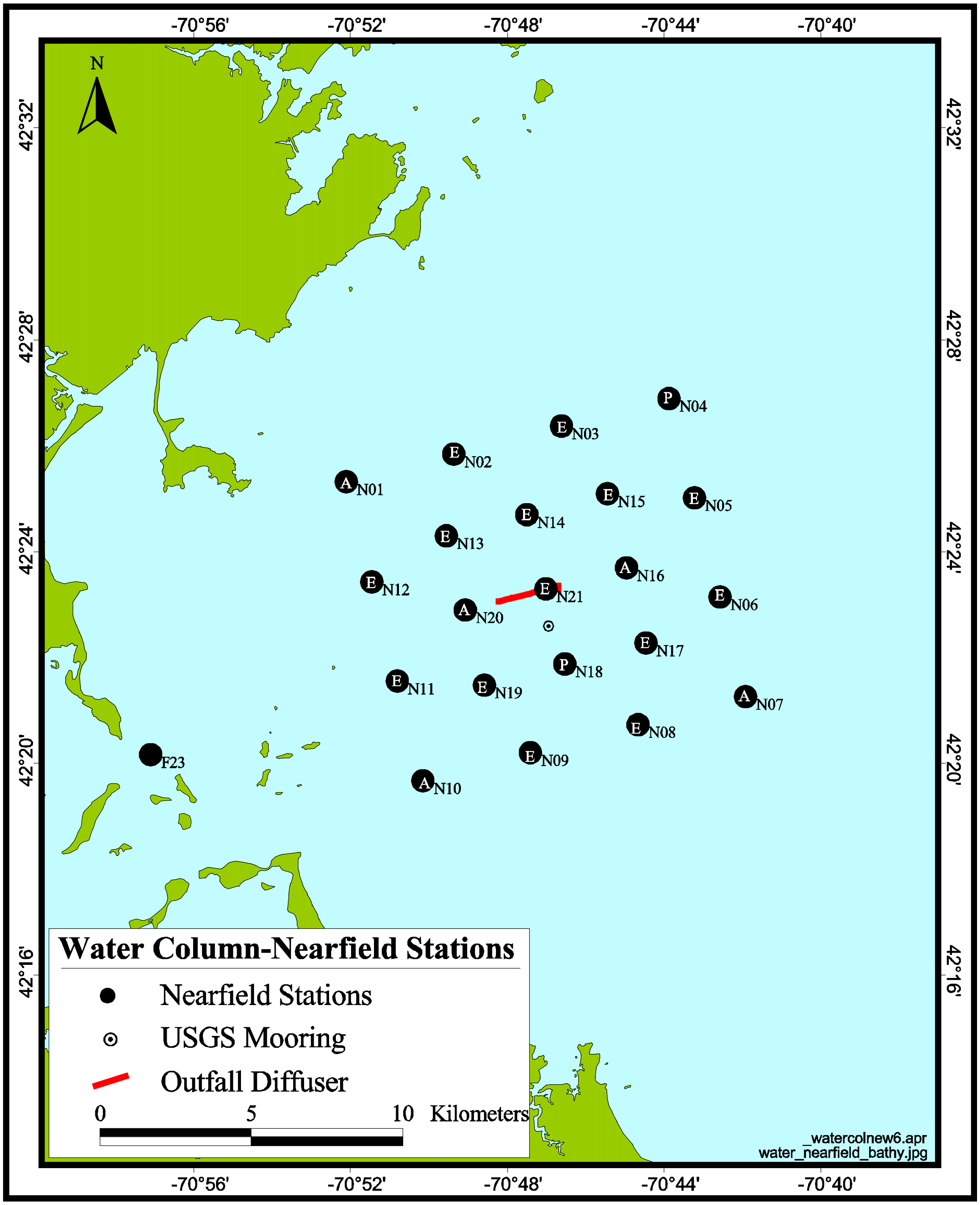


Figure A-1 Locations of MWRA nearfield stations and USGS mooring.

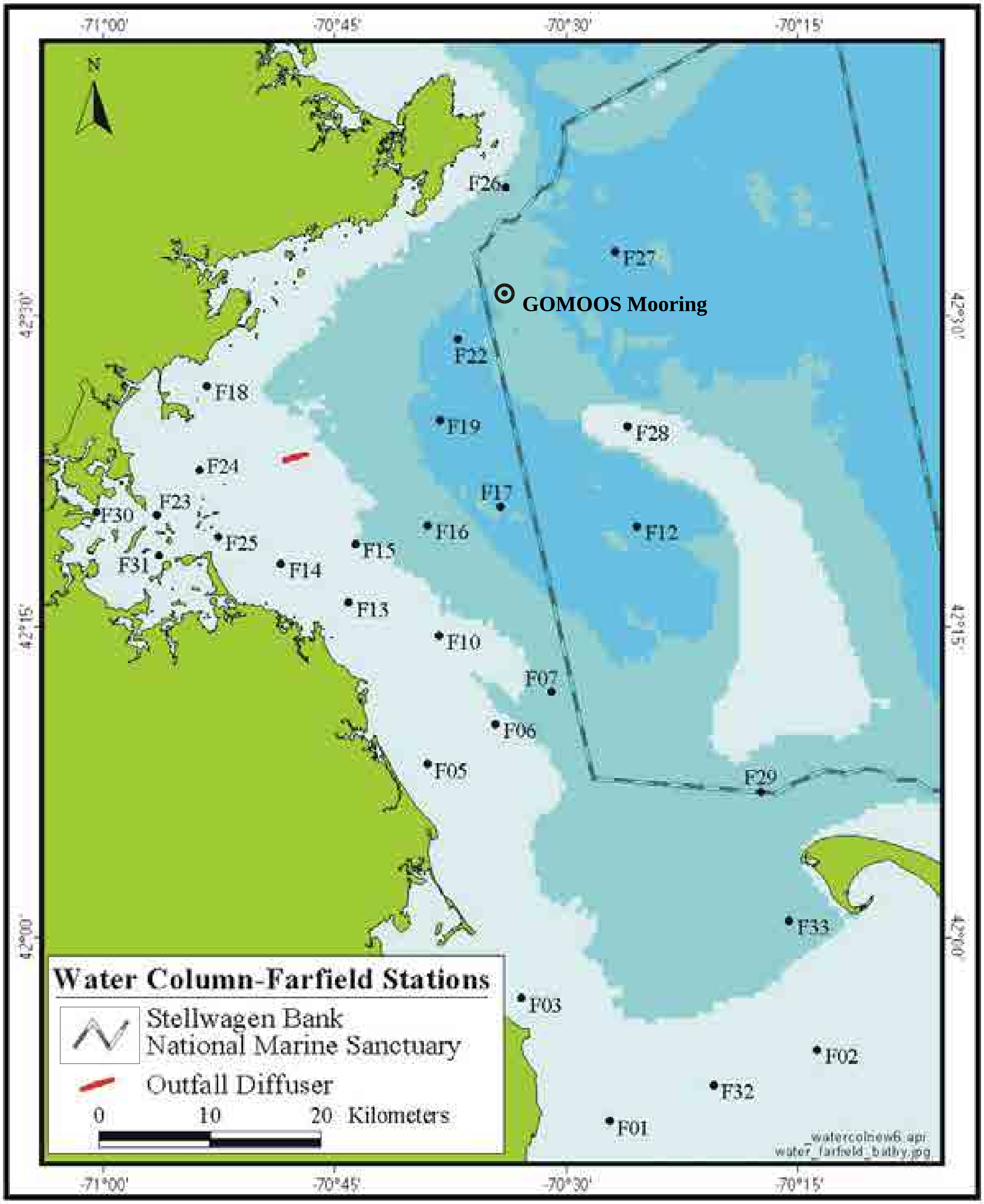


Figure A-2 Locations of MWRA farfield stations and GOMOOS mooring.

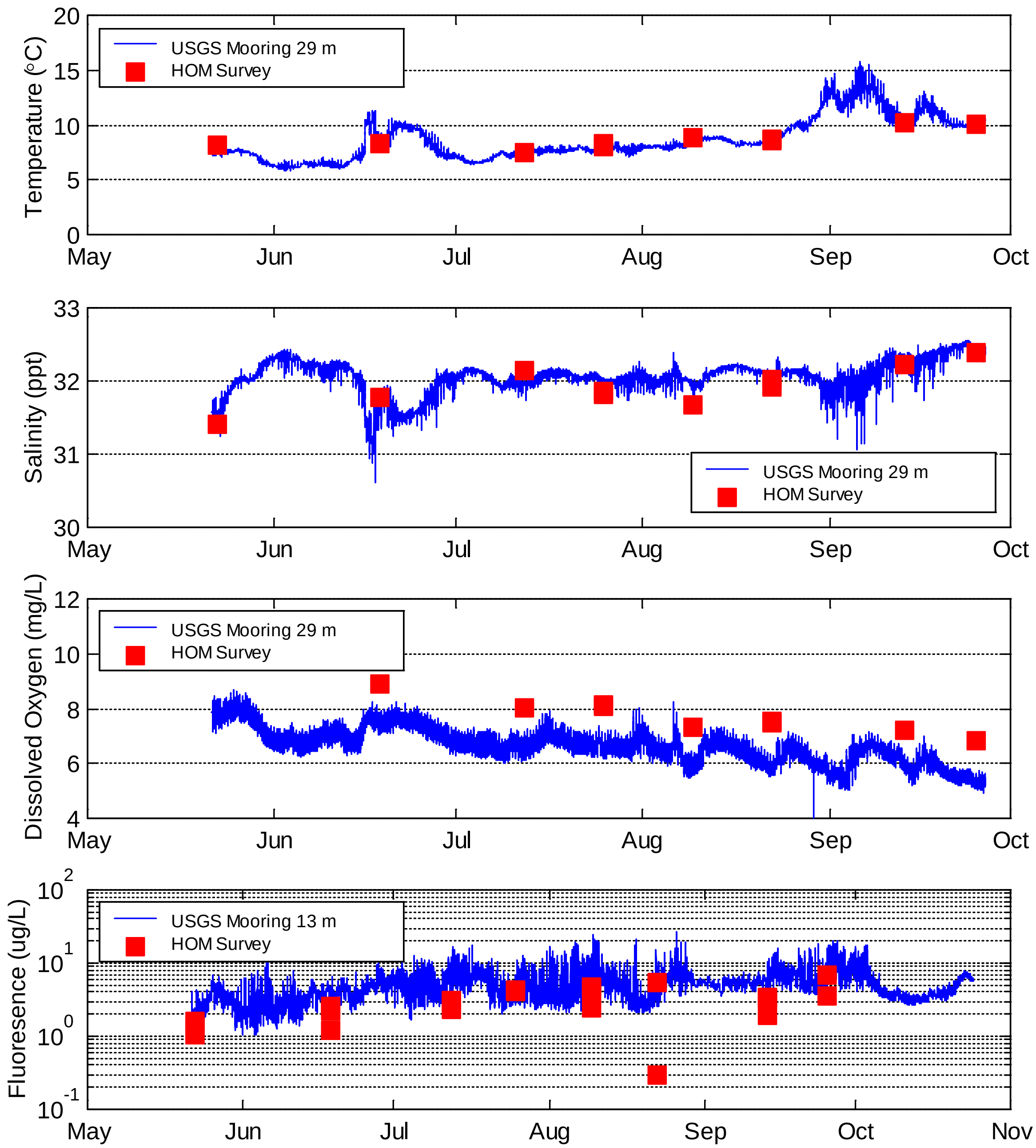


Figure A-3 Shipboard versus USGS mooring measurements in the nearfield.

Figure A-3 shows shipboard measurements of temperature, salinity, dissolved oxygen, and fluorescence from stations N18 and N21 superimposed on time series measurements from the USGS mooring located near those stations. Presented is the period May through October, 2002. Data are from mooring sensors and shipboard measurements at comparable depths.

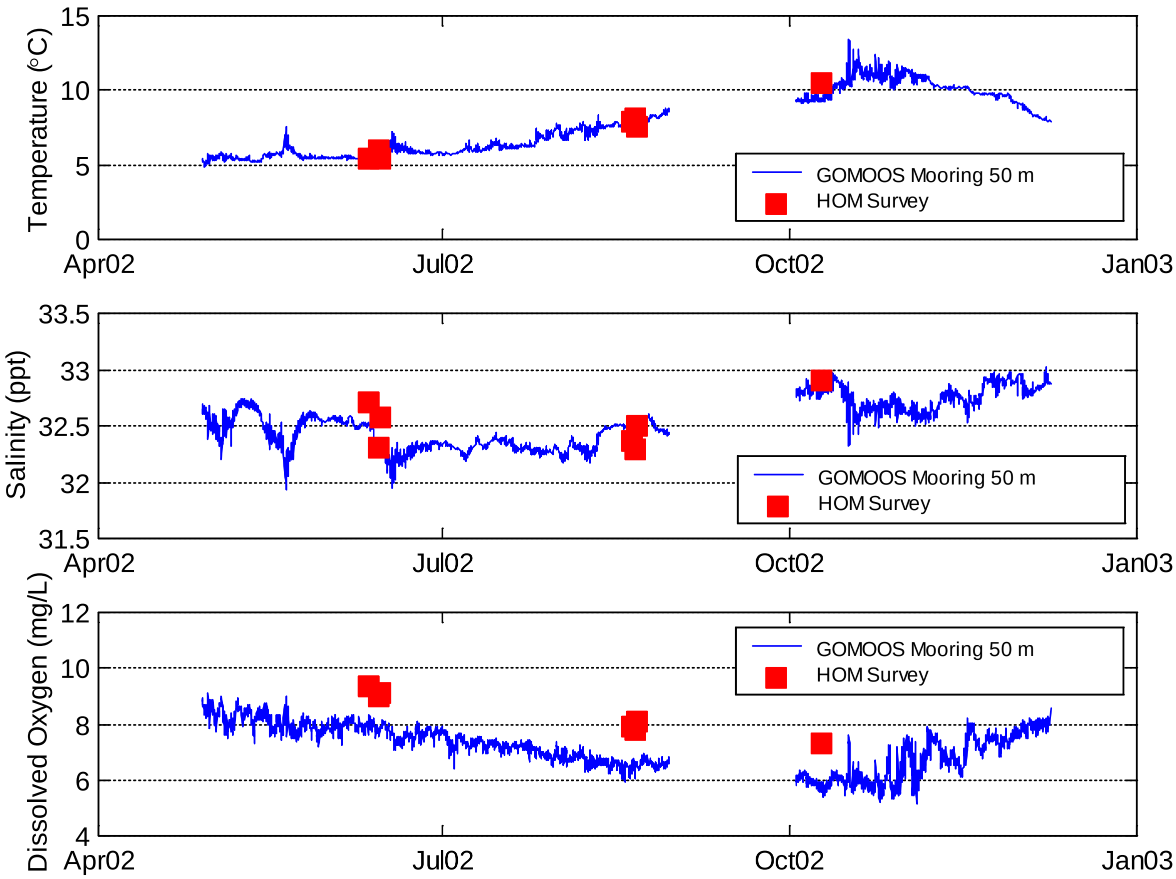


Figure A-4 Shipboard versus GoMOOS mooring measurements near Cape Anne.

Figure A-4 shows shipboard measurements of temperature, salinity, and dissolved oxygen from stations F22, F26, and F27 superimposed on time series measurements from the GOMOOS "A" mooring located near those stations. Presented is the period April 2002 through January 2003. Data are from mooring sensors and shipboard measurements at comparable depths.

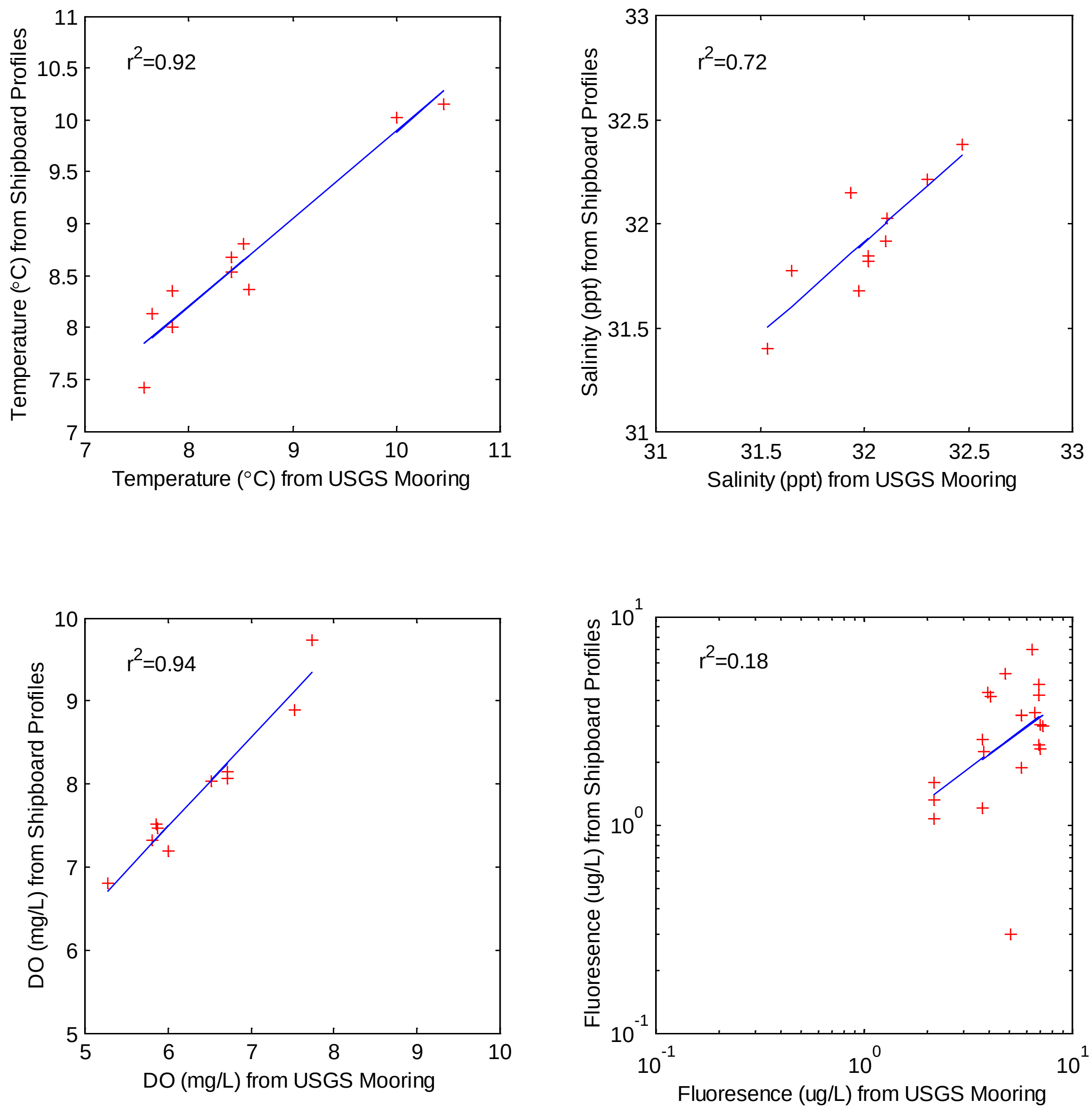


Figure A-5 Correlation of the shipboard versus USGS mooring measurements.

Figure A-5 shows a comparison of the temperature, salinity, dissolved oxygen, and fluorescence from the USGS mooring and shipboard measurements from stations N18 and N21 using linear regression. Presented are data from May through October, 2002.

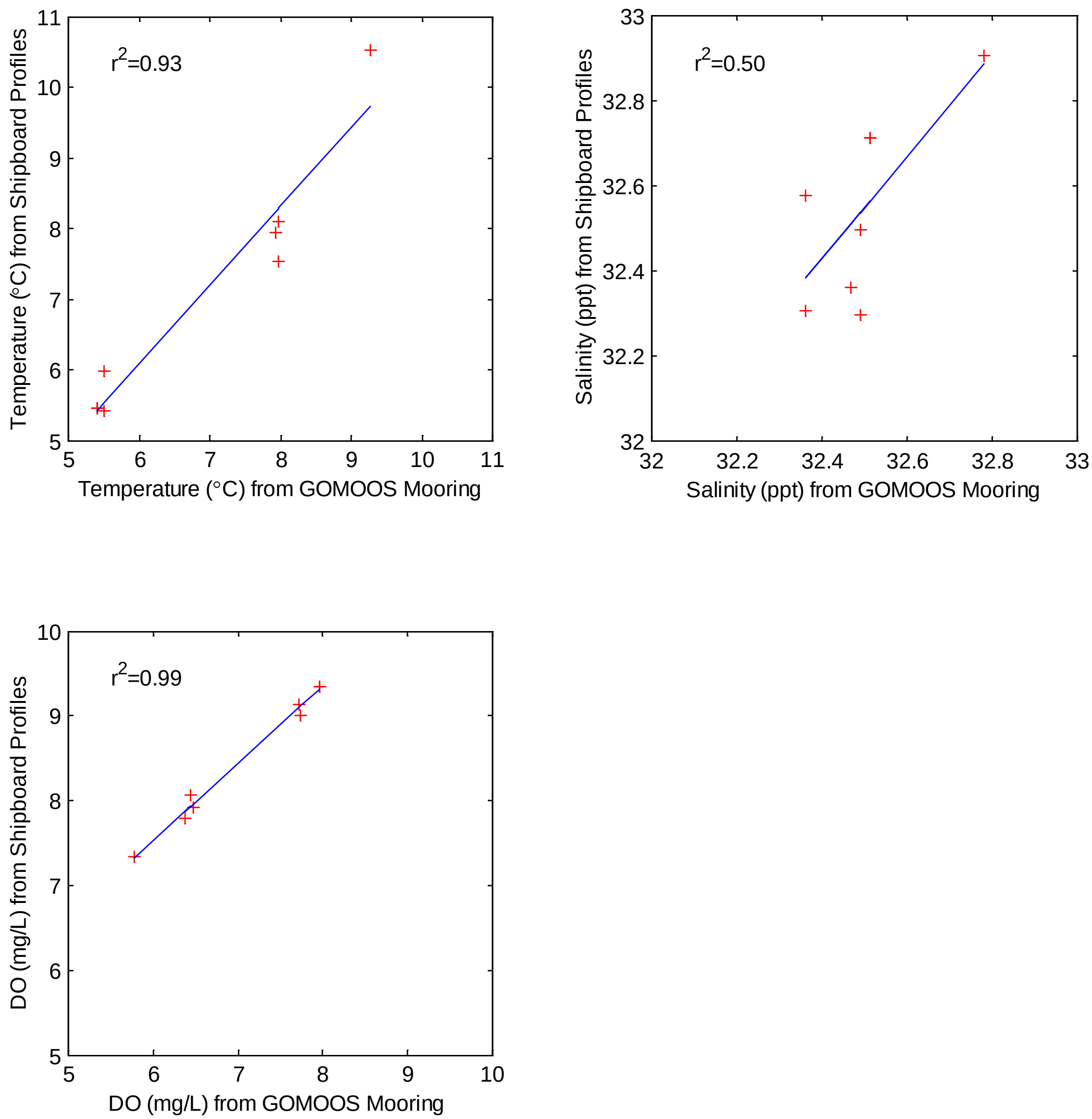


Figure A-6 Correlation of the shipboard versus GoMOOS mooring measurements.

Figure A-6 shows acomparison of the temperature, salinity, and dissolved oxygen from the GOMOOS mooring “A” and shipboard measurements from stations F22, F26, and F27 using linear regression. Presented are data from April 2002 through January 2003.

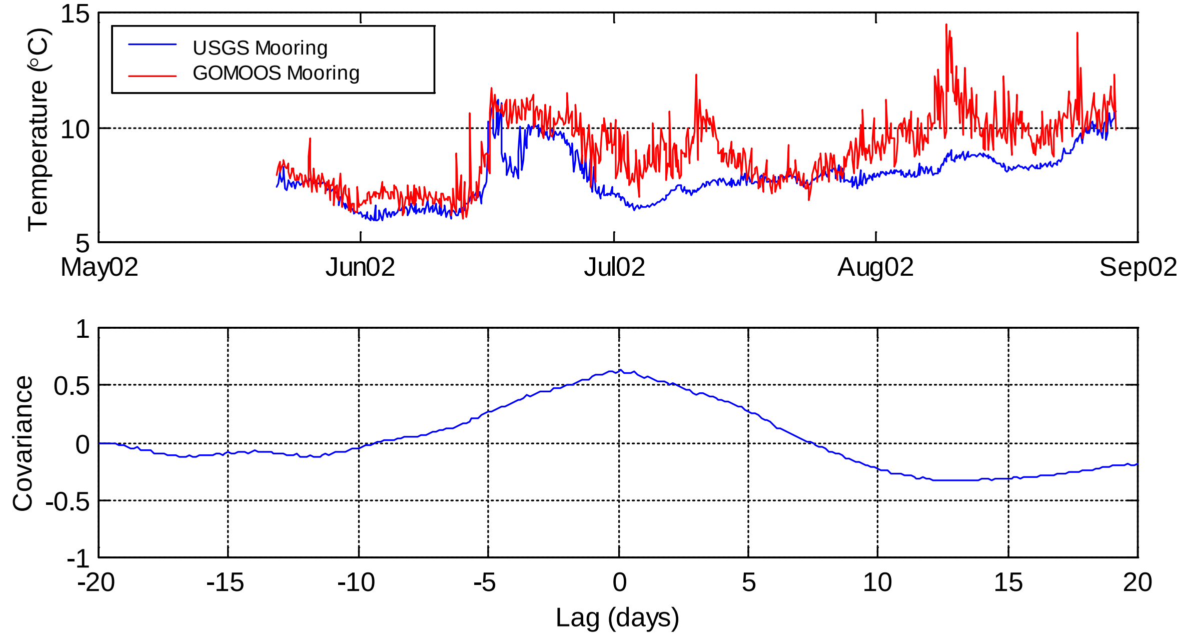


Figure A-7 Time-series of temperature from the USGS and GOMOOS moorings.

Figure A-7 shows a time-series measurements of temperature from the USGS and GOMOOS moorings from sensors at 29 and 20 m depth, respectively, (upper panel) and normalized cross-covariance function for the same time-series (lower panel). Positive lag represents GOMOOS observations leading USGS.

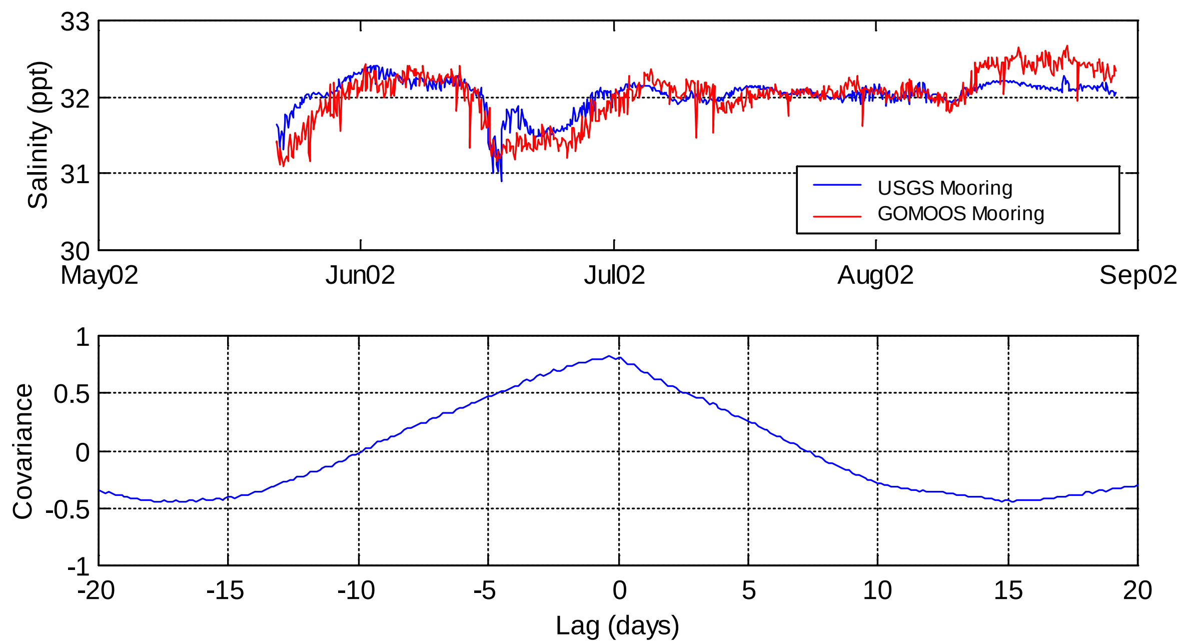


Figure A-8 Time-series of salinity from the USGS and GOMOOS moorings.

Figure A-8 shows a time-series measurements of salinity from the USGS and GOMOOS moorings from sensors at 29 and 20 m depth, respectively, (upper panel) and normalized cross-covariance function for the same time-series (lower panel). Positive lag represents GOMOOS observations leading USGS.

APPENDIX B

B. REMOTE SENSING

Ajit Subramaniam

B.1 Patterns in SeaWIFS chlorophyll

The analysis of the annual means of satellite derived chlorophyll concentrations for Massachusetts Bay show that the mean concentration increases from 1998 to 2000 and then decreases in 2001 (Table B-1 and Figure B-1.) Overall, the increase in chlorophyll concentration do not seem to be related to the outfall, since that came online only in September 2000, but appear to be a part of a larger regional trend in increasing chlorophyll concentrations during this period. The chlorophyll concentrations increased both in spatial extent and in intensity during 1999. The low chlorophyll concentration patch (< 1 mg/m^3) seen east of the 70W longitude, corresponding to the region of water depths greater than 200m in 1998, disappears in 1999 and is found to reappear over a small area in 2000. While the area of high chlorophyll concentration is smaller in 2000 is than in 1999, it has an overall higher mean chlorophyll concentration due to increased concentrations along the shore. The low chlorophyll patch east of 70W is more extensive in 2001. The apparent high chlorophyll at the harbor mouth and along the shore south of the harbor may not be real (Figure B-1), as the numbers of samples at these locations are low and these pixels are more likely to be affected by land adjacency effects. Also, chlorophyll algorithm at these pixels is more likely to be affected by nonchlorophyll constituents such as chromophoric dissolved organic matter runoff from land and suspended sediments. On the other hand, the relatively high chlorophyll concentration seen at the pixel centered on 42.36N, 70.75W just east of the outfall is more likely to reflect true changes in chlorophyll concentrations there. The highest variations in chlorophyll concentrations are seen around the harbor mouth and along the coast (best seen in Figure B-2). In 1999 and 2000, the patterns are not as obvious and 2000 has the highest variability. The Stellwagen Bank shows high variability in 1999 and to a lesser extent in 2000. For all years, at most pixels, the number of samples used to calculate the above statistics is higher than 150. The lowest number of observations is usually along the coast, probably due to coastal fog and advective cloud formation and this might also contribute to the high standard deviation seen along the shore. The years 1999 and 2001 have the highest number of observations.

B.2 Time series of SeaWIFS chlorophyll

The temporal variability in chlorophyll concentration for this region is also studied using the 8-day standard mapped image (SMI) data extracted at four pixels corresponding to the GoMOOS, F26, N16, and F02 stations (Figure B-3). The results show a large seasonal and interannual variability in chlorophyll concentration at these locations. However, the one very obvious pattern is the large signal of the spring bloom each year at all the locations. Stations N16 and F02 are examined in greater detail (Figure B-4) and the in-situ measurements made from shipboard surveys are compared to the satellite measurements. It is evident that the in-situ chlorophyll is much lower than the satellite derived chlorophyll, especially in 1998. The discrepancy is greater at the N16 than at F26. However, it is also evident that seasonal and interannual patterns seen in the field data are mimicked by the satellite-derived data. Both the timing and magnitude of the spring and fall blooms can be seen to vary from year to year as well as the fact that the chlorophyll values are generally lower in 1998 and 2001 compared to 1999 and 2000 (Figure B-5).

B.3 Correlation between pixels.

Both auto and lag correlations were done for four locations corresponding to the GoMOOS Buoy B site, stations F26, N16, and F02 (Figure B-3). There was significant (>95% confidence) correlation between all stations except F02 and GoMOOS (Table B-2). The highest correlation was between F26 and N16 where 55% of the changes at station N16 could be explained by changes at station F26. There is also good correlation between station F26 and the GoMOOS site. The correlation between N16 and the GoMOOS site is weaker. An 8-day lag correlation analysis shows that N16 is slightly better correlated with the GoMOOS site after 8 days, indicating the length of time for transport between the two locations. All other correlations are weaker for both 8-day and 16-day lags, indicating that the transport time between F26 and N16 is less than 8 days and from GoMOOS to N16 is less than 16 days. Station F02 is weakly correlated with the others after 8 days and is not significantly correlated with the others after 16 days.

Table B-1 Comparison of the SMI derived Annual Mean Chlorophyll concentration data in Massachusetts Bay.

Statistics	1998	1999	2000	2001	2002
	1.0965	1.5488	1.135	1.0965	1.3490
Maximum	13.1826	19.2752	18.6209	9.0157	12.3027
Median	2.4266	3.1989	3.6728	2.6915	2.6002
Mean	2.7227	3.5444	3.9193	3.1469	3.2526
Standard Deviation	1.4940	1.8247	2.3643	1.7208	1.8295
Mode	1.7500	2.7500	2.7500	1.2500	1.8500
Points selected/Points in area	178/225	180/225	180/225	179/225	179/225

Table B-2 Lag correlation analysis for 9 km square, 8-day binned satellite-derived chlorophyll concentrations at stations F02, N16, F26, and the GoMOOS Buoy B Location.

The analysis was done for the 5 year period September 1997 to September 2002. The values shown in bold are significant (>95% confidence); red is r^2>0.4.

0 Days	F02	N16	F26	GoMOOS
F02	1	**0.20**	**0.20**	0.14
N16		1	**0.55**	**0.41**
F26			1	**0.52**
GoMOOS				**1**
-8 Days	F02	N16	F26	GoMOOS
F02	**0.43**	**0.18**	0.12	0.16
N16	0.07	**0.30**	**0.31**	**0.43**
F26	**0.17**	**0.43**	**0.46**	**0.37**
GoMOOS	0.16	**0.30**	**0.42**	**0.46**
-16 Days	F02	N16	F26	GoMOOS
F02	**0.25**	0.06	0.04	0.22
N16	0.09	**0.24**	.018	0.15
F26	**0.15**	**0.28**	**0.24**	**0.21**
GoMOOS	0.14	**0.22**	**0.22**	**0.25**

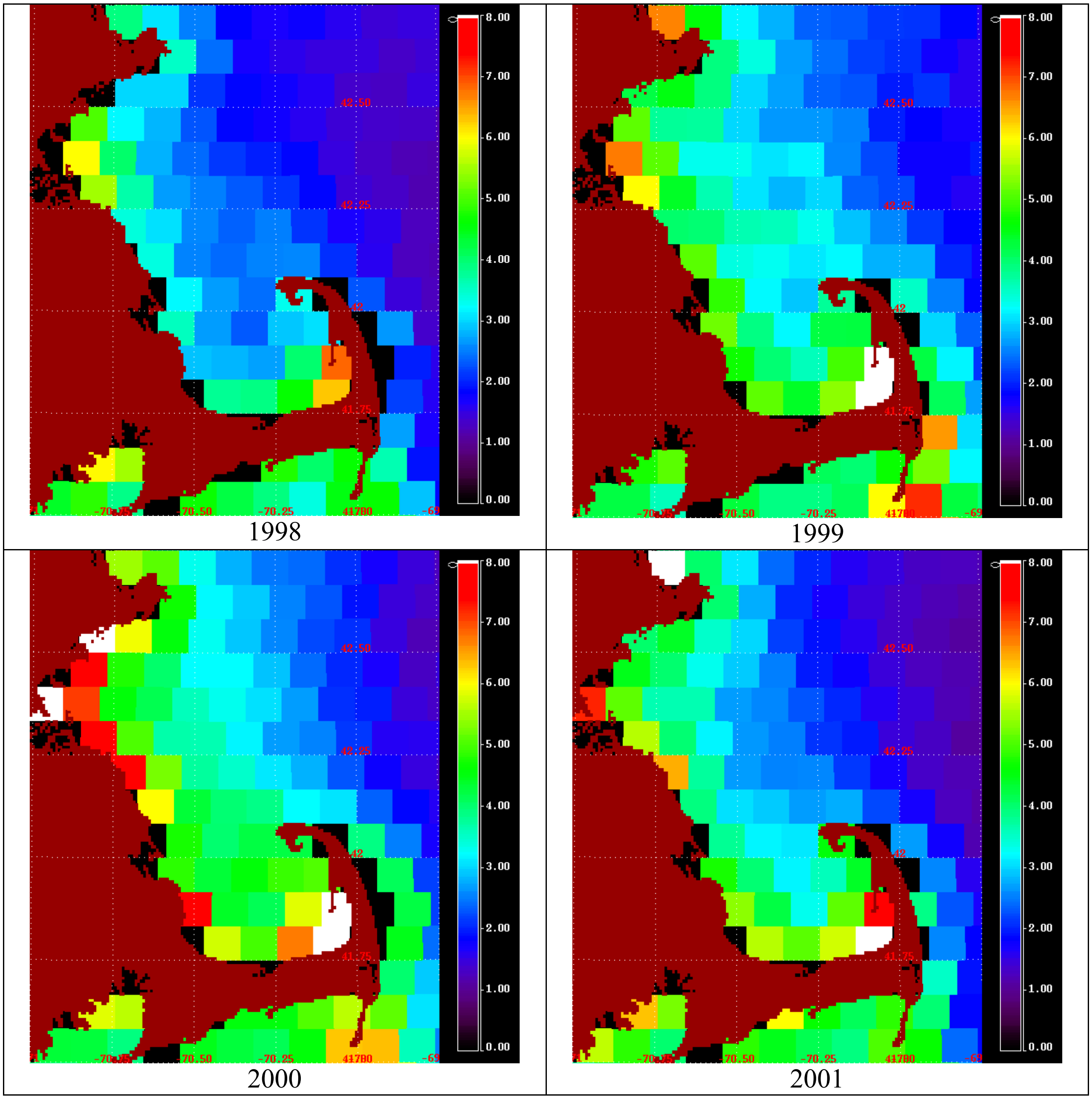


Figure B-1 SeaWIFS-derived annual mean chlorophyll concentration.

The scale in Figures B-1 and B-2 ranges from 0 to 8 mg/m^3. (1 mg/m^3 = 1 ug/L)

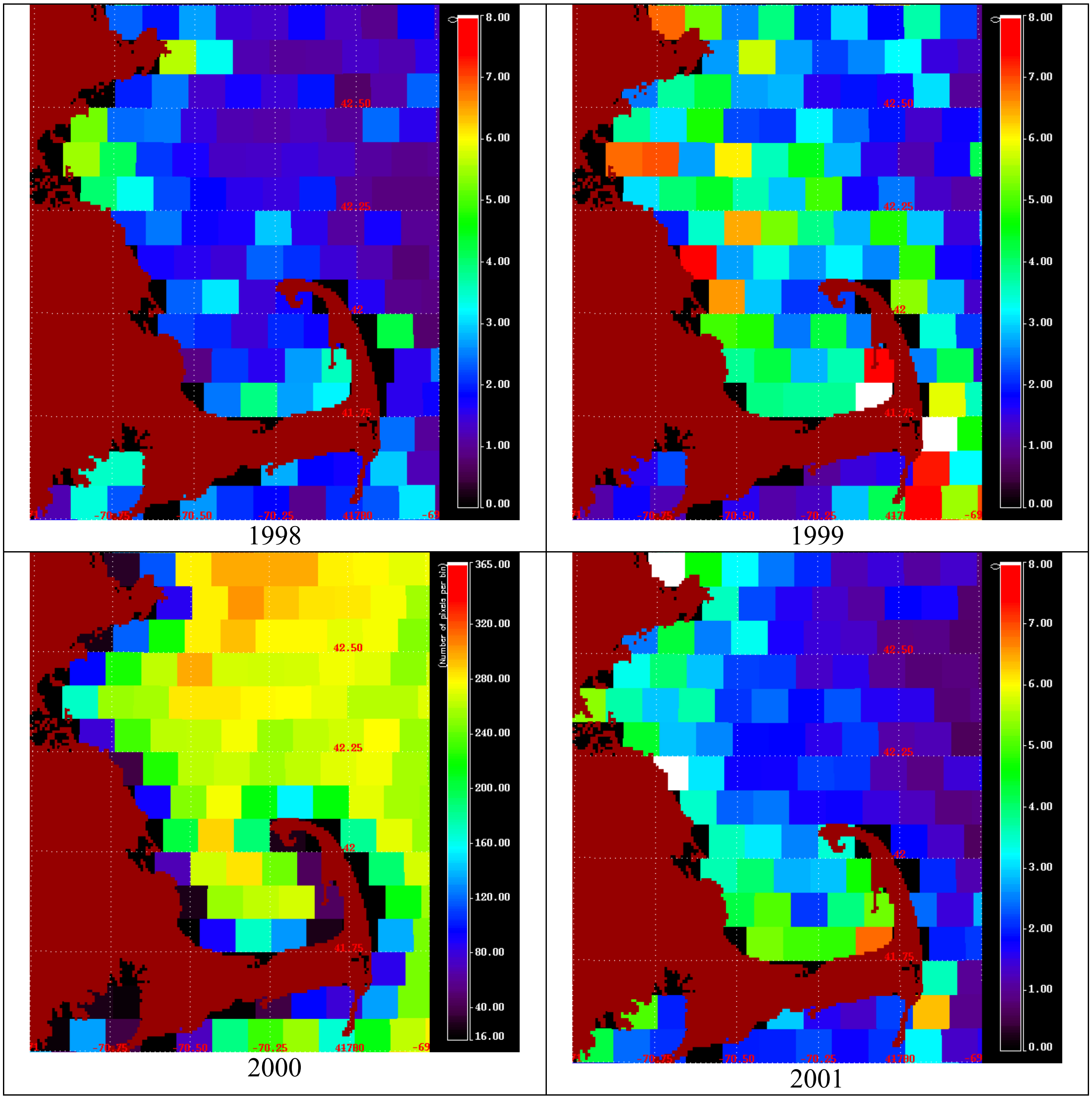


Figure B-2 Standard deviation in SeaWIFS-derived chlorophyll concentrations.

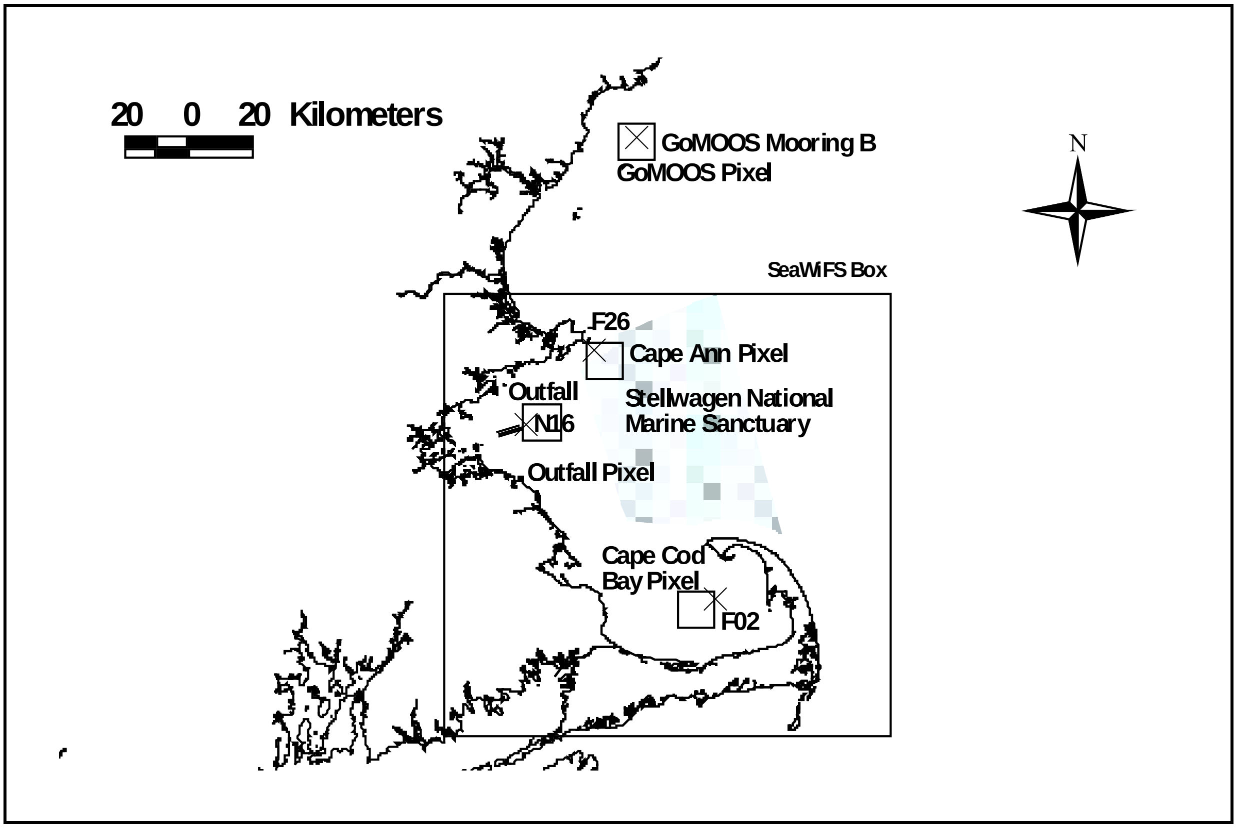


Figure B-3 Locations of the points used to create the time series.

Figure B-3 shows the locations of the points used to create the time series shown in subsequent figures. The size of the square shown here indicates the area covered by the SeaWiFS level-3 pixel used. The *in situ* data shown in Figure B-4 is taken from stations N16 and F27 for the Outfall and Cape Ann pixels respectively. The pixels are 9 km^2 in area. Stations N16 and F26 were chosen because they have a long record of *in situ* chlorophyll measurements that can be used for comparison to the satellite data.

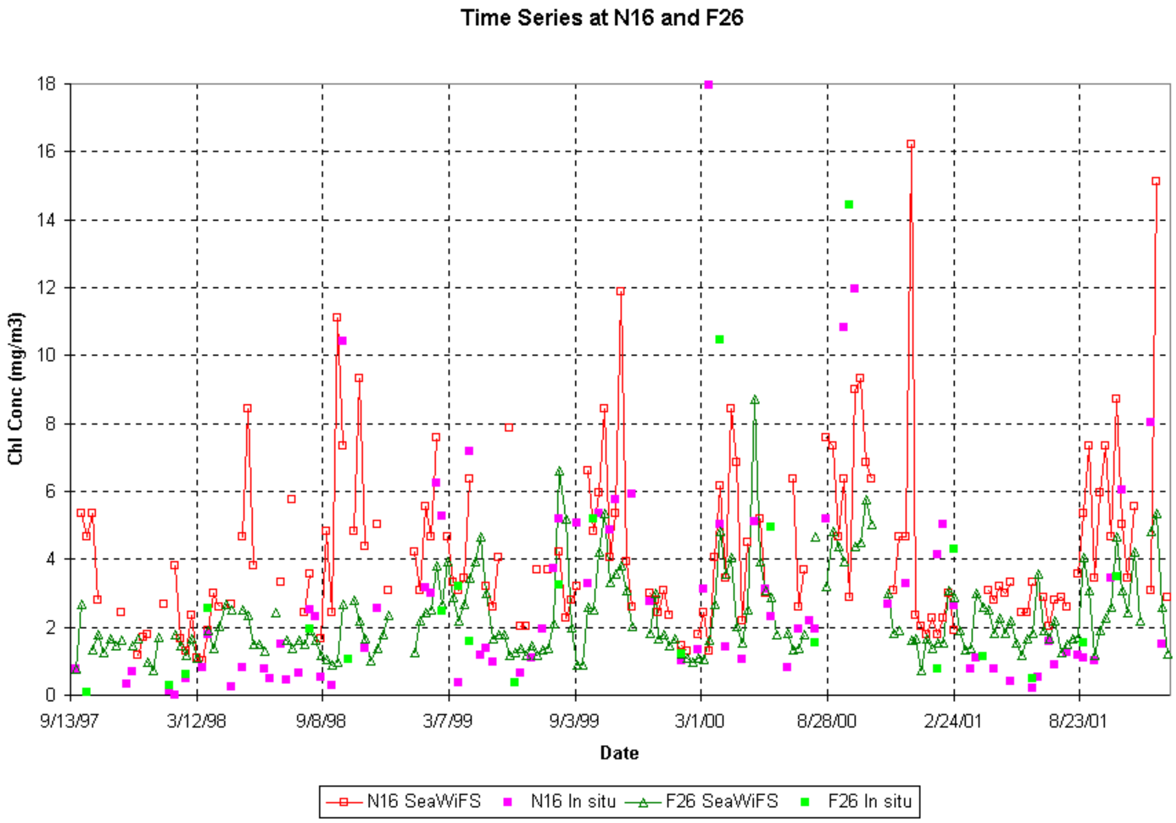
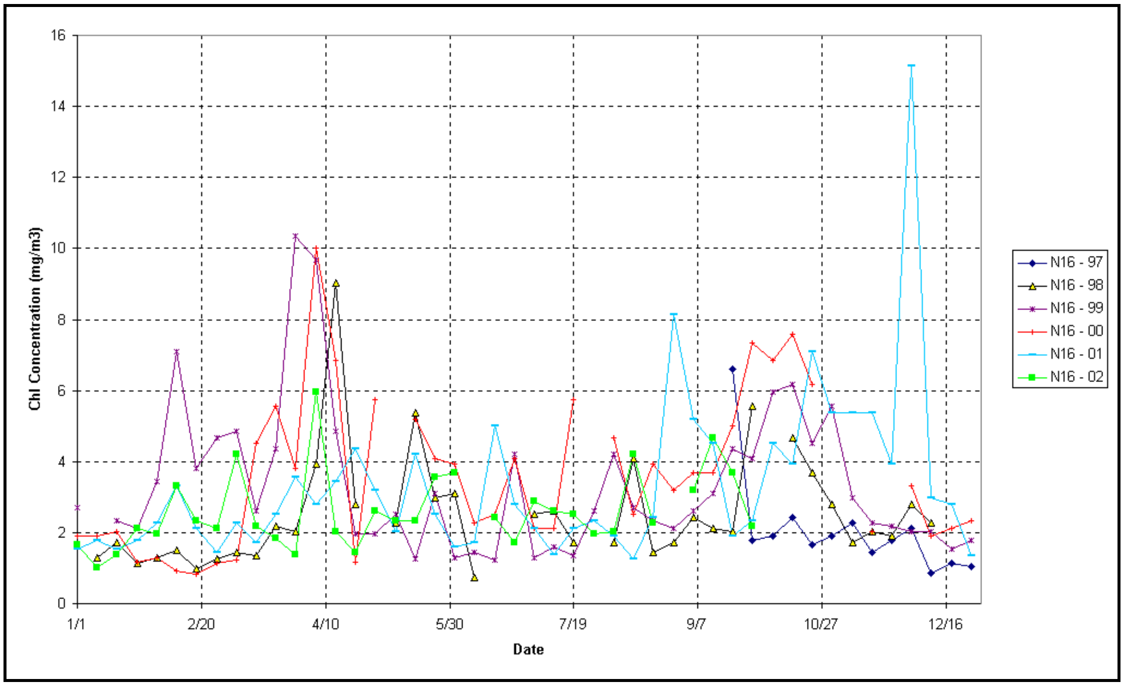


Figure B-4 **Time series of SeaWIFS data at two locations, compared to shipboard measurements.**

Figure B-4 shows a time series (open symbols) from September 1997 to December 2001 of chlorophyll *a* concentration constructed from SeaWiFS level 3 (8 day composite, 9 km^2 pixel) data from the two locations shown in Figure B-3. The line connecting the open symbols is broken when there is no data due to clouds. Also shown (solid symbols) are the *in situ* chlorophyll concentrations measured at stations N16 and F27 during the monitoring cruises. The annual trend of spring and fall blooms can be seen. The years 1999 and 2000 have higher chlorophyll compared to other years.



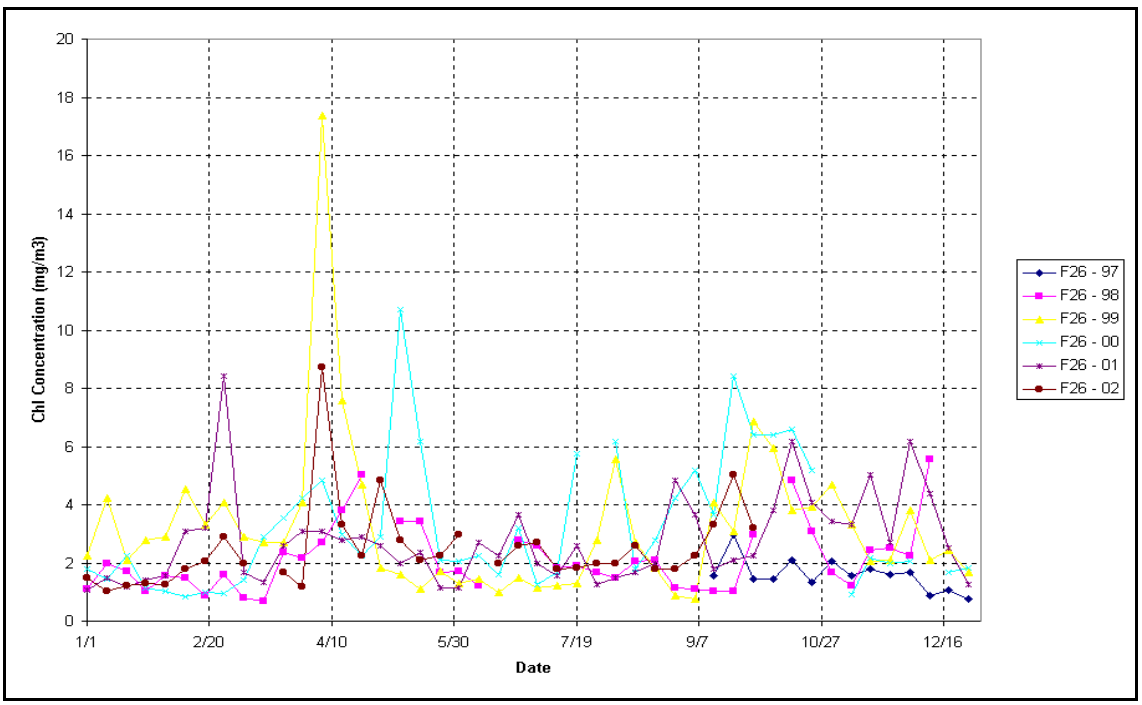


Figure B-5 Annual pattern of SeaWIFS data at two locations.

Figure B-5 shows data from the pixels F26 (Cape Ann) and N16 (outfall) presented as an annual cycle to show seasonal and inter annual variability. A spring bloom and a significant fall bloom are clearly seen, as is a strong interannual variability.

APPENDIX C

C. ADDITIONAL RESULTS OF EMPIRICAL ANALYSES OF STATION AND SURVEY REDUCTIONS

Suh Yuen Liang

C.1 Effect of reducing number of stations

Table C-1 Frequency table of the deviation of survey means of areal chlorophyll from 21 stations to 7, 3, and one stations. As the number of stations in a subset decreases the deviation of survey means from those for the full dataset increases.

Deviation of areal chlorophyll*	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.14%	0	.00%	0	.00%
0.0 - 0.1	146	84.09%	98	55.68%	54	30.68%
0.1 - 0.2	21	96.02%	54	86.36%	44	55.68%
0.2 - 0.3	4	98.30%	15	94.89%	38	77.27%
0.3 - 0.4	1	98.86%	6	98.30%	19	88.07%
0.4 - 0.5	2	100.00%	1	98.86%	10	93.75%
0.5 - 0.6	0	100.00%	1	99.43%	3	95.45%
0.6 - 0.7	0	100.00%	0	99.43%	2	96.59%
0.7 - 0.8	0	100.00%	0	99.43%	1	97.16%
0.8 - 0.9	0	100.00%	1	100.00%	1	97.73%
0.9 - 1.0	0	100.00%	0	100.00%	3	99.43%
>1.0	0	100.00%	0	100.00%	1	100.00%

* Deviation is calculated by the absolute difference between the mean from N=21 and reduced stations divided by the mean from N=21 stations.

Table C-2 Frequency table of the deviation of survey means of bottom dissolved oxygen from 21 stations to 7, 3, and one stations. 98% or more of survey means for all subsets differ by less than 10% of current means.

Deviation of Bottom dissolved oxygen*	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	1	.58%	0	.00%	0	.00%
0.0 - 0.1	170	100.00%	171	100.00%	167	97.66%
0.1 - 0.2	0	100.00%	0	100.00%	4	100.00%
0.2 - 0.3	0	100.00%	0	100.00%	0	100.00%
0.3 - 0.4	0	100.00%	0	100.00%	0	100.00%
0.4 - 0.5	0	100.00%	0	100.00%	0	100.00%
0.5 - 0.6	0	100.00%	0	100.00%	0	100.00%
0.6 - 0.7	0	100.00%	0	100.00%	0	100.00%
0.7 - 0.8	0	100.00%	0	100.00%	0	100.00%
0.8 - 0.9	0	100.00%	0	100.00%	0	100.00%
0.9 - 1.0	0	100.00%	0	100.00%	0	100.00%
>1.0	0	100.00%	0	100.00%	0	100.00%

Table C-3 Frequency table of the deviation of survey means of ammonium from 21 stations to 7, 3, and one stations. The deviations in survey means decrease for all subsets as the depth increases for both ammonium and nitrate/nitrite.

Surface depth						
Deviation of ammonium*	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	47	27.37%	31	17.32%	25	13.97%
0.1 - 0.2	39	49.16%	30	34.08%	14	21.79%
0.2 - 0.3	28	64.80%	25	48.04%	22	34.08%
0.3 - 0.4	27	79.89%	23	60.89%	20	45.25%
0.4 - 0.5	12	86.59%	27	75.98%	19	55.87%
0.5 - 0.6	11	92.74%	19	86.59%	15	64.25%
0.6 - 0.7	4	94.97%	7	90.50%	17	73.74%
0.7 - 0.8	3	96.65%	10	96.09%	12	80.45%
0.8 - 0.9	1	97.21%	3	97.77%	7	84.36%
0.9 - 1.0	3	98.88%	2	98.88%	9	89.39%
>1.0	2	100.00%	2	100.00%	19	100.00%
Mid surface depth						
Deviation of ammonium	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	1	.56%
0.0 - 0.1	47	27.37%	22	12.29%	16	9.50%
0.1 - 0.2	42	50.84%	32	30.17%	16	18.44%
0.2 - 0.3	35	70.39%	25	44.13%	21	30.17%
0.3 - 0.4	21	82.12%	26	58.66%	20	41.34%
0.4 - 0.5	13	89.39%	26	73.18%	19	51.96%
0.5 - 0.6	7	93.30%	20	84.36%	21	63.69%
0.6 - 0.7	4	95.53%	12	91.06%	18	73.74%
0.7 - 0.8	1	96.09%	5	93.85%	15	82.12%
0.8 - 0.9	3	97.77%	3	95.53%	6	85.47%
0.9 - 1.0	1	98.32%	4	97.77%	10	91.06%
>1.0	3	100.00%	4	100.00%	16	100.00%

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Table C-3 (continued). Frequency table of the deviation of survey means of ammonium from 21 stations to 7, 3, and one stations.

Mid depth						
Deviation of ammonium	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.13%	0	.00%	0	.00%
0.0 - 0.1	48	28.25%	38	21.47%	30	16.95%
0.1 - 0.2	38	49.72%	39	43.50%	17	26.55%
0.2 - 0.3	38	71.19%	24	57.06%	16	35.59%
0.3 - 0.4	18	81.36%	20	68.36%	22	48.02%
0.4 - 0.5	14	89.27%	25	82.49%	19	58.76%
0.5 - 0.6	8	93.79%	11	88.70%	12	65.54%
0.6 - 0.7	4	96.05%	8	93.22%	18	75.71%
0.7 - 0.8	5	98.87%	4	95.48%	12	82.49%
0.8 - 0.9	0	98.87%	3	97.18%	11	88.70%
0.9 - 1.0	1	99.44%	2	98.31%	8	93.22%
>1.0	1	100.00%	3	100.00%	12	100.00%
Mid bottom depth						
Deviation of ammonium	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	76	43.58%	62	34.64%	33	18.44%
0.1 - 0.2	45	68.72%	37	55.31%	27	33.52%
0.2 - 0.3	30	85.47%	27	70.39%	22	45.81%
0.3 - 0.4	14	93.30%	24	83.80%	25	59.78%
0.4 - 0.5	6	96.65%	11	89.94%	25	73.74%
0.5 - 0.6	4	98.88%	11	96.09%	11	79.89%
0.6 - 0.7	2	100.00%	3	97.77%	11	86.03%
0.7 - 0.8	0	100.00%	1	98.32%	5	88.83%
0.8 - 0.9	0	100.00%	2	99.44%	3	90.50%
0.9 - 1.0	0	100.00%	1	100.00%	4	92.74%
>1.0	0	100.00%	0	100.00%	13	100.00%

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Table C-3 (continued). Frequency table of the deviation of survey means of ammonium from 21 stations to 7, 3, and one stations.

Bottom depth						
Deviation of ammonium	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	83	47.49%	69	38.55%	35	19.55%
0.1 - 0.2	40	69.83%	33	56.98%	37	40.22%
0.2 - 0.3	27	84.92%	28	72.63%	24	53.63%
0.3 - 0.4	15	93.30%	17	82.12%	21	65.36%
0.4 - 0.5	4	95.53%	13	89.39%	16	74.30%
0.5 - 0.6	5	98.32%	9	94.41%	13	81.56%
0.6 - 0.7	2	99.44%	4	96.65%	10	87.15%
0.7 - 0.8	0	99.44%	4	98.88%	3	88.83%
0.8 - 0.9	1	100.00%	2	100.00%	7	92.74%
0.9 - 1.0	0	100.00%	0	100.00%	2	93.85%
>1.0	0	100.00%	0	100.00%	11	100.00%

* Deviation is calculated by the absolute difference between the mean from N=21 and reduced stations divided by the mean from N=21 stations.

Table C-4 Frequency table of the deviation of survey means of nitrate plus nitrite from 21 stations to 7, 3, and one stations.

Surface depth						
Deviation of nitrate+nitrite*	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	3	1.68%	2	1.12%	1	.56%
0.0 - 0.1	76	44.13%	60	34.64%	47	26.82%
0.1 - 0.2	32	62.01%	25	48.60%	26	41.34%
0.2 - 0.3	12	68.72%	15	56.98%	16	50.28%
0.3 - 0.4	16	77.65%	17	66.48%	14	58.10%
0.4 - 0.5	8	82.12%	15	74.86%	11	64.25%
0.5 - 0.6	7	86.03%	12	81.56%	9	69.27%
0.6 - 0.7	8	90.50%	13	88.83%	8	73.74%
0.7 - 0.8	2	91.62%	6	92.18%	20	84.92%
0.8 - 0.9	3	93.30%	3	93.85%	4	87.15%
0.9 - 1.0	4	95.53%	1	94.41%	11	93.30%
>1.0	8	100.00%	10	100.00%	12	100.00%

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Table C-4 (continued). Frequency table of the deviation of survey means of nitrate plus nitrite from 21 stations to 7, 3, and one stations.

Mid surface depth						
Deviation of nitrate+nitrite	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	3	1.68%	1	.56%	1	.56%
0.0 - 0.1	86	49.72%	58	32.96%	39	22.35%
0.1 - 0.2	23	62.57%	26	47.49%	25	36.31%
0.2 - 0.3	21	74.30%	16	56.42%	11	42.46%
0.3 - 0.4	15	82.68%	13	63.69%	11	48.60%
0.4 - 0.5	11	88.83%	14	71.51%	14	56.42%
0.5 - 0.6	6	92.18%	20	82.68%	17	65.92%
0.6 - 0.7	3	93.85%	11	88.83%	13	73.18%
0.7 - 0.8	4	96.09%	4	91.06%	11	79.33%
0.8 - 0.9	2	97.21%	7	94.97%	17	88.83%
0.9 - 1.0	1	97.77%	2	96.09%	14	96.65%
>1.0	4	100.00%	7	100.00%	6	100.00%
Mid depth						
Deviation of nitrate+nitrite	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	89	51.12%	68	38.20%	42	23.60%
0.1 - 0.2	34	70.22%	25	52.25%	26	38.20%
0.2 - 0.3	22	82.58%	24	65.73%	15	46.63%
0.3 - 0.4	14	90.45%	18	75.84%	14	54.49%
0.4 - 0.5	7	94.38%	9	80.90%	10	60.11%
0.5 - 0.6	4	96.63%	14	88.76%	16	69.10%
0.6 - 0.7	1	97.19%	7	92.70%	9	74.16%
0.7 - 0.8	2	98.31%	3	94.38%	10	79.78%
0.8 - 0.9	1	98.88%	2	95.51%	20	91.01%
0.9 - 1.0	1	99.44%	4	97.75%	10	96.63%
>1.0	1	100.00%	4	100.00%	6	100.00%

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Table C-4 (continued). Frequency table of the deviation of survey means of nitrate plus nitrite from 21 stations to 7, 3, and one stations.

Mid bottom depth						
Deviation of nitrate+nitrite	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	131	74.72%	87	48.88%	66	37.08%
0.1 - 0.2	29	91.01%	48	75.84%	33	55.62%
0.2 - 0.3	10	96.63%	18	85.96%	18	65.73%
0.3 - 0.4	2	97.75%	13	93.26%	17	75.28%
0.4 - 0.5	1	98.31%	5	96.07%	11	81.46%
0.5 - 0.6	1	98.88%	2	97.19%	9	86.52%
0.6 - 0.7	0	98.88%	0	97.19%	9	91.57%
0.7 - 0.8	0	98.88%	3	98.88%	2	92.70%
0.8 - 0.9	0	98.88%	0	98.88%	3	94.38%
0.9 - 1.0	1	99.44%	0	98.88%	10	100.00%
>1.0	1	100.00%	2	100.00%	0	100.00%
Bottom depth						
Deviation of nitrate+nitrite	From N21 to N7		From N21 to N3		From N21 to N1	
	frequency	*Cumulative %*	*frequency*	*Cumulative %*	*frequency*	*Cumulative %*
0	2	1.12%	0	.00%	0	.00%
0.0 - 0.1	143	81.01%	127	70.95%	73	40.78%
0.1 - 0.2	20	92.18%	26	85.47%	31	58.10%
0.2 - 0.3	6	95.53%	13	92.74%	17	67.60%
0.3 - 0.4	3	97.21%	5	95.53%	19	78.21%
0.4 - 0.5	2	98.32%	1	96.09%	11	84.36%
0.5 - 0.6	2	99.44%	2	97.21%	6	87.71%
0.6 - 0.7	0	99.44%	2	98.32%	9	92.74%
0.7 - 0.8	0	99.44%	0	98.32%	4	94.97%
0.8 - 0.9	0	99.44%	0	98.32%	2	96.09%
0.9 - 1.0	0	99.44%	1	98.88%	7	100.00%
>1.0	1	100.00%	2	100.00%	0	100.00%

* Deviation is calculated by the absolute difference between the mean from N=21 and reduced stations divided by the mean from N=21 stations.

C.2 Combined effect of reducing numbers of surveys and number of stations

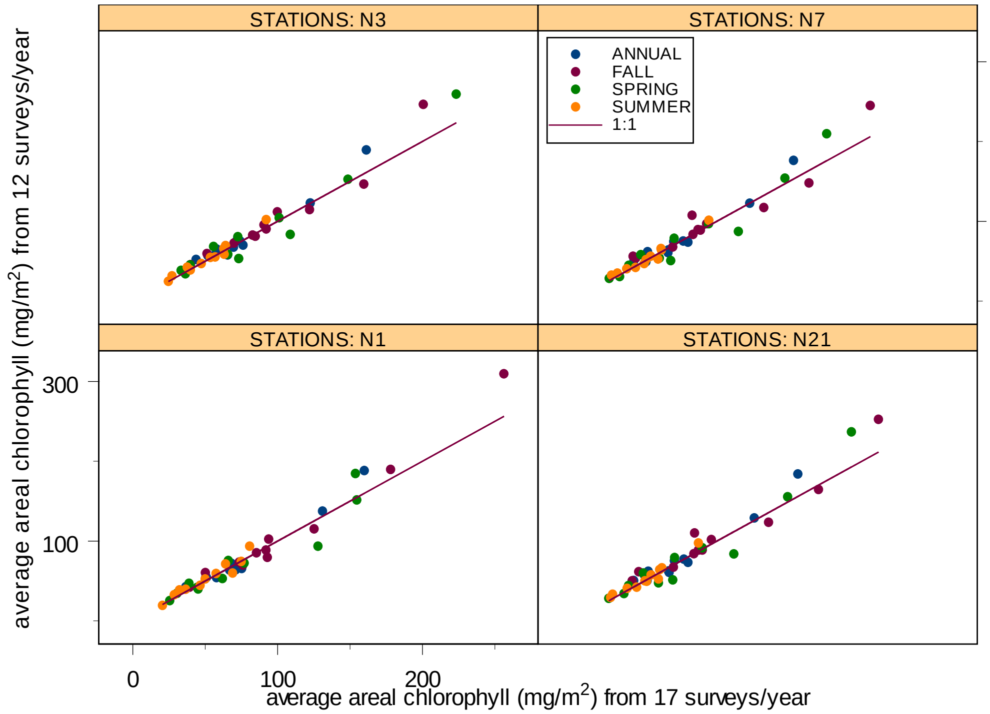


Figure C-1 Deviation of annual and seasonal averages of areal chlorophyll from current 17 to 12 surveys per year with four different scenarios of sample stations in the nearfield.

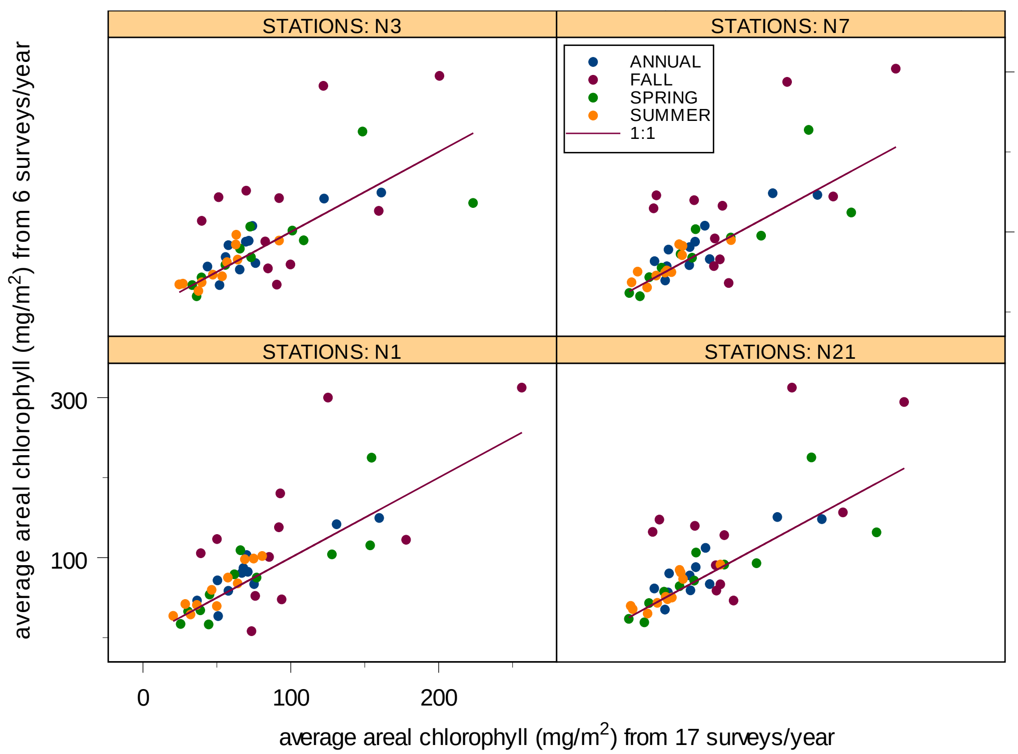


Figure C-2 Deviation of annual and seasonal averages of areal chlorophyll from current 17 to 6 surveys per year with four different scenarios of sample stations in the nearfield.

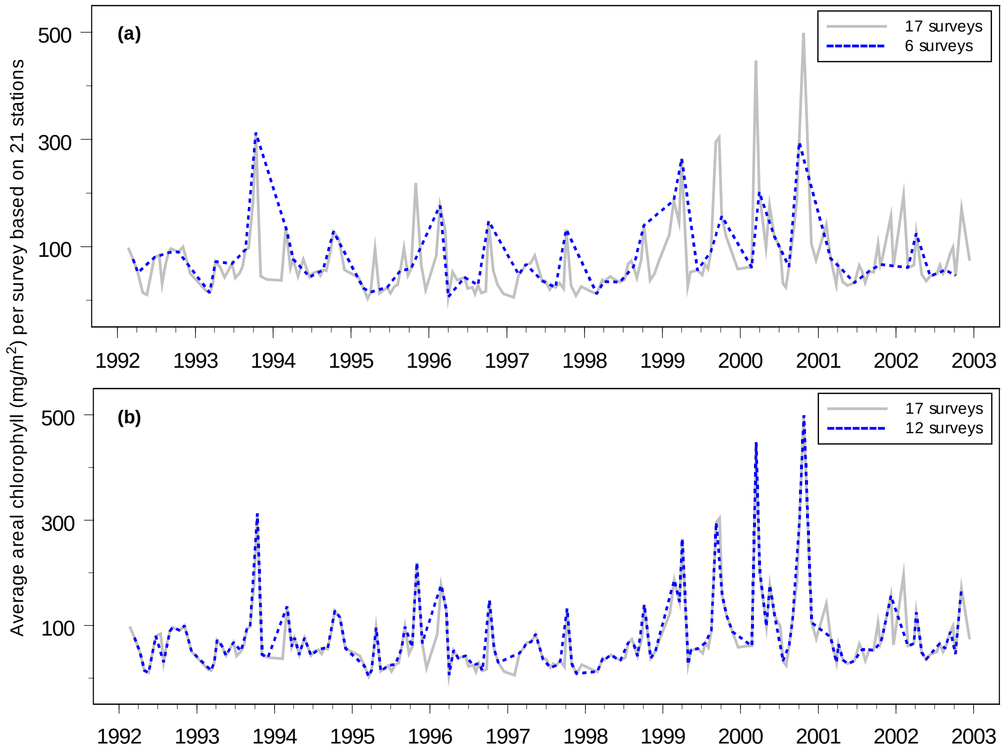


Figure C-3 Deviation of temporal pattern of average areal chlorophyll per survey based on 21 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

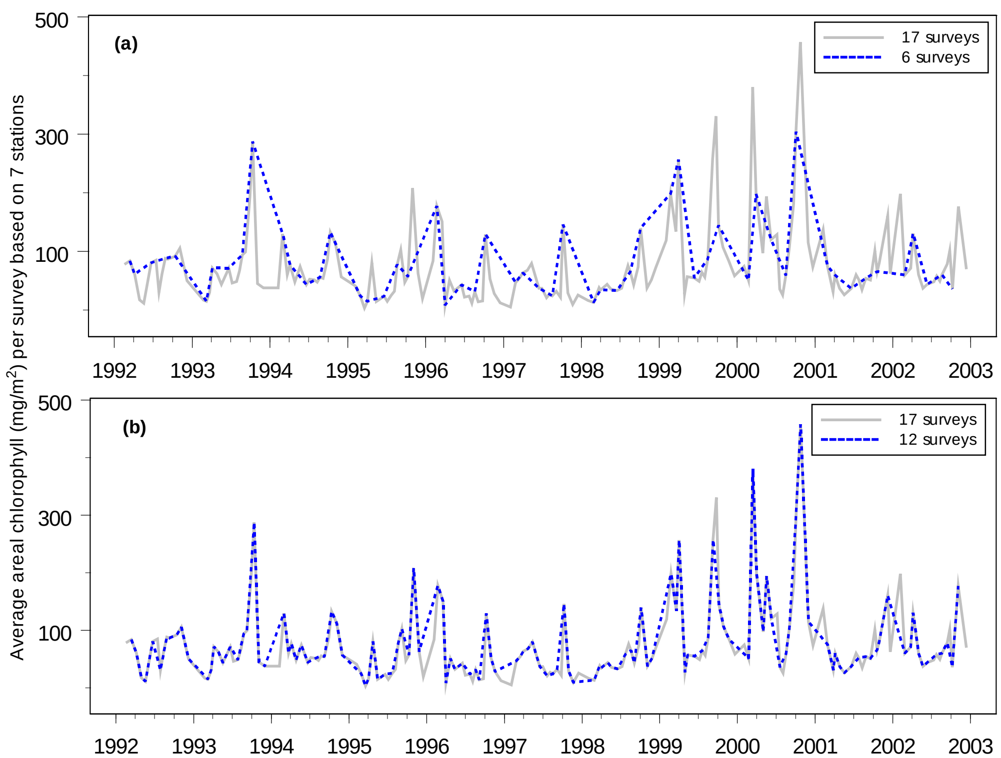


Figure C-4 Deviation of temporal pattern of average areal chlorophyll per survey based on 7 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

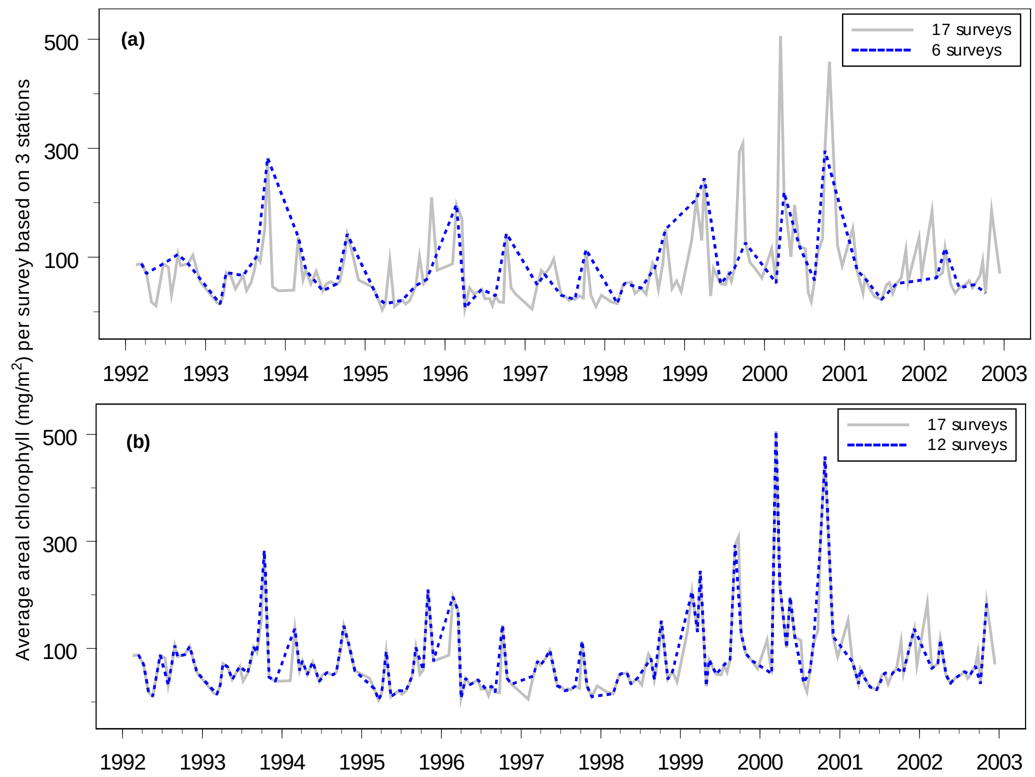


Figure C-5 Deviation of temporal pattern of average areal chlorophyll per survey based on 3 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

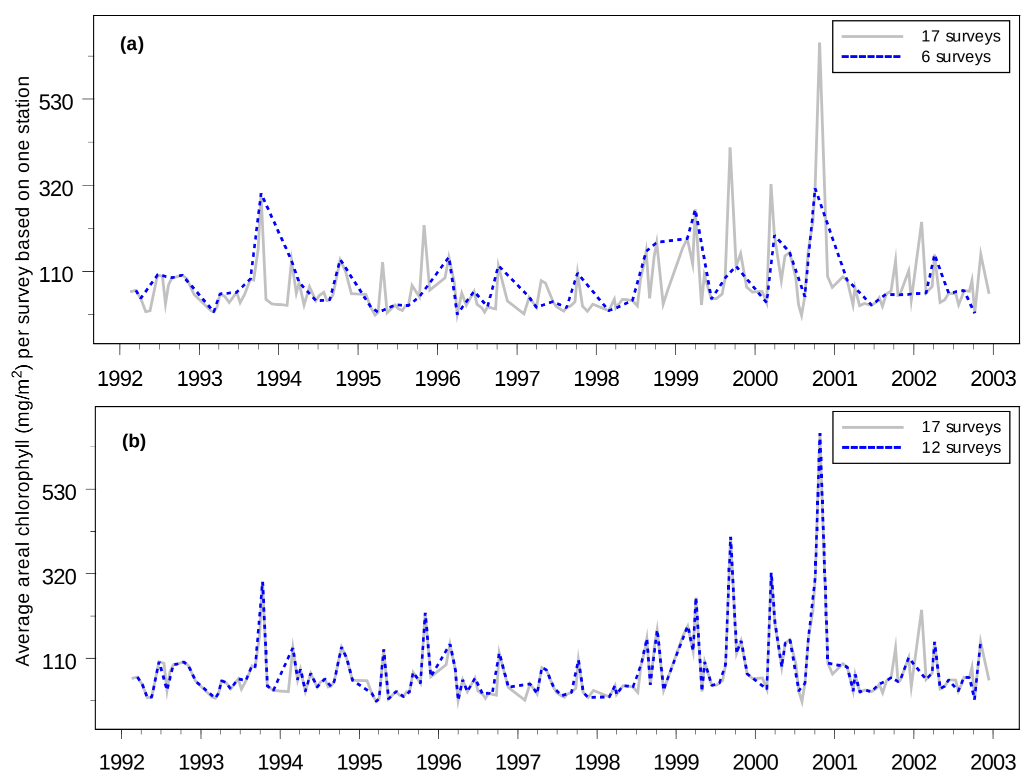


Figure C-6 Deviation of temporal pattern of average areal chlorophyll per survey based on one station from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

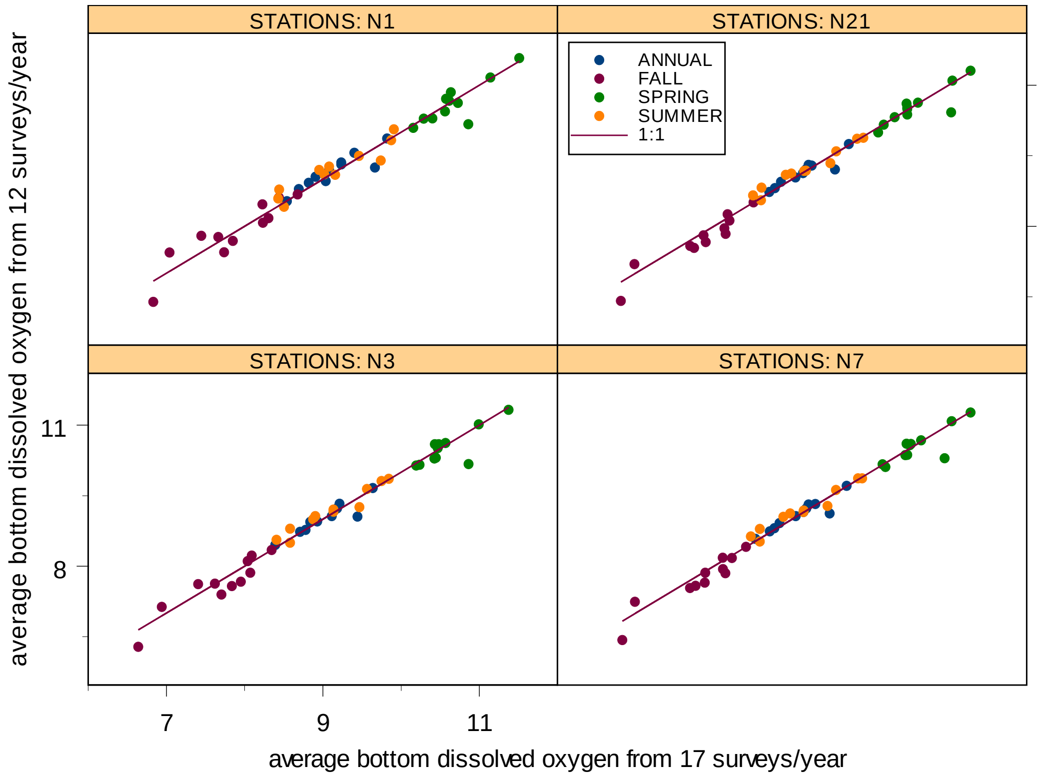


Figure C-7 **Deviation of annual and seasonal averages of areal chlorophyll from current 17 to 12 surveys per year with four different scenarios of sample stations in the nearfield.**

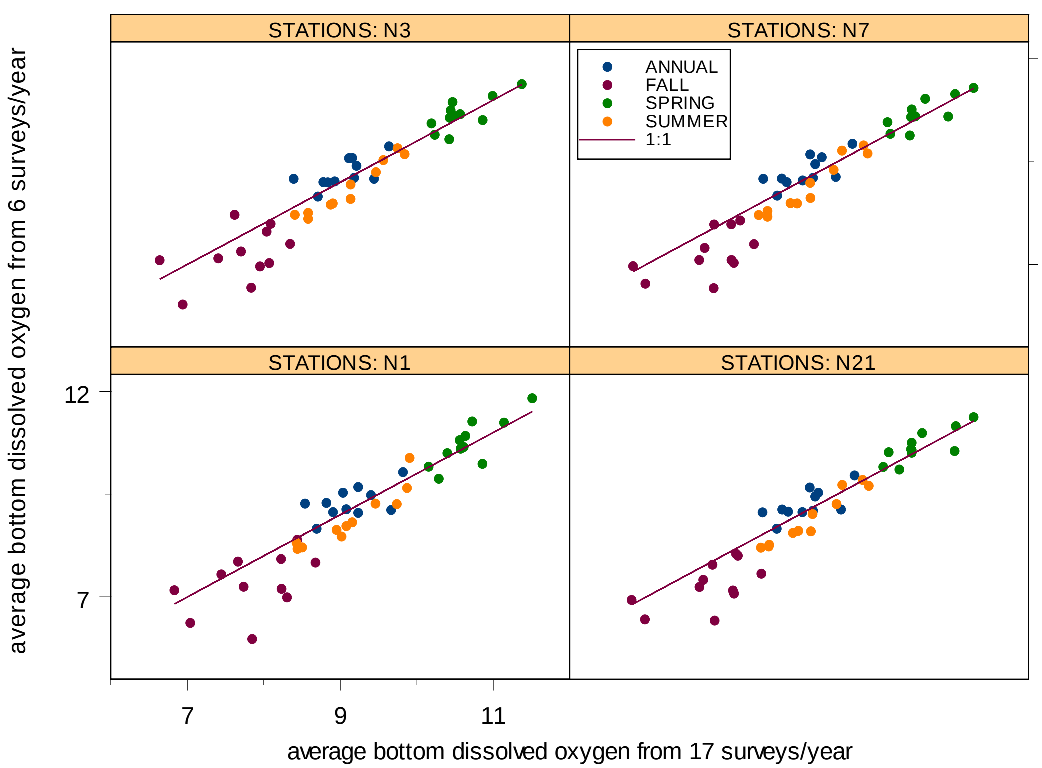


Figure C-8 **Deviation of annual and seasonal averages of areal chlorophyll from current 17 to 6 surveys per year with four different scenarios of sample stations in the nearfield.**

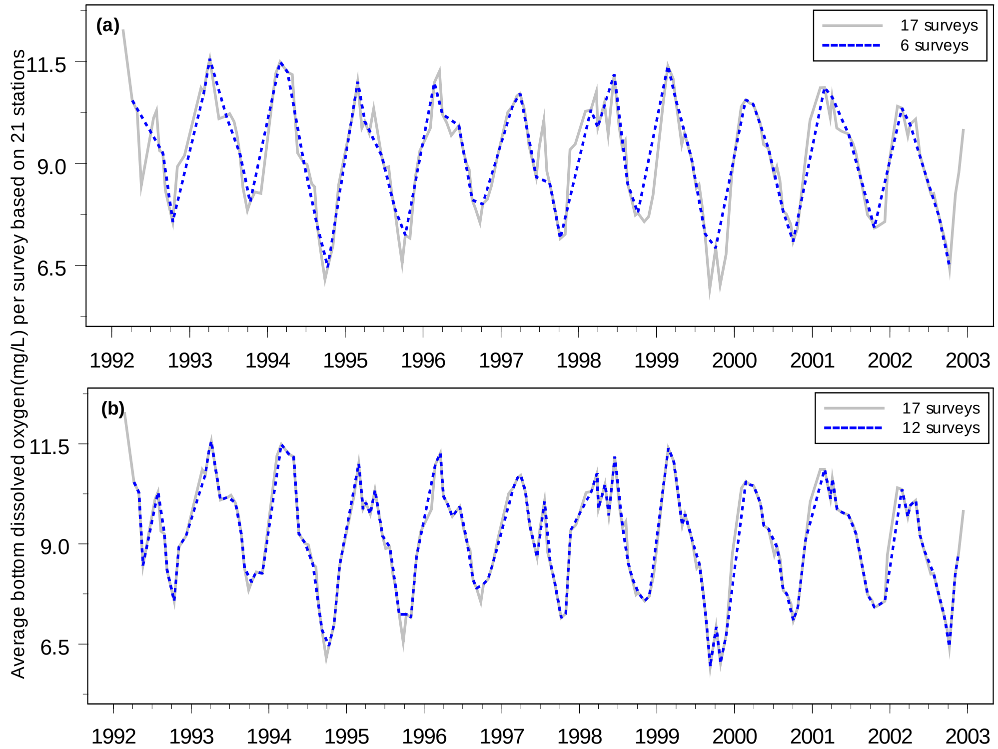


Figure C-9 **Deviation of temporal pattern of average bottom dissolved oxygen per survey based on 21 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).**

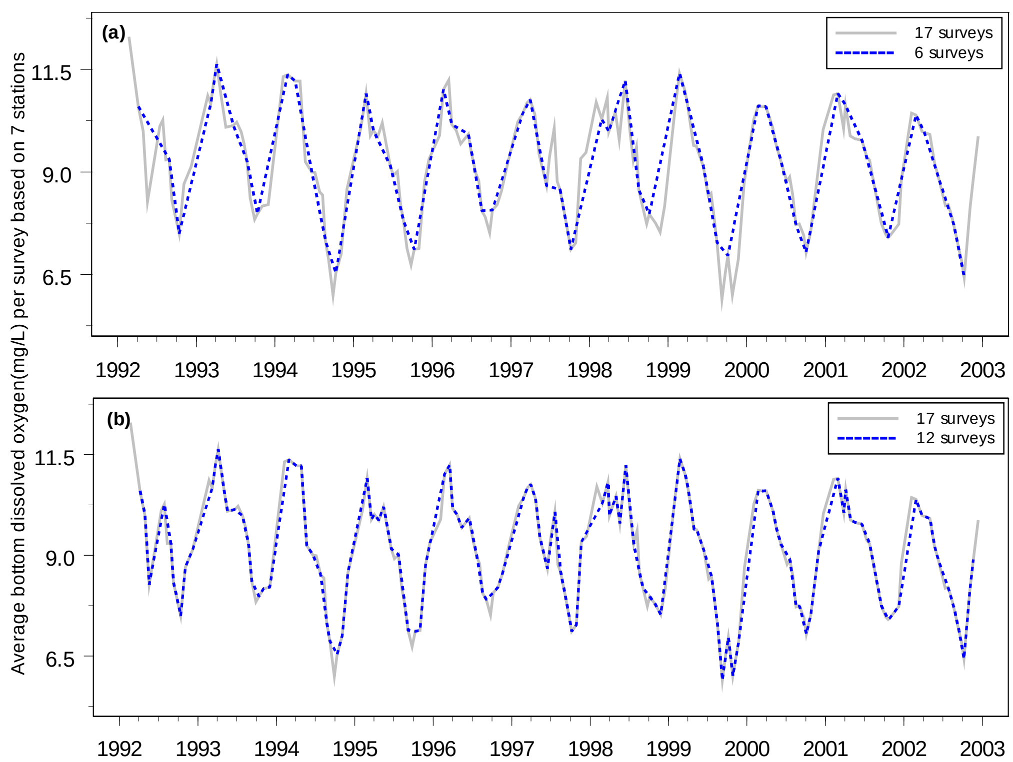


Figure C-10 **Deviation of temporal pattern of average bottom dissolved oxygen per survey based on 7 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).**

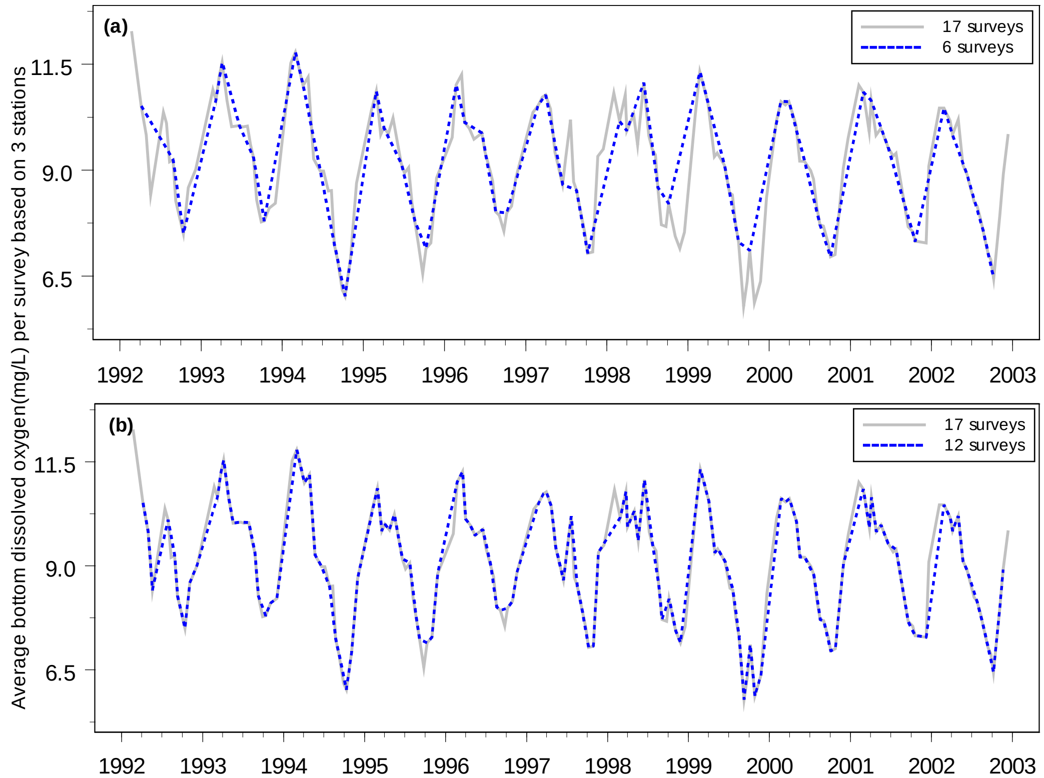


Figure C-11 Deviation of temporal pattern of average bottom dissolved oxygen per survey based on 3 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

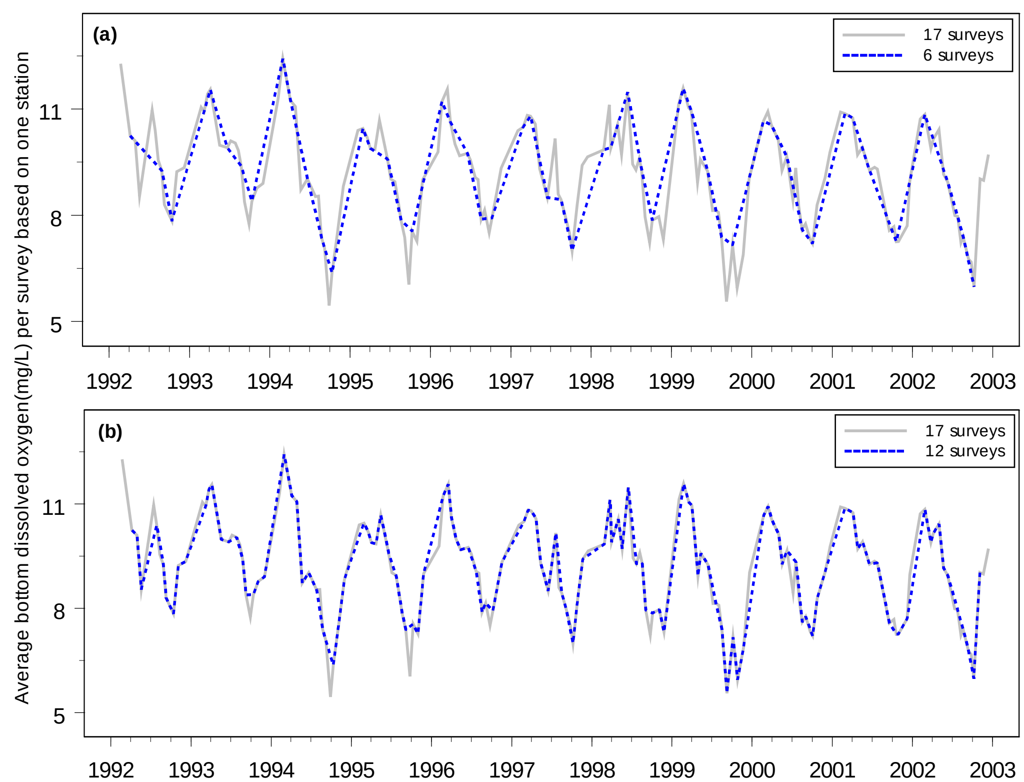


Figure C-12 Deviation of temporal pattern of average bottom dissolved oxygen per survey based on 3 stations from current 17 to 6 surveys per year (a) and to 12 surveys per year (b).

C.3 Sensitivity to number and timing of surveys

Many combinations of 10-12 surveys/year seem to do a fair job of reproducing the pattern (if not the absolute values) in nearfield seasonal mean chlorophyll, while many fewer 8 and 6 survey subsets do. For both of those, the top 5 ranked combinations seem to overestimate high chlorophyll seasons and slightly underestimate low chlorophyll seasons.

Tables C-5 through C-8 summarize the survey layout for the 5 subsets per "n" whose seasonal means have the strongest correlations with those for the full dataset.

Table C-5 Subsets of 12 surveys/year with highest *r* between subset seasonal means and those of whole dataset.

Index	643	644	328	639	337
Rank	1	2	3	4	5
r	0.9893	0.9890	0.9877	0.9873	0.9867
Surveys	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	7	7	6	7	6
	9	9	8	9	8
	12	13	10	12	10
	14	14	11	13	11
	15	15	12	14	13
	16	16	14	15	15
	17	17	16	16	17
Surveys/season					
Spring	4.5	4.5	4.5	4.5	4.5
Summer	2.5	2.5	4.5	2.5	4.5
Fall	5	5	3	5	3

Table C-6	Subsets of 10 surveys/year with highest *r* between subset seasonal means and those of whole dataset.				
Index	456	465	591	500	462
Rank	1	2	3	4	5
r	0.9825	0.9819	0.9785	0.9766	0.9749
Surveys	1	1	1	1	1
	2	2	2	2	2
	3	3	3	3	3
	4	4	4	4	4
	5	5	5	5	5
	7	7	8	7	7
	9	9	9	10	9
	12	13	13	13	13
	14	15	15	15	14
	16	17	17	17	16
Surveys/season					
Spring	4.5	4.5	4.5	4.5	4.5
Summer	2.5	2.5	2.5	2.5	2.5
Fall	3	3	3	3	3

Table C-7	Subsets of 8 surveys/year with highest *r* between subset seasonal means and those of whole dataset.				
Index	525	441	546	5661	5850
Rank	1	2	3	4	5
r	0.9663	0.9651	0.9605	0.9602	0.9600
Surveys	1	1	1	1	1
	2	2	2	3	3
	3	3	3	4	4
	4	4	4	6	7
	8	7	8	8	8
	9	9	10	10	9
	13	13	13	13	13
	15	15	15	15	15
Surveys/season					
Spring	4	4	4	3	3
Summer	2	2	2	3	3
Fall	2	2	2	2	2

Table C-8	**Subsets of 6 surveys/year with highest r between subset seasonal means and those of whole dataset.**				
Index	2176	1559	2092	2197	2113
Rank	1	2	3	4	5
r	0.9419	0.9402	0.9380	0.9375	0.9341
Surveys	1	1	1	1	1
	3	3	3	3	3
	8	4	7	8	7
	9	8	9	10	10
	13	13	13	13	13
	15	15	15	15	15
Surveys/season					
Spring	2	3	2	2	2
Summer	2	1	2	2	2
Fall	2	2	2	2	2

APPENDIX D

D. EFFECT OF REDUCING NUMBERS OF NEARFIELD STATIONS - BEFORE AND AFTER DIVERSION OF FLOW TO THE NEW OUTFALL

Suh Yuen Liang

D.1 Background

This analysis is supplementary to Section 7.3, which demonstrated—using three alternative scenarios of stations and four key parameters—the effect of reducing the number of water column stations on the distribution of and deviation from the current (21-station) survey means. These analyses showed that the survey means and variances from seven stations were very similar to those based on data collected at 21 stations. These analyses were performed on data collected before and after the outfall went on-line grouped together. At the June 19, 2003 workshop which reviewed the water column monitoring, OMSAP requested that the analyses be carried out on the post-diversion data separately, to confirm that the statistical relationships held for that data set.

D.2 Data analysis and results

Chlorophyll

Figure D-1 shows scatterplots for the pre-diversion and post-diversion data for areal chlorophyll. The survey means from the full station set (21 stations) were plotted against those from each of three alternative scenarios to show the linear association. Figure D-1 shows a strong linear association, with the slopes close to a one-to-one relationship between 21-station means and those from all three alternatives in both the pre-diversion and post-diversion periods. The correlation coefficients between 21-station means and those from each of three alternative scenarios for both periods are all greater than 0.93 (Table D-1). Figure D-2 shows the cumulative density curves of deviation from 21-station means in the pre- and post-diversion period. The pre- and post-diversion curves are similar to each other for all three scenarios. The proportion of deviation from 21-station means is smallest for the 7-station scenario and greatest for the 1-station scenario, as also shown in Table C-1.

Dissolved oxygen

Figure D-3 shows scatterplots for the pre-diversion and post-diversion data for bottom dissolved oxygen. The result is similar to areal chlorophyll, with a strong linear association between 21-station means and those from three alternative scenarios for both periods. The correlation coefficients between 21-station means and each of alternative scenarios for both periods are all greater than 0.97, with little difference between periods (Table D-1). Figure D-4 shows the cumulative density of deviations from the 21-station survey means in the pre- and post-diversion period. No difference in the deviation from 21-station means between pre- and post-diversion periods is found for all three scenarios. The deviation increases as the number of sampling stations decreases, similar to the results in Table C-2.

Ammonium
Figure D-5 shows scatterplots for the pre-diversion and post-diversion data for ammonium at all five sampling depths. The linear association with 21-station means is better for the 7-station scenario and worse for the 1-station scenario at all five discrete depths. The correlations between the 21-station means and those from the 7-station scenario at five depths are consistently stronger in the pre-diversion period than in the post-diversion period (Table D-1). This pattern is not seen in the 3- and 1-station scenarios. Figure D-6 shows cumulative density curves at five depths in the pre- and post-diversion period. The curves show a higher proportion of mean departure from 21-station means in the post-diversion period than in the pre-diversion period for all three scenarios. The deviation also increases as the number of sampling stations decreases.

Nitrate+Nitrite
The linear association and correlation coefficients between 21-station means and three alternative scenarios for nitrite + nitrate at five depths are all relatively high and generally similar for both pre-diversion and post-diversion periods (Figure D-6 and Table D-1). All three alternative scenarios seem to be able to account for approximately 90% or more of the variability seen by the current 21-station design before and after diversion. The difference in deviation from 21-station means between periods is smallest for the 7-station scenario at five depths (Figure D-7). The 7-station scenario also has the least departure from 21-station means among three alternative scenarios.

D.3 Summary
The high linear association between current (21-station) means and those from each of three alternative sampling scenarios in the pre- and post-diversion period suggests that all alternative scenarios are capable of capturing the trend of means from the present sampling design for areal chlorophyll, bottom dissolved oxygen, and nitrite + nitrate in both periods. The mean departure from current means increases as the number of sampling stations decreases and is relatively consistent between pre- and post-discharge periods for these three parameters. In contrast, the survey means for ammonium from the 7-station scenario correlate with current 21-station means better at all five depths in both periods than those from the other two alternative scenarios. Furthermore, there is a decrease in linear association and an increase in deviation between current means and those from the each of three alternative scenarios for ammonium in the post-diversion period. The results are consistent with an increase in spatial variability for ammonium in the post-diversion period, which is reasonable given that the outfall is the major local source for ammonium. Despite the increase in spatial variability of ammonium in the nearfield due to discharge through the new outfall, the proposed 7-station scenario still can capture 80% or more of the variability seen by the current sampling design.

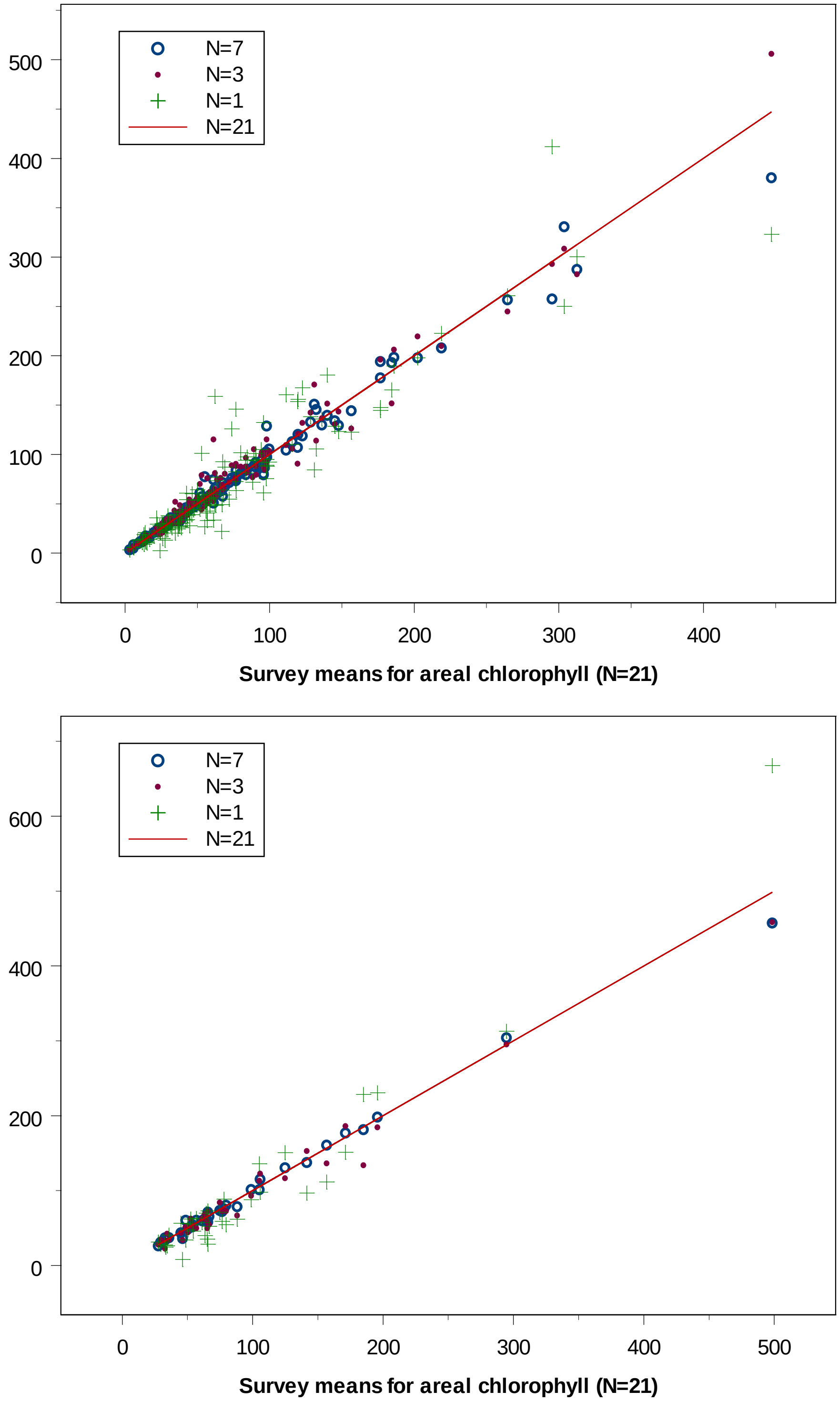


Figure D-1 Scatterplot of subset survey means of areal chlorophyll compared to those from all nearfield stations in the pre-diversion (top) and post-diversion (bottom) period.

The red line is one-to-one ratio of the survey means from all nearfield stations.

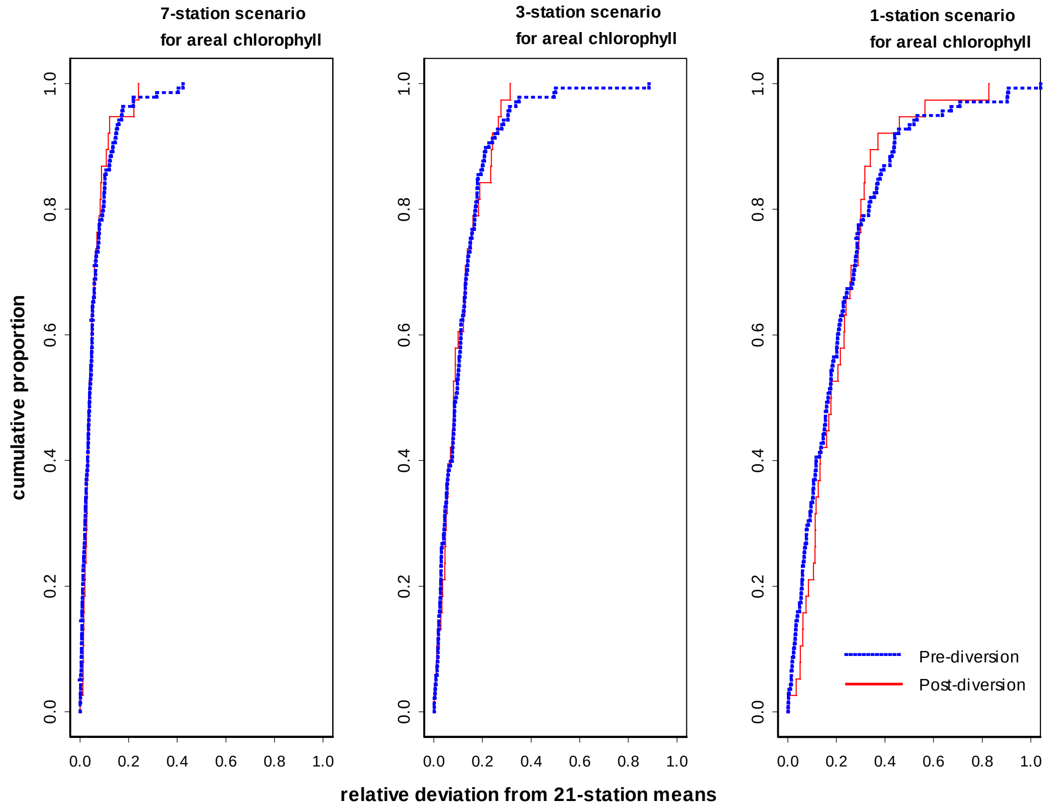
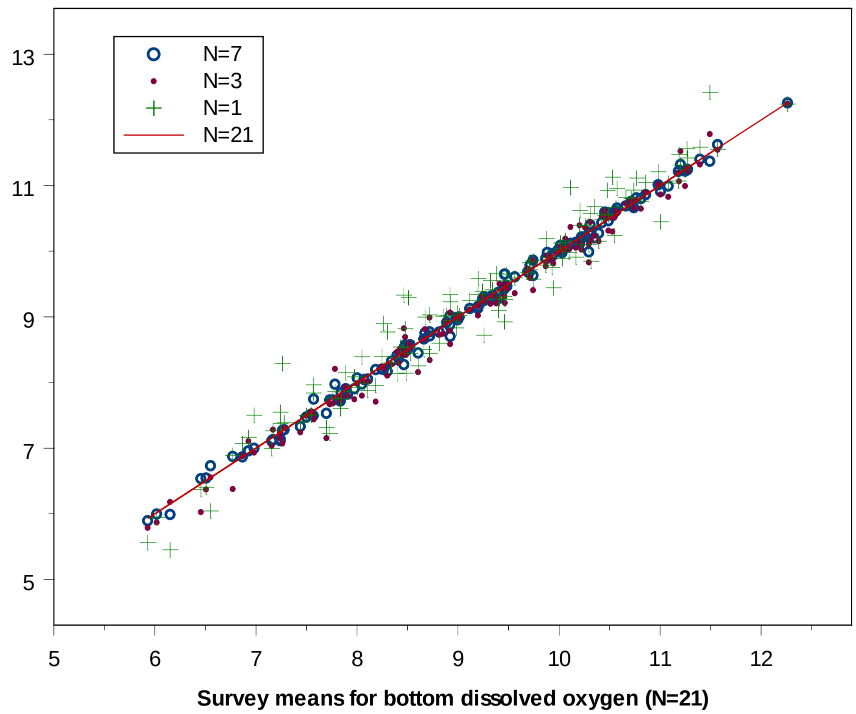


Figure D-2 Cumulative density of deviation from 21-station means for areal chlorophyll for 7-station, 3-station, and 1-station scenario from 21-station means in the pre-and post-diversion period.

Relative deviation is defined as the absolute difference between the 21-station mean and the mean from the alternative scenario divided by the 21-station mean.



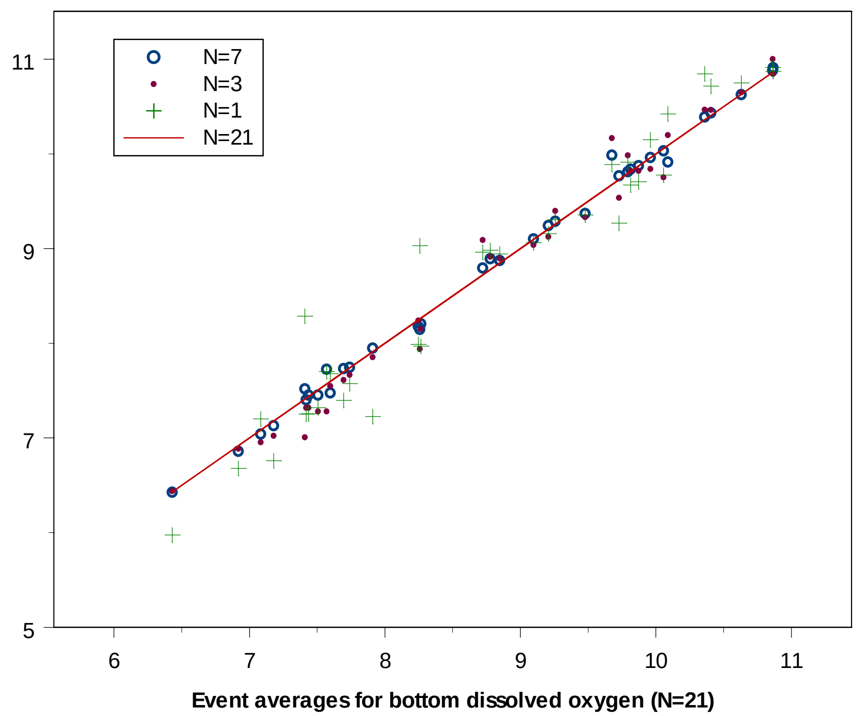


Figure D-3 Scatterplot of subset survey means of bottom dissolved oxygen compared to those from all nearfield stations in the pre-diversion (top) and post-diversion (bottom) period

The red line is one-to-one ratio of the survey means from all nearfield stations.

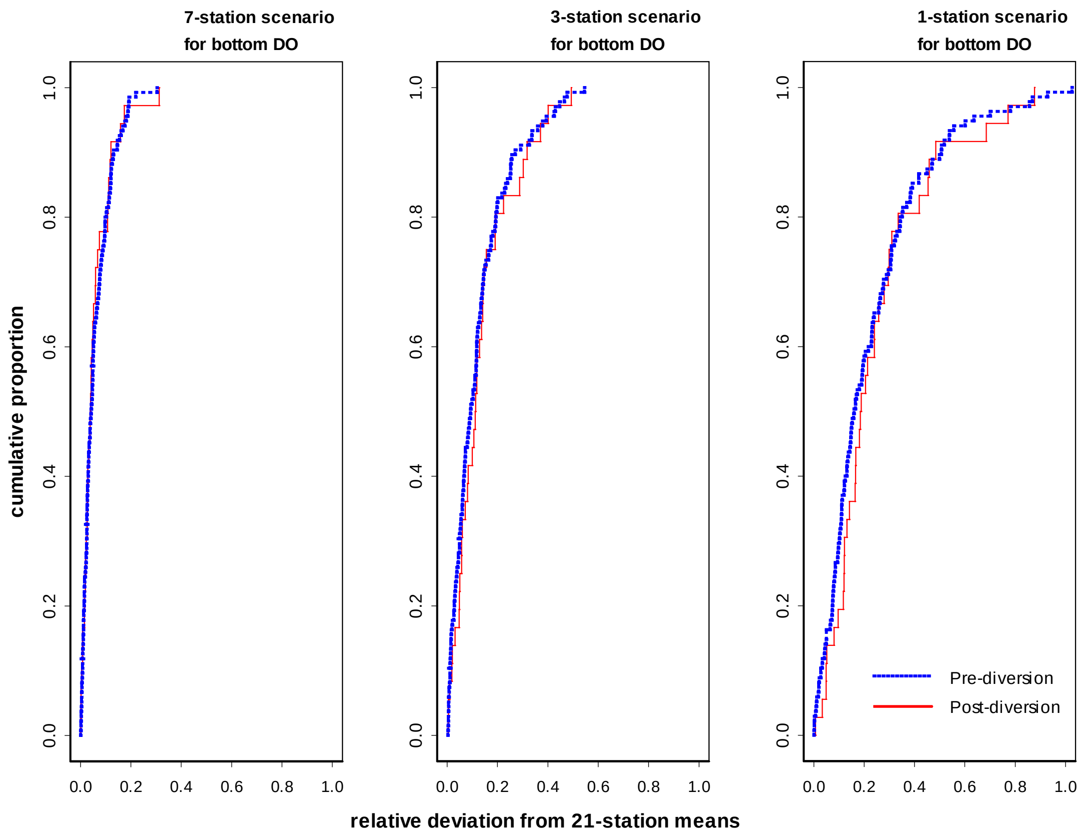


Figure D-4 Cumulative density of deviation from 21-station means for bottom dissolved oxygen for 7-station, 3-station, and 1-station scenario from 21-station means in the pre-and post-diversion period.

Relative deviation is defined as the absolute difference between the 21-station mean and the mean from the alternative scenario divided by the 21-station mean.

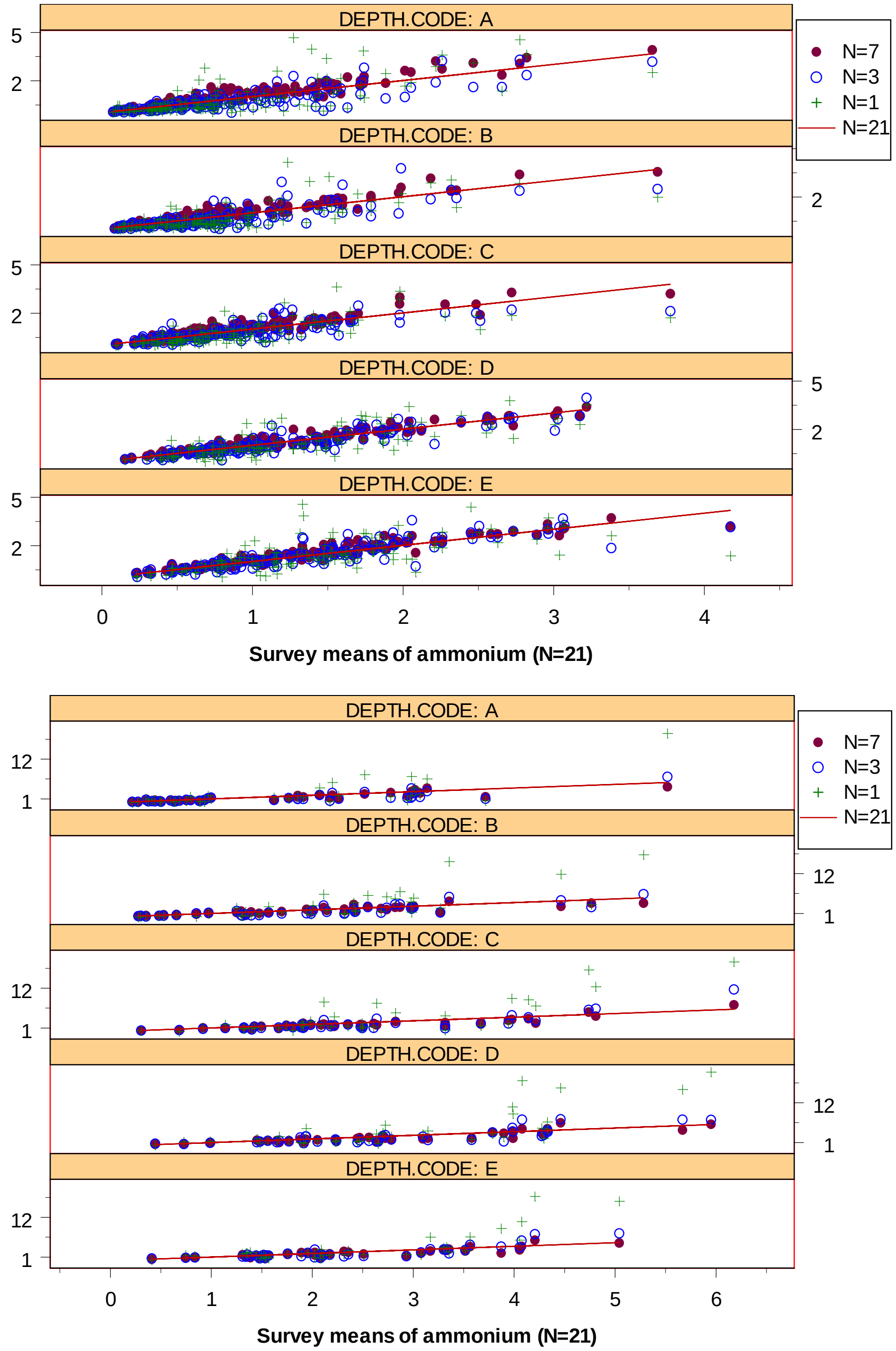
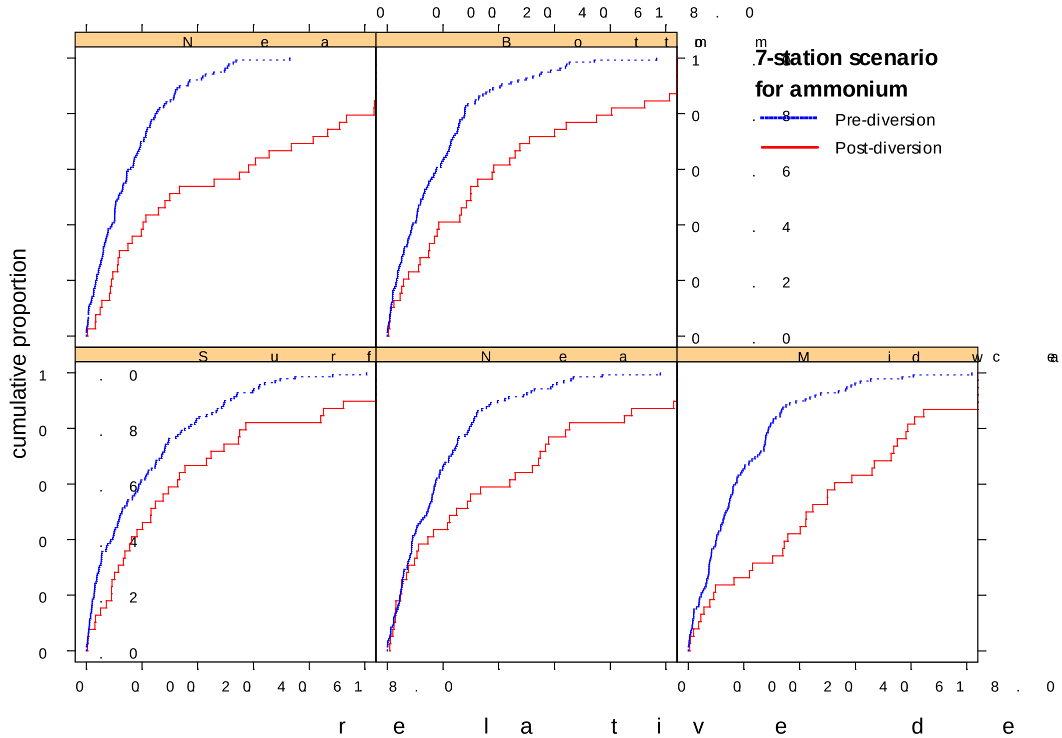


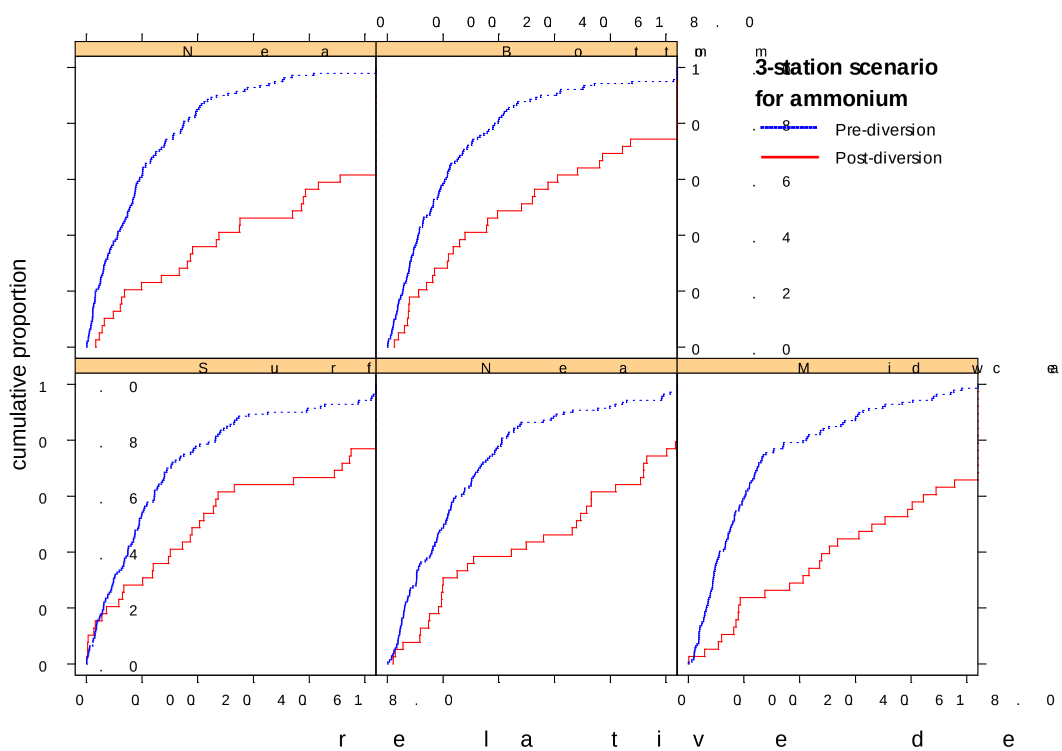
Figure D-5 Scatterplot of subset survey means of ammonium compared to those from all nearfield stations at five depths in the pre-diversion (top) and post-diversion (bottom) period.

The red line is one-to-one ratio of the survey means from all nearfield stations.

(a)


7-station scenario
for ammonium
Pre-diversion
Post-diversion
cumulative proportion

(b)


3-station scenario
for ammonium
Pre-diversion
Post-diversion
cumulative proportion

(c)

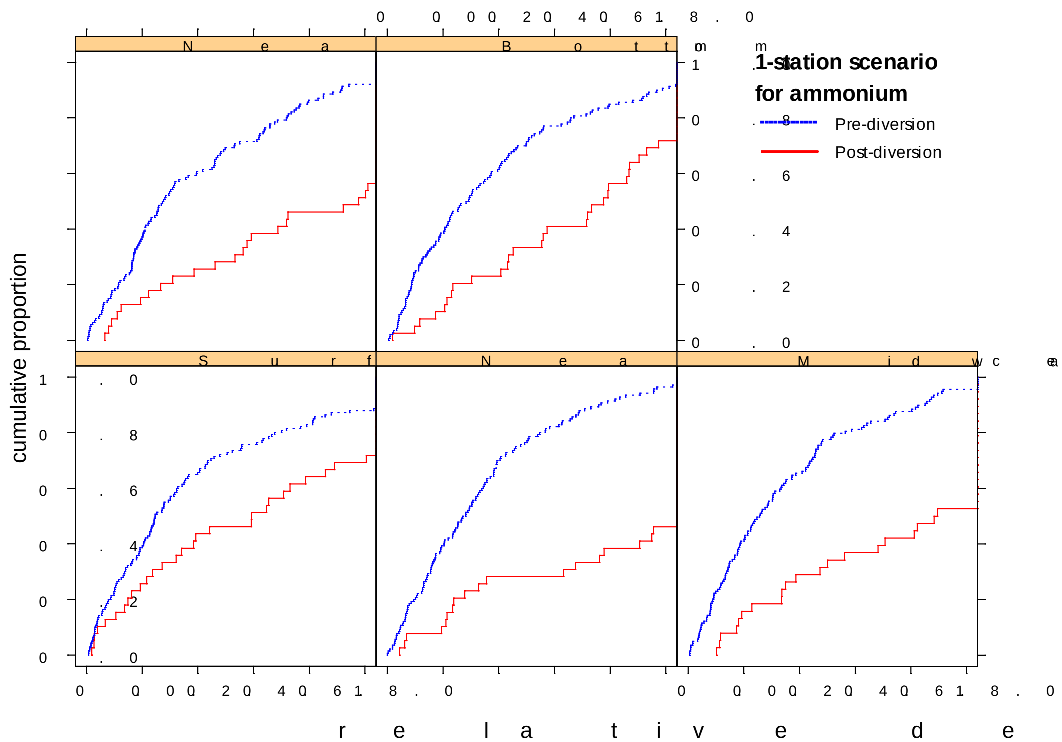
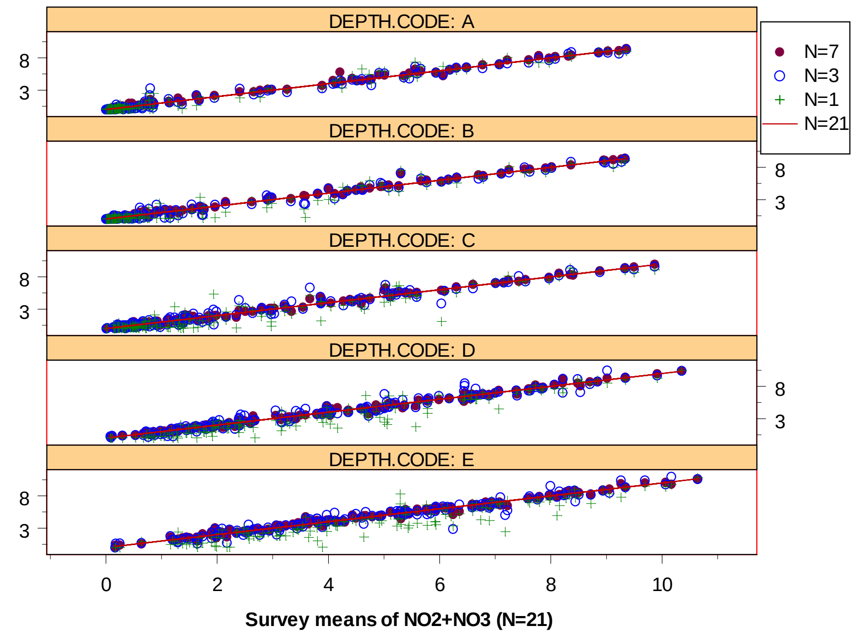


Figure D-6 Cumulative density curves of deviation from 21-station means for ammonium for 7-station (a), 3-station (b), and 1-station (c) scenario at five depths (surface, near-surface, midwater, near-bottom, and bottom depth) in the pre-and post-diversion period.

Relative deviation is defined as the absolute difference between the 21-station mean and the mean from each of the alternative scenarios divided by the 21-station mean.



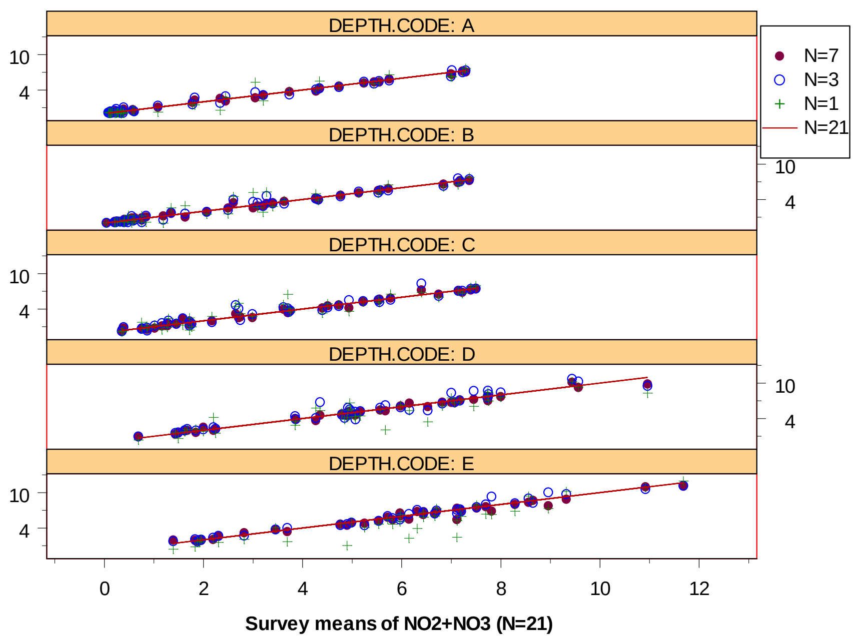
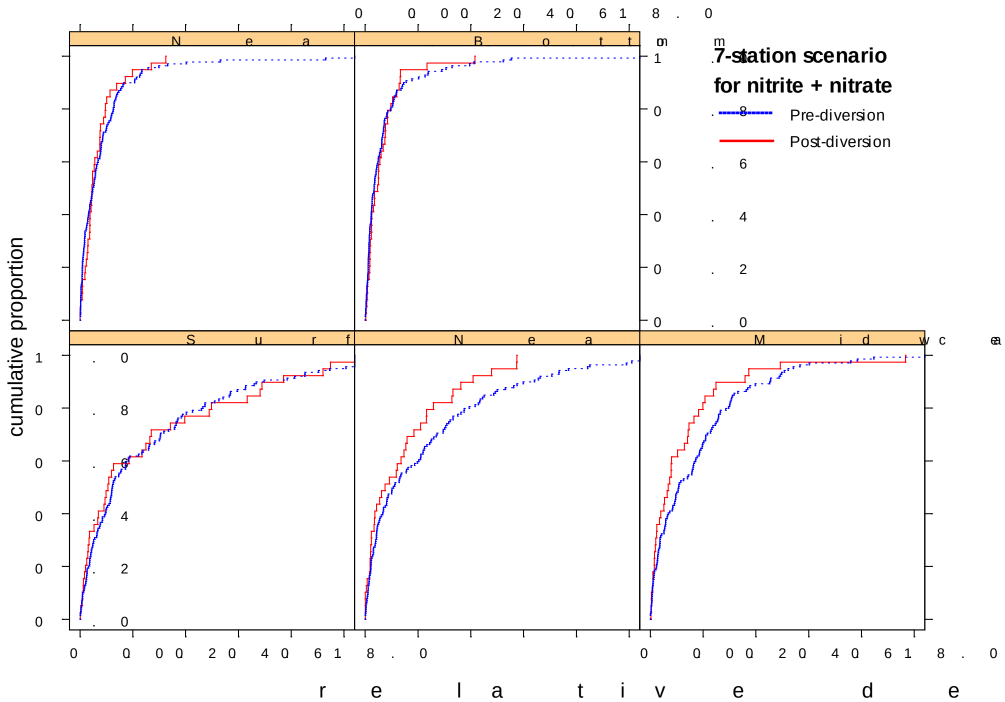


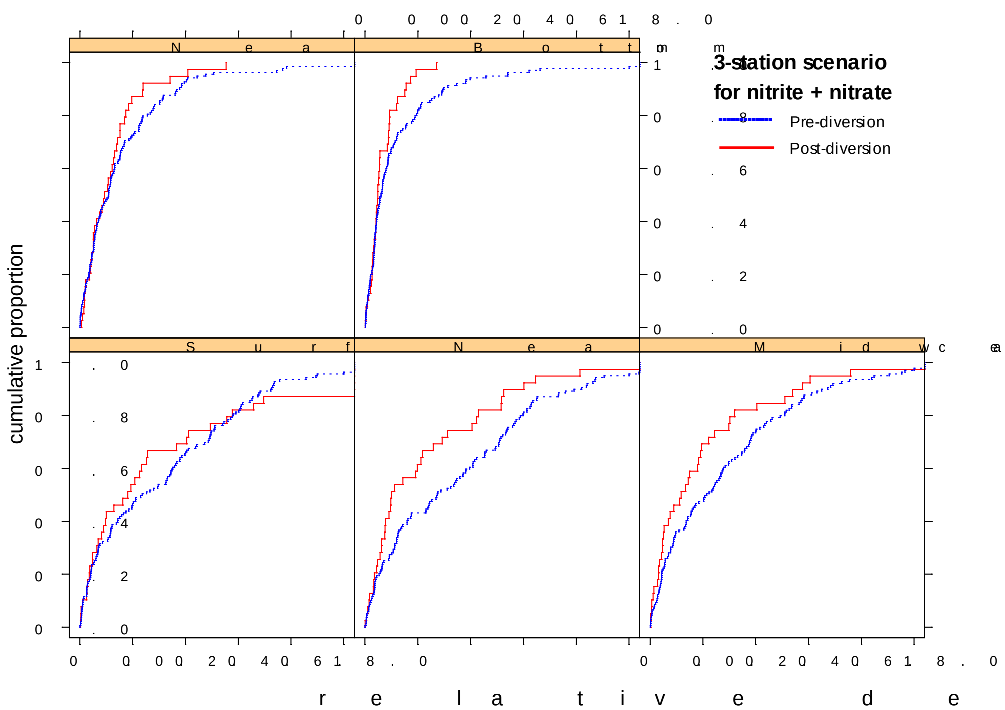
Figure D-7 Scatterplot of subset survey means of nitrite + nitrate compared to those from all nearfield stations at five depths in the pre-diversion (top) and post-diversion (bottom) period.

Depth code A to E denote surface, near-surface, midwater, near-bottom, and bottom depth, respectively. The red line is one-to-one ratio of the survey means from all nearfield stations.

(a)


cumulative proportion
7-station scenario
for nitrite + nitrate
Pre-diversion
Post-diversion

(b)


cumulative proportion
3-station scenario
for nitrite + nitrate
Pre-diversion
Post-diversion

(c)

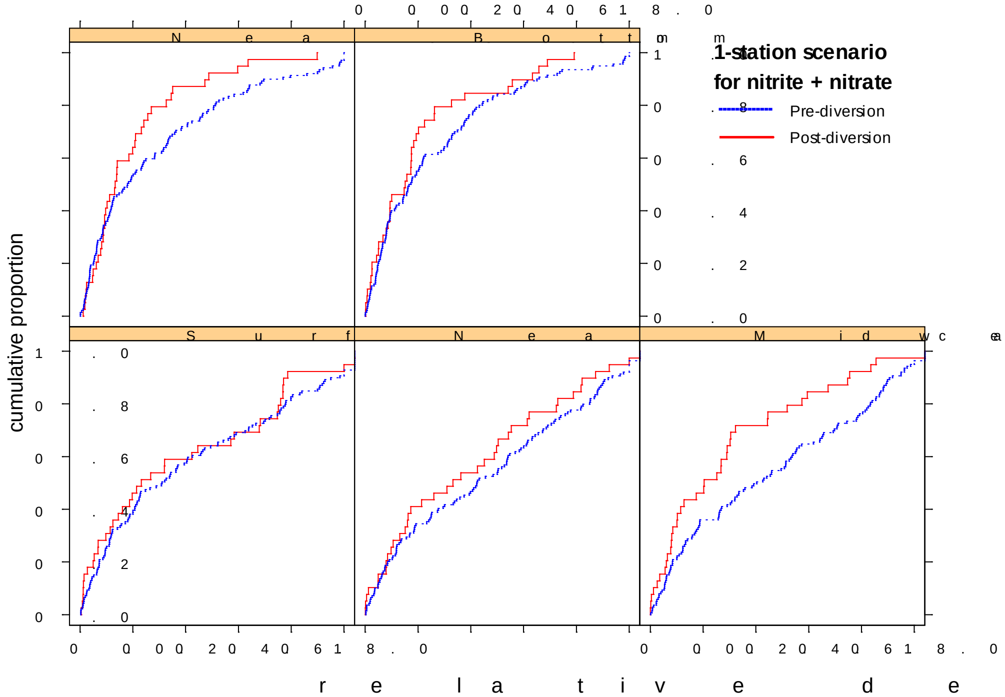


Figure D-8 Cumulative density curves of deviation from 21-station means for nitrite+nitrate for 7-station (a), 3-station (b), and 1-station (c) scenario at five depths (surface, near-surface, midwater, near-bottom, and bottom depth) in the pre-and post-diversion period.

Relative deviation is defined as the absolute difference between the 21-station mean and the mean from the alternative scenario divided by the 21-station mean.

Table D-1 Correlation coefficients between nearfield survey means for the current design (21 stations) and three alternative scenarios of stations (7, 3, and 1 station) before and after diversion.

Pre and Post denote the pre-diversion and post-diversion period, respectively.

Parameter/ depth	Station Subset					
	7		3		1	
	Pre	Post	Pre	Post	Pre	Post
Areal chlorophyll	0.991	0.996	0.985	0.990	0.932	0.976
Bottom DO	0.998	0.998	0.994	0.992	0.979	0.974
Ammonium						
Surface	0.949	0.903	0.819	0.795	0.697	0.715
Near-surface	0.942	0.864	0.779	0.820	0.717	0.738
Midwater	0.921	0.899	0.782	0.831	0.679	0.800
Near-bottom	0.957	0.880	0.904	0.810	0.763	0.748
Bottom	0.951	0.866	0.878	0.847	0.684	0.769
Nitrate/Nitrite						
Surface	0.996	0.998	0.990	0.992	0.986	0.972
Near-surface	0.997	0.995	0.988	0.983	0.973	0.944
Midwater	0.994	0.991	0.978	0.966	0.943	0.933
Near-bottom	0.994	0.991	0.977	0.959	0.951	0.896
Bottom	0.992	0.985	0.971	0.985	0.923	0.899

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