

MASSACHUSETTS BAYS PROGRAM (MBP) RESEARCH AND PLANNING GRANTS

FY 2012

Final Report

28 December 2012

Project Title: Determining the nature and causes of turbidity events in Salem Harbor (MA) through estuarine water quality monitoring

PI: J. Bradford Hubeny, Ph.D.

Department of Geological Sciences, Salem State University

Abstract:

Continuous water quality monitoring was conducted at five new buoy monitoring stations in Salem Harbor from May – December 2012 in order to better constrain the nature and causes of turbidity events in the harbor. Surface temperature, conductivity, and turbidity were quantified along with bottom temperature, water level, and meteorological data to test four specific hypothetical causes for increased turbidity: wind events, runoff events, tidal currents, or phytoplankton increases. Seasonal phytoplankton increases appear to dominate the turbidity data during the summer months, mostly overwhelming potential signals from the other causes. Wind events appear to initiate turbid conditions during periods in which winds are high and shifting (veering or backing). Although the linkage between wind and turbidity is likely due to boats shifting on their moorings, linkages between wind and turbidity after most boats were removed in the fall suggest that other processes, such as shallow water wave resuspension, may provide an additional mechanism. Weak linkages were observed between precipitation and turbidity, suggesting that runoff may provide particulate matter to the harbor. No apparent connection was observed between tidal currents and turbidity, suggesting that this cause of turbidity is not significant in Salem Harbor. Seasonal stratification of the water column in deeper sites complicates resuspension dynamics due to a lack of communication between bottom and surface waters. Further monitoring and geochemical characterization of the particulate matter in Salem Harbor is recommended in order to further refine the interpretations presented here.

Introduction

Poor water quality in Massachusetts' coastal water bodies can cause adverse ecological effects (Chase et al., 2002; Costello and Kenworthy, 2011; Evans et al., 2011). Turbidity, which is an optical property that quantifies light transmission through the water column, is a key water quality parameter due to its direct influence on the photosynthetic compensation depth. Specific ecologic effects of high turbidity, and associated suspended particulate matter, include light limitation of submerged aquatic vegetation (SAV) such as eelgrass (Dennison et al., 1993; Moore et al., 1997; Nielsen et al., 2002; Olesen, 1996) and the associated reduced dissolved oxygen; various effects on pelagic and benthic invertebrates associated with clogging of filtration systems, burial, and substrate alteration (Wilber and Clarke, 2001; Zweig and Rabeni, 2001); and effects on fish through gill clogging and associated reduced resistance to disease, and stress to migrating, spawning, and developing fish eggs and larvae (Newcombe, 2003; Newcombe and Jensen, 1996; Wilber and Clarke, 2001).

Salem Harbor is part of Salem Sound and located along Massachusetts' North Shore. A comprehensive survey of Salem Sound has demonstrated the relative good health of this estuary and highlighted the resources within the water body (Chase et al., 2002). Recent monitoring of eelgrass areal abundance, however, has demonstrated that Salem Harbor has experienced one of the state's largest declines in eelgrass abundance over the period 1995 – 2006 (Costello and Kenworthy, 2011). Over roughly this same period, turbidity has increased as estimated by secchi depth measurements taken adjacent to the red #22 buoy south of Winter Island. The average secchi depth measured in the Division of Marine Fisheries assessment in 1997 was 3.5 meters (Chase et al., 2002). Hubeny and Salem Sound Coastwatch (SSCW) monitored this same location during 2010 – 2011 and obtained an average secchi depth of 3.2 meters for the period (unpublished data), thus illustrating a *decrease in water clarity* during the same period as the observed *decrease in eelgrass habitat*. Further, a station within the central harbor had average secchi depth values of 2.5 meters (Hubeny unpublished data), demonstrating the enhanced turbidity in the harbor-proper. Although not definitive, the connection in timing between turbidity increases and eelgrass decreases (as an indicator of ecologic health) warrants the further study of turbidity in Salem Harbor in order to determine the nature and causes of turbidity events.

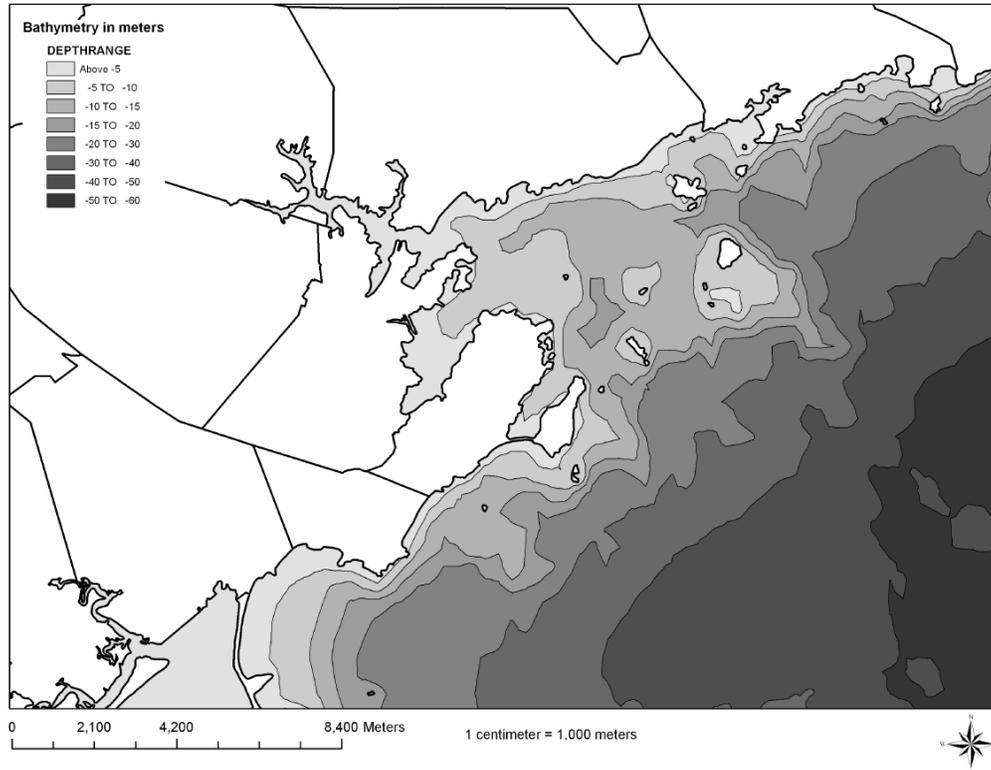


Figure 1: Locus map of Salem Sound, MA. This study was conducted in Salem Harbor, located between the towns of Salem and Marblehead, MA.

This study was initiated in order to constrain the causes of the turbidity events in Salem Harbor as a first step toward suggesting a solution to this environmental concern. The primary goal for the project was to utilize high temporal resolution (15-minute) monitoring data from Salem Harbor to quantify turbidity variability and attempt to determine the factors responsible for initiating turbidity events in Salem Harbor. Affiliated goals for this research monitoring project were 1) to establish a sustainable high-sampling resolution estuarine water quality monitoring network in Salem Harbor, MA that can be used for continued monitoring efforts, and 2) to propose initial recommendations for the management of turbidity in Salem Harbor that will further limit habitat degradation and will steer Phase 2 of this project. Phase 2, funded by MA MET for 2013-2014, will continue monitoring and assess the geochemical nature of the suspended particulate matter in order to better identify the origin of the particulates.

Four working hypotheses were tested:

1. Wind events (high velocities and shifting prevailing directions) shift boats on their moorings, and the large number of moored boats will resuspend surface sediments in the harbor, leading to a turbidity event.
2. Precipitation events, and associated increases in storm water runoff and stream discharge, will carry suspended matter into the harbor, thus leading to a turbidity event.

3. Tidal currents provide enough energy to resuspend surface sediments in the harbor, leading to a turbidity event
4. Nutrient loading will lead to turbidity events by fertilizing and increasing the amount of phytoplankton in the water column (*ie.* phytoplankton blooms).

The study addressed the following priority action items (in order of relevance) of the Massachusetts Bays Program 2009-2012 Strategic Plan:

A7f) Conduct local and regional water quality monitoring efforts,

A7c) Provide information gathered in monitoring efforts to constituents and the general public,

A1e) Investigate, monitor, and limit habitat degradation.

This report represents Phase 1 of a 2 -Phase research initiative. Phase 1 was designed to establish the infrastructure needed for long-term, high temporal resolution estuarine monitoring in Salem Harbor, and to gather enough data (March – November 2012) to test the working hypotheses regarding the causes of turbidity events in Salem Harbor. Phase 2 of the project will extend the monitoring period by 2 years, to the end of 2014 in order to fully evaluate variability over a more comprehensive period, and will utilize geochemical signatures of the suspended particulate matter to identify the origination/source of that material. Barbara Warren (SSCW) has secured funding from the Massachusetts Environmental Trust for the second phase of the Salem Harbor turbidity study.

Methods

Continuous water quality monitoring was conducted at five moored stations in Salem Harbor (Figure 2, Appendix A). Buoys were deployed on Monday 7 May 2012, and the necessary QAPP was approved by the Environmental Protection Agency on 3 May 2012. Two of the stations (B and C) are located within present mooring fields, two are located at the mouths of the two stream inputs to the harbor (Forest and South Rivers, Stations D and E, respectively), and the fifth is a control site located at the mouth of the harbor (Station A). The research team worked with the Salem and Marblehead Harbormasters to determine the optimal locations for each buoy within the bounds of the project goals.

Each buoy has housed within it a Manta2 probe with temperature, conductivity, and turbidity sensors. The probes recorded values every 15 minutes and data are logged in the probes. One of the stations (Salem Harbor B) recorded water level with a HOBO water level sensor at depth and a second HOBO pressure transducer housed within the buoy to correct for atmospheric pressure. The water level sensor was used to record the actual tidal stage for the monitoring period as well as bottom temperature at Station B. The other four monitoring stations have HOBO temperature loggers at depth to monitor bottom temperature.

At regular intervals, the research team revisited each station and uploaded data, conducted any necessary maintenance/antifouling, reloaded fresh batteries, and recalibrated the sensors before redeploying the multiprobes. We experienced some technical difficulties with the loggers, battery sources, and antifouling devices that resulted in logging gaps within the records. Since the Manta2's are under warranty, we were able to address and fix all issues, and there are enough data available from the year to test the hypotheses of this project.

Meteorological data were acquired from the Salem State University Weather Station continuously, and reported as hourly values for the study period. Dr. W. Hamilton provided all data.



Figure 2: Salem Harbor (MA) with proposed sampling locations. Thick black line illustrates the seaward boundary of the harbor as it is defined in this study. Red squares are monitoring locations cited within mooring fields. Green squares are monitoring locations cited at the mouths of the South River (northern square) and Forest River (southern square). The yellow square is the control monitoring location cited at the mouth of the harbor, away from moored boats and fluvial inputs. The orange circle shows the location of the SSU Geology meteorological station (roof of 6-story high Meier Hall).

Results and Discussion

Data Series

The network of five water-quality monitoring buoys was established successfully in Salem Harbor, MA. Data are presented here from 7 May – 14 December 2012. Complete data series are presented graphically in the appendices of the report. I will highlight specific portions of the data series to address the study's hypotheses within the body of the report. The buoy network is still deployed and logging data, and Salem Sound Coastwatch has secured funding from the MA Environmental Trust to continue active monitoring until December 2014.

Difficulties were encountered with the loggers with regards to the electronics, battery sources, and anti-fouling components. As a result, there are gaps in the data series that were unavoidable. In addition, some components of the series are “noisier” than one might expect, likely a result of issues with biofouling components of the loggers. Our procedures have been modified accordingly to limit the amount of time between service visits. Faulty components of the loggers have been replaced under warranty.

Much of the noise in the turbidity and salinity data sets occur during the summer months, while the early and late part of the record these series are less noisy. Personal observations revealed substantially increased biofouling and organic matter in the water column during the summer months. I believe that we can make two conclusions based on these observations. First, the turbidity is higher and more variable during the summer months as compared to the spring and fall. This observation suggests that phytoplankton growth may be a significant contributor to water column turbidity. Second, biofouling affects the sensors more than we had anticipated based on past experience. Therefore, we plan on increasing our field days with continued monitoring in order to service and clean the sensors at closer to one-month intervals rather than the 8-10 week intervals conducted over the past year.

Temperature data logged in surface and bottom waters of each station provide information on water column stratification (Figure 3), where different surface and bottom temperatures illustrate periods of stratification. Seasonal stratification is apparent during the summer months when surface waters are heated by the atmosphere. The effect is most pronounced at the deep control site (Station A), and less so at the other sites. The mooring sites (B and C) appear to experience intermittent stratification during the summer, while the river sites (D and E) are mostly well mixed. The differences in the locations are likely due to both water depth (shallow sites will mix more easily) as well as Station A's proximity to open marine waters that are colder and denser than the coastal waters. Stratified conditions will separate bottom from surface waters, and therefore will discourage the resuspension of bottom sediment to the surface waters.

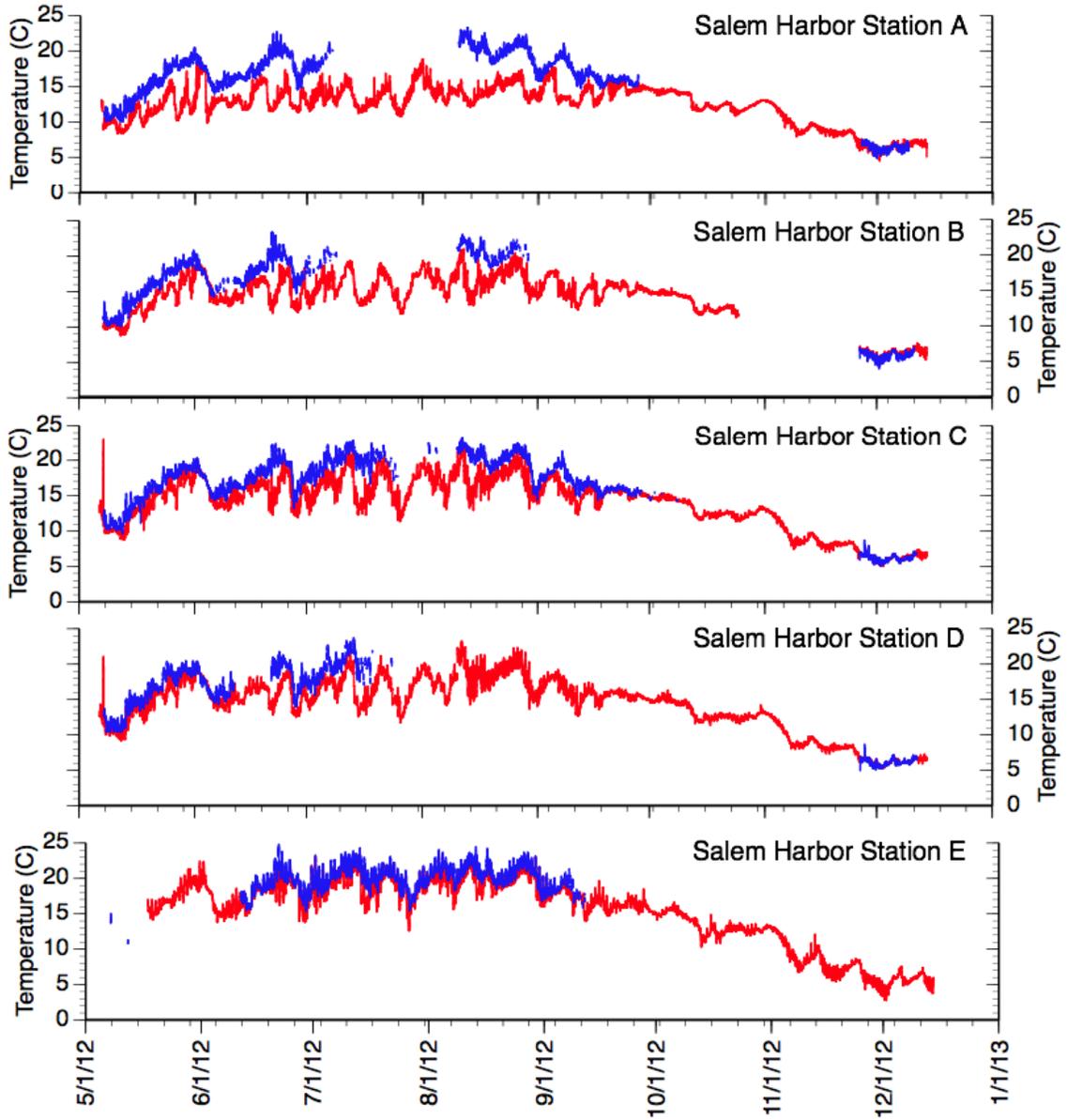


Figure 3: Surface (blue) and bottom (red) water temperature recorded at Salem Harbor monitoring stations. Times in which surface and bottom water temperatures are the same indicate periods of water column mixing. Stratified water conditions are observed when surface waters are warmer than bottom waters.

Turbidity events and their causes

As stated earlier in the report, there were four hypotheses that were tested with regard to the causes of turbidity events:

1. Wind events (high velocities and shifting prevailing directions) shift boats on their moorings, and the large number of moored boats will resuspend surface sediments in the harbor, leading to a turbidity event.
2. Precipitation events, and associated increases in storm water runoff and stream discharge, will carry suspended matter into the harbor, thus leading to a turbidity event.
3. Tidal currents provide enough energy to resuspend surface sediments in the harbor, leading to a turbidity event
4. Nutrient loading will lead to turbidity events by fertilizing and increasing the amount of phytoplankton in the water column (*ie.* phytoplankton blooms).

In the following sections, I present data that test these hypotheses, and discuss my interpretations. For each section I will focus on turbidity data from three different time periods: May 1 – June 12 (spring), August 1 – August 30 (summer), and November 25 – December 14 (fall).

Wind Events and Shifting Moorings

Support for this hypothesis will be attained if stations within the mooring fields record turbidity events that are significantly correlated to wind events, defined by changes in velocity and/or direction of wind. Further, we would expect that stations that are not within mooring field will yield less significant or non-significant correlations to wind events.

Spring 2012: Turbidity data from the control, mooring, and South River stations were plotted and analyzed with regard to wind speed, direction, and atmospheric pressure (Figures 4, 5, 6, respectively). Two particular wind events occurred during the period, on May 10-11 and on June 3-4. In both cases, a low-pressure system passed through the region (Figure 6), and peak winds were recorded at over 30 MPH (Figure 4). During the May event, wind was steadily out of the western quadrant, while during the June event wind veered around the compass rose from the east to the northeast (Figure 5).

Turbidity events were observed at both mooring sites during the June event, but not during the May event. There was no clear turbidity event observed at the control site during this time, and the South River station did not record data during this event likely due to biofouling. The data suggest that wind events could be a contributing factor to spring turbidity events in the case that wind shifts during the event. In the case of the May event, wind speed was high, but steady. Therefore, any boats that were on moorings would not be shifting and moving the mooring chain. In the June event, wind velocity was similar to the May event, however the wind direction veered through $\frac{3}{4}$ of the compass rose. Therefore, mooring chains would have swung accordingly, potentially resuspending bottom sediments.

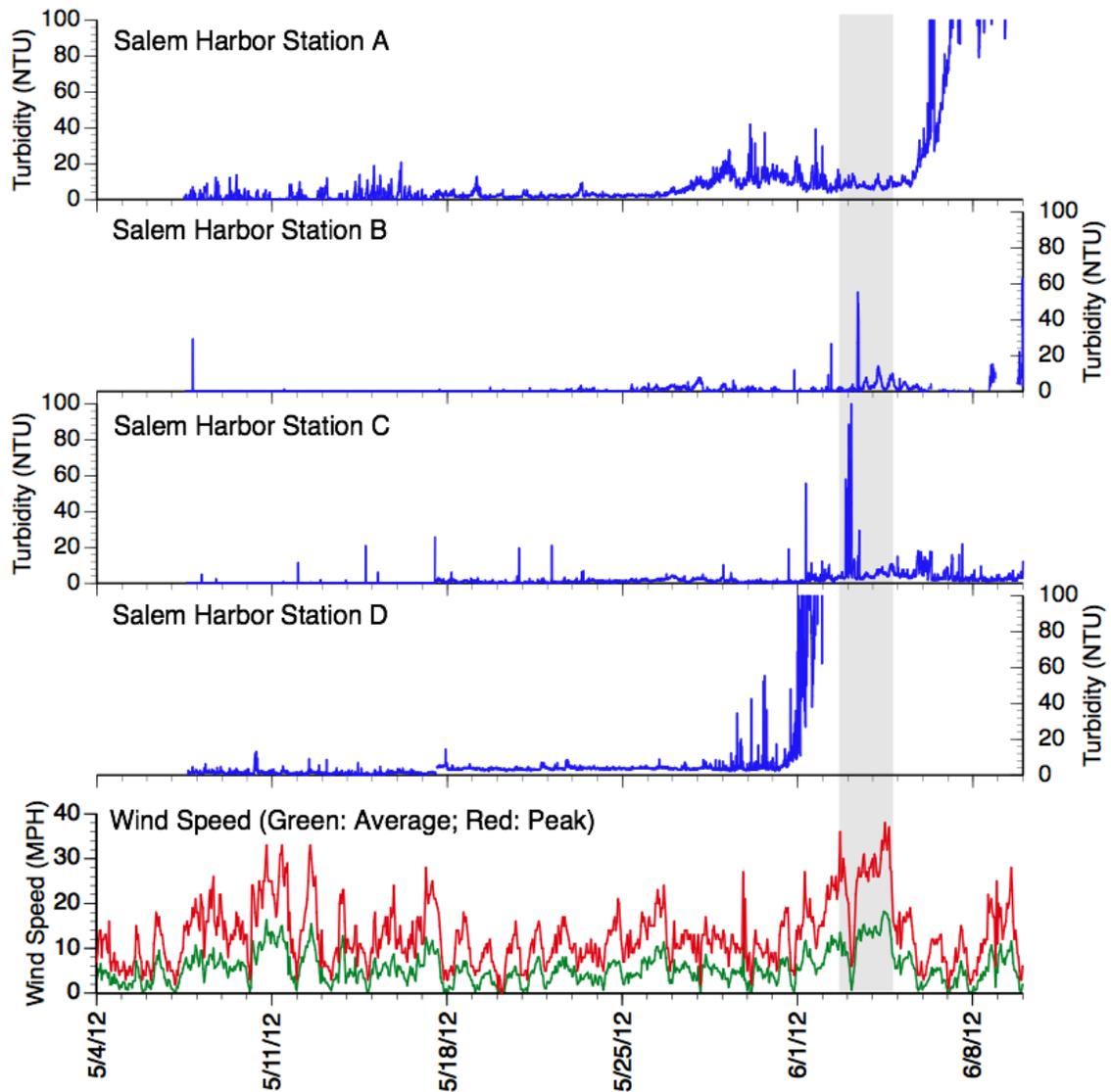


Figure 4: Turbidity and wind speed data for the period May 1 – June 12, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Wind speed data are hourly averages (green) and peaks (red).

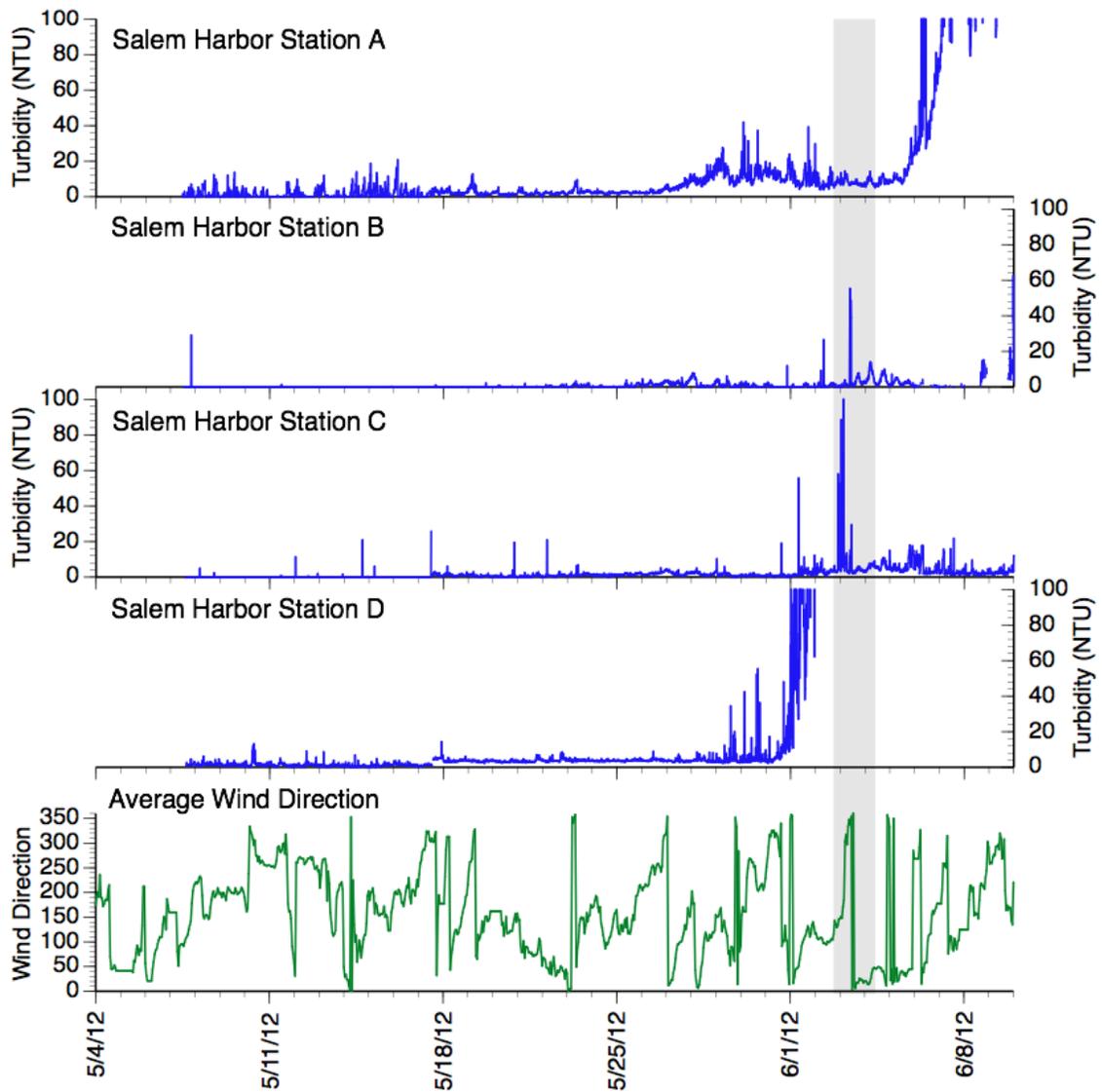


Figure 5: Turbidity and wind direction data for the period May 1 – June 12, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Wind direction data are hourly averages and reported as azimuth values.

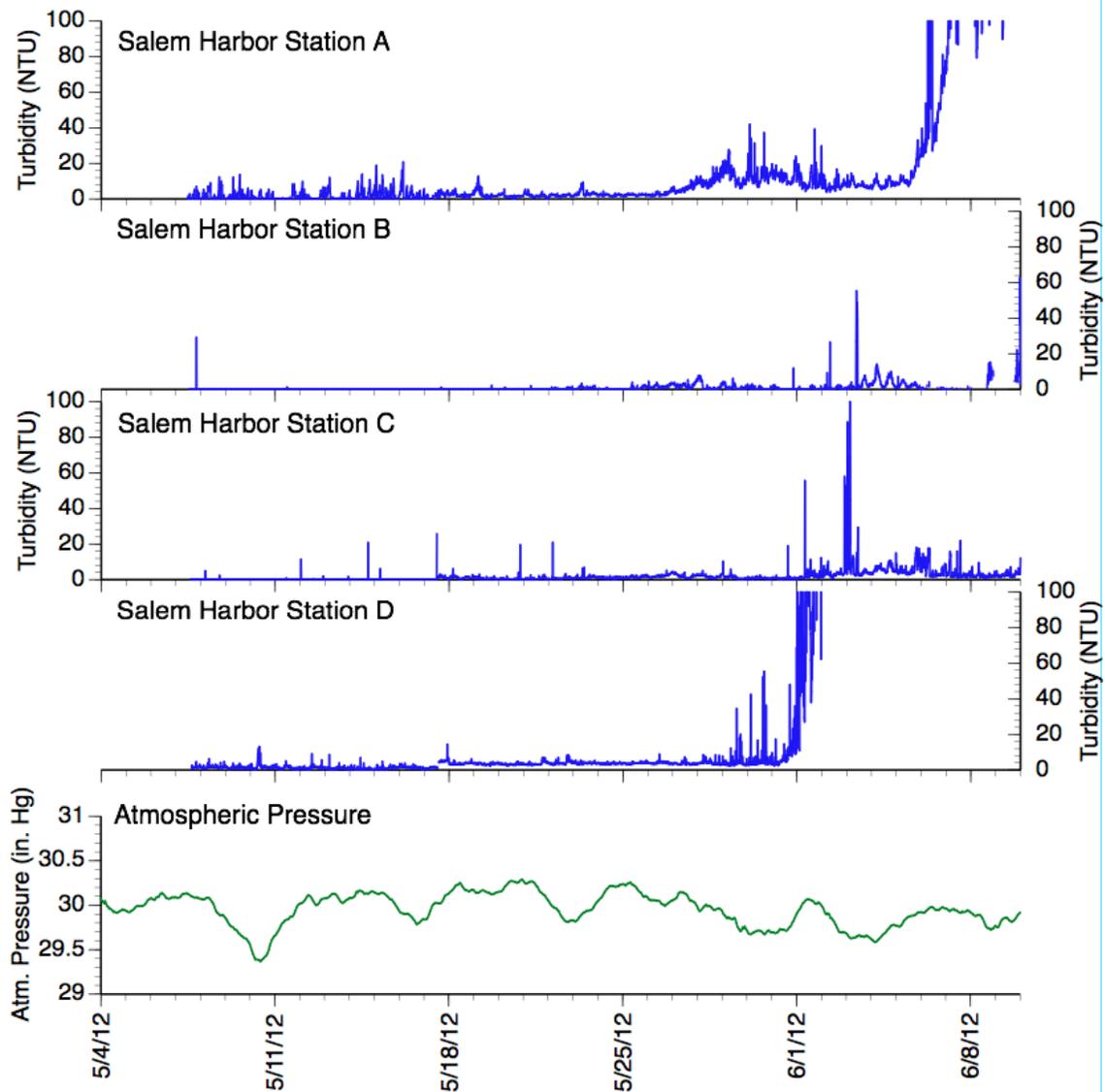


Figure 6: Turbidity and atmospheric pressure data for the period May 1 – June 12, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Atmospheric pressure data are hourly averages.

Summer 2012: Turbidity data from the control, mooring, and Forest River stations were plotted and analyzed with regard to wind speed, direction, and atmospheric pressure (Figures 7, 8, 9, respectively). Turbidity data during the period were higher and more variable as compared to the spring or fall data (see appendices and Figures 4 – 18). Further, there is no clear connection between turbidity variability and wind or pressure systems during the period. I believe that the lack of coherence between turbidity and wind during this time is likely associated with two conditions. First, there was a distinct lack of frontal activity during the period, so there may not have been a wind event large enough to cross a certain threshold needed to observe a signal. Second, increased productivity and organic matter in the water column during the summer months (as indicated by increased turbidity values and variability) may dominate the particulate matter, and turbidity dynamics, during the summer.

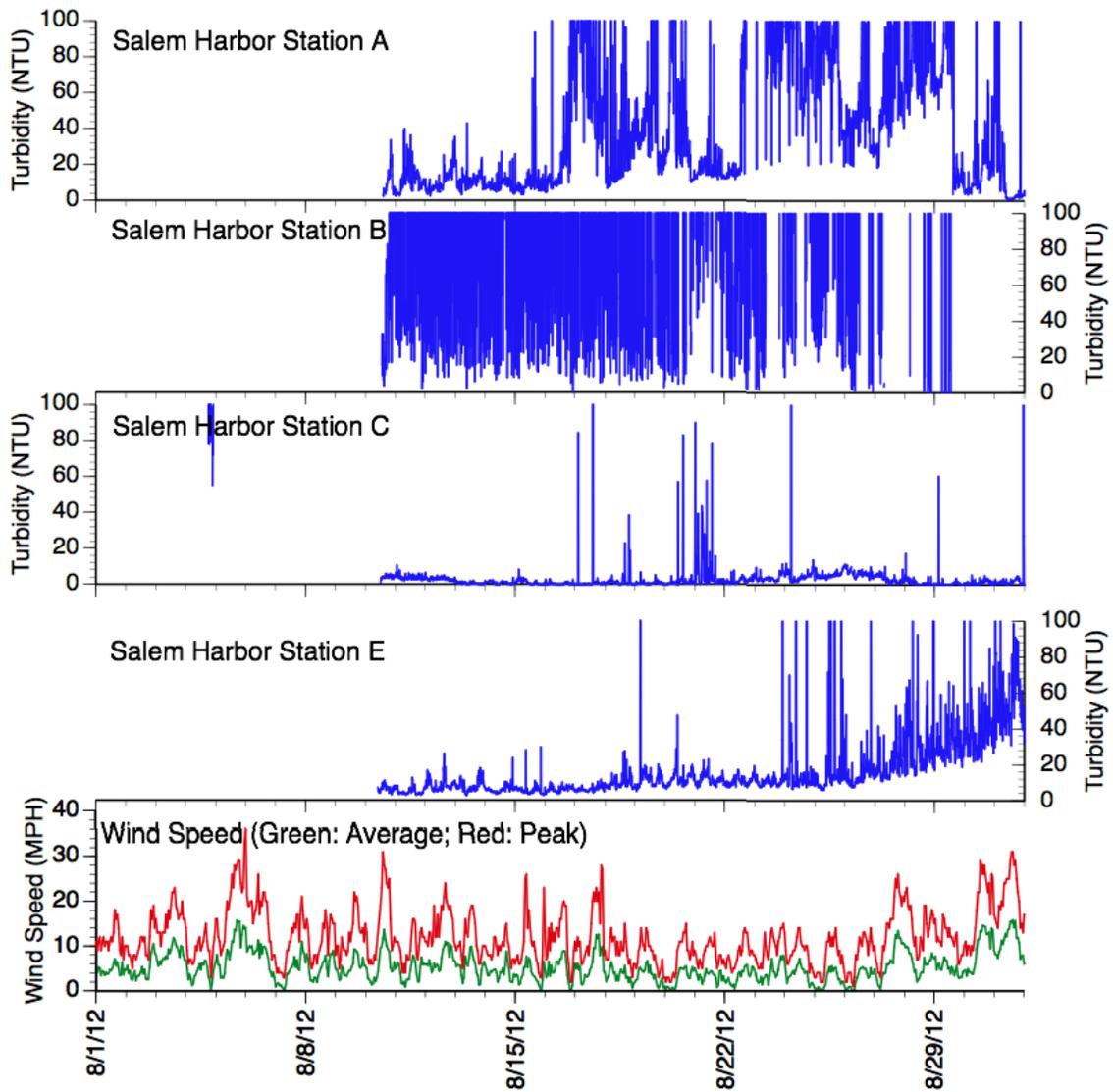


Figure 7: Turbidity and wind speed data for the period August 1 – August 30, 2012. Station A is the control, Stations B and C are within mooring fields, and Station E is at the mouth of the Forest River. Wind speed data are hourly averages (green) and peaks (red).

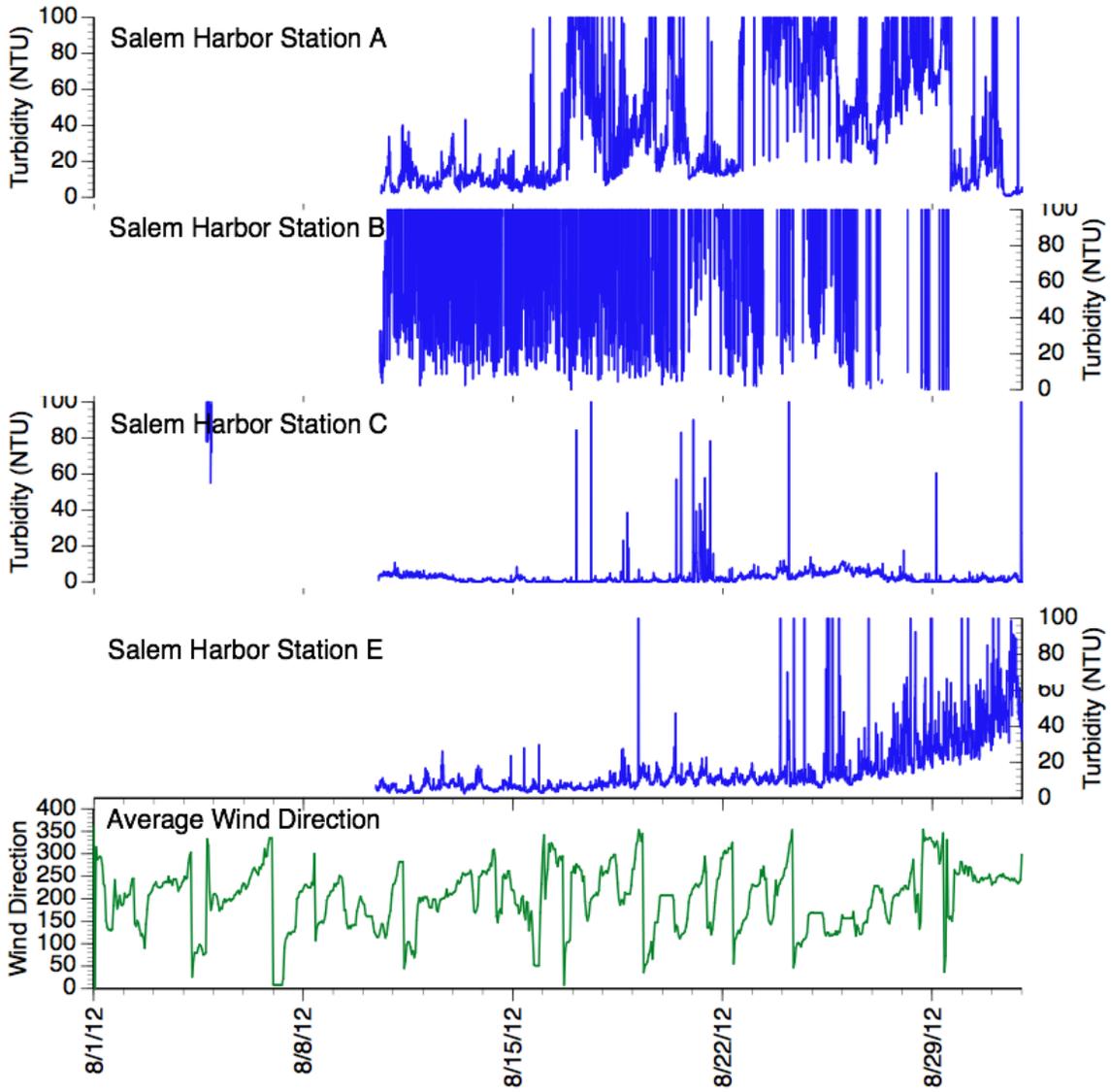


Figure 8: Turbidity and wind direction data for the period August 1 – August 30, 2012. Station A is the control, Stations B and C are within mooring fields, and Station E is at the mouth of the Forest River. Wind direction data are hourly averages and reported as azimuth values.

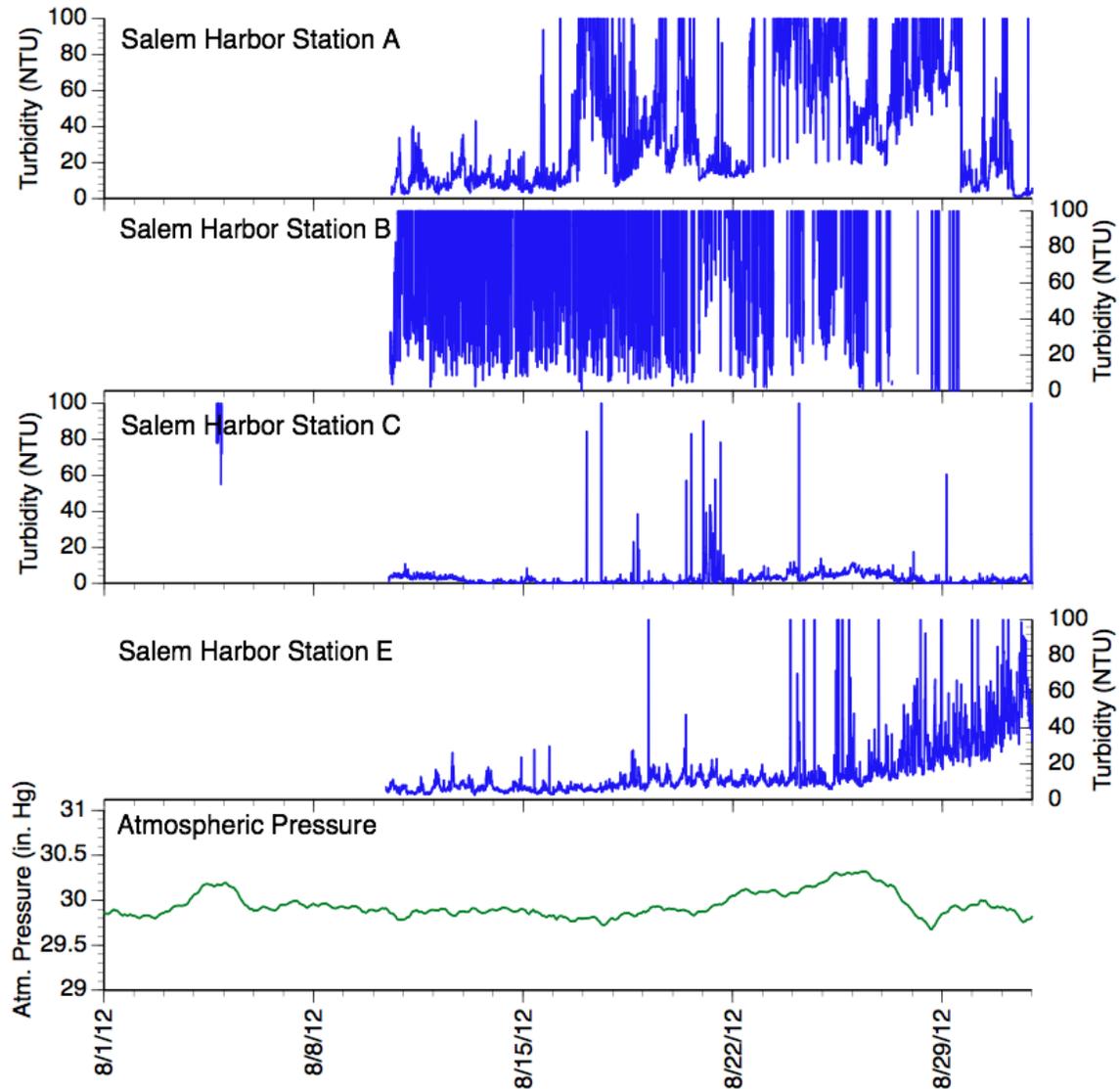


Figure 9: Turbidity and atmospheric pressure data for the period August 1 – August 30, 2012. Station A is the control, Stations B and C are within mooring fields, and Station E is at the mouth of the Forest River. Atmospheric pressure data are hourly averages.

Fall 2012: Turbidity data from the control, mooring, and South River stations were plotted and analyzed with regard to wind speed, direction, and atmospheric pressure (Figures 10, 11, 12, respectively). Three specific wind events occurred during the period, November 26, December 6, and December 8. The November 26 and December 6 events had associated system-wide increases in turbidity. The December 8 event was only noted at the control site, and was a much weaker wind event, although it was associated with a low-pressure system.

There appears to be a connection between wind and turbidity during this fall period. It is interesting that the amplitude of the events is lower than the June wind event discussed above, and that the turbidity increases are system-wide. It may be that since almost all of the boats had been removed from moorings by this time period, and that since mooring balls will not be affected as much by wind as a boat will, that the wind: turbidity connection during this period was more associated with resuspension of sediments in shallow water reaches of the harbor due to wave action. This possibility complicates the interpretation of moored boats being linked to turbidity events.

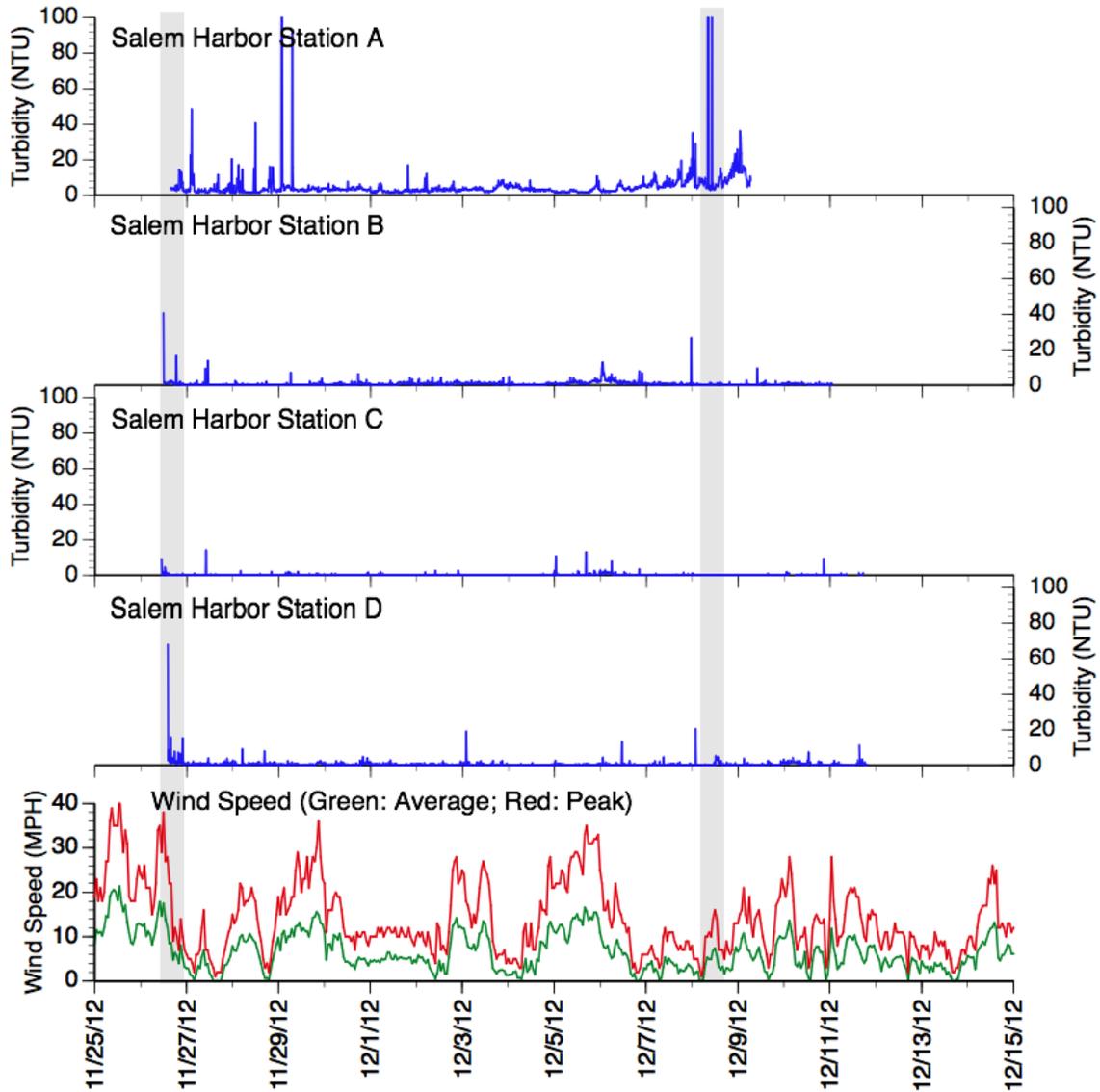


Figure 10: Turbidity and wind speed data for the period November 25 – December 15, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Wind speed data are hourly averages (green) and peaks (red).

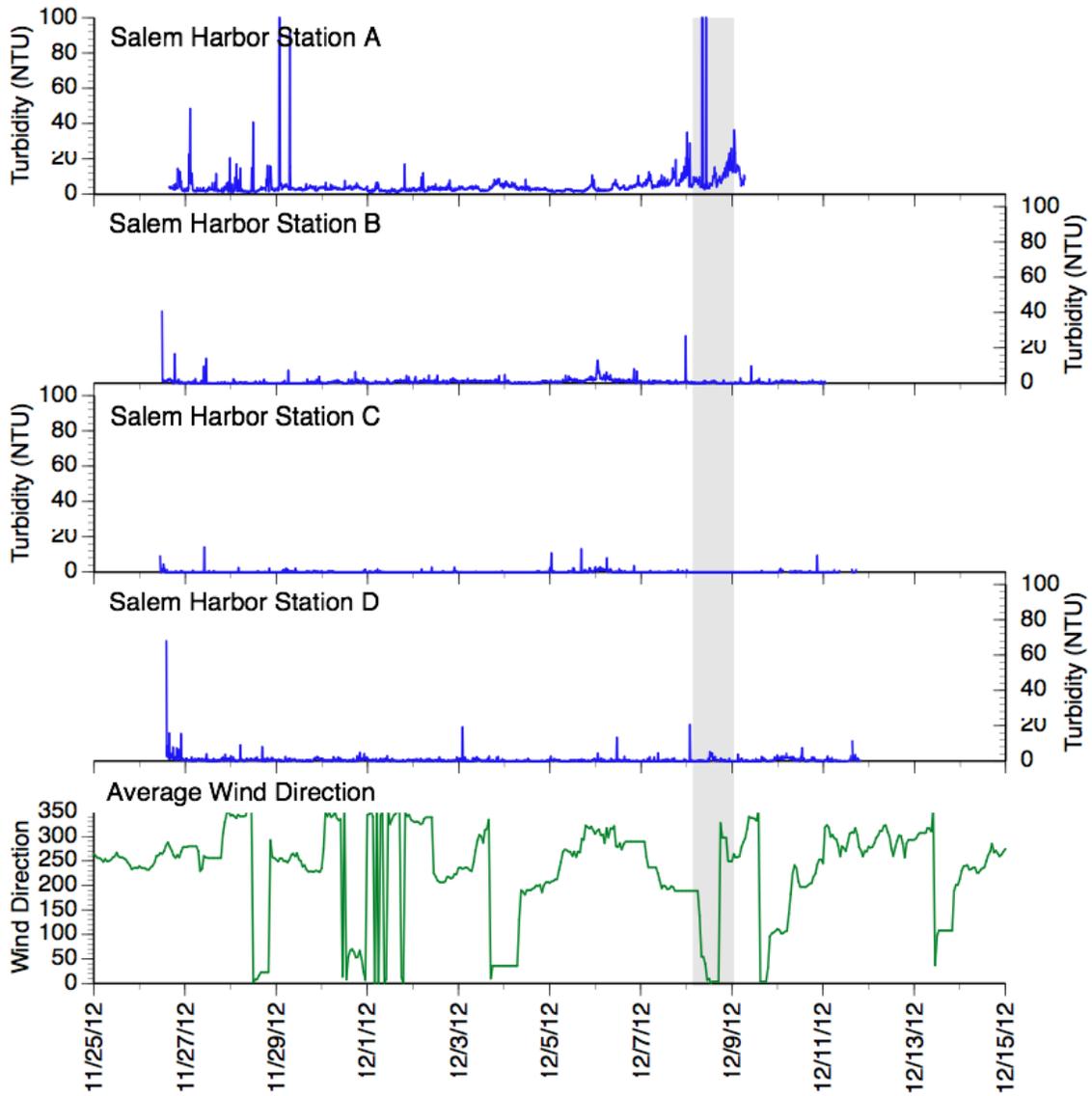


Figure 11: Turbidity and wind direction data for the period November 25 – December 15, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Wind direction data are hourly averages and reported as azimuth values.

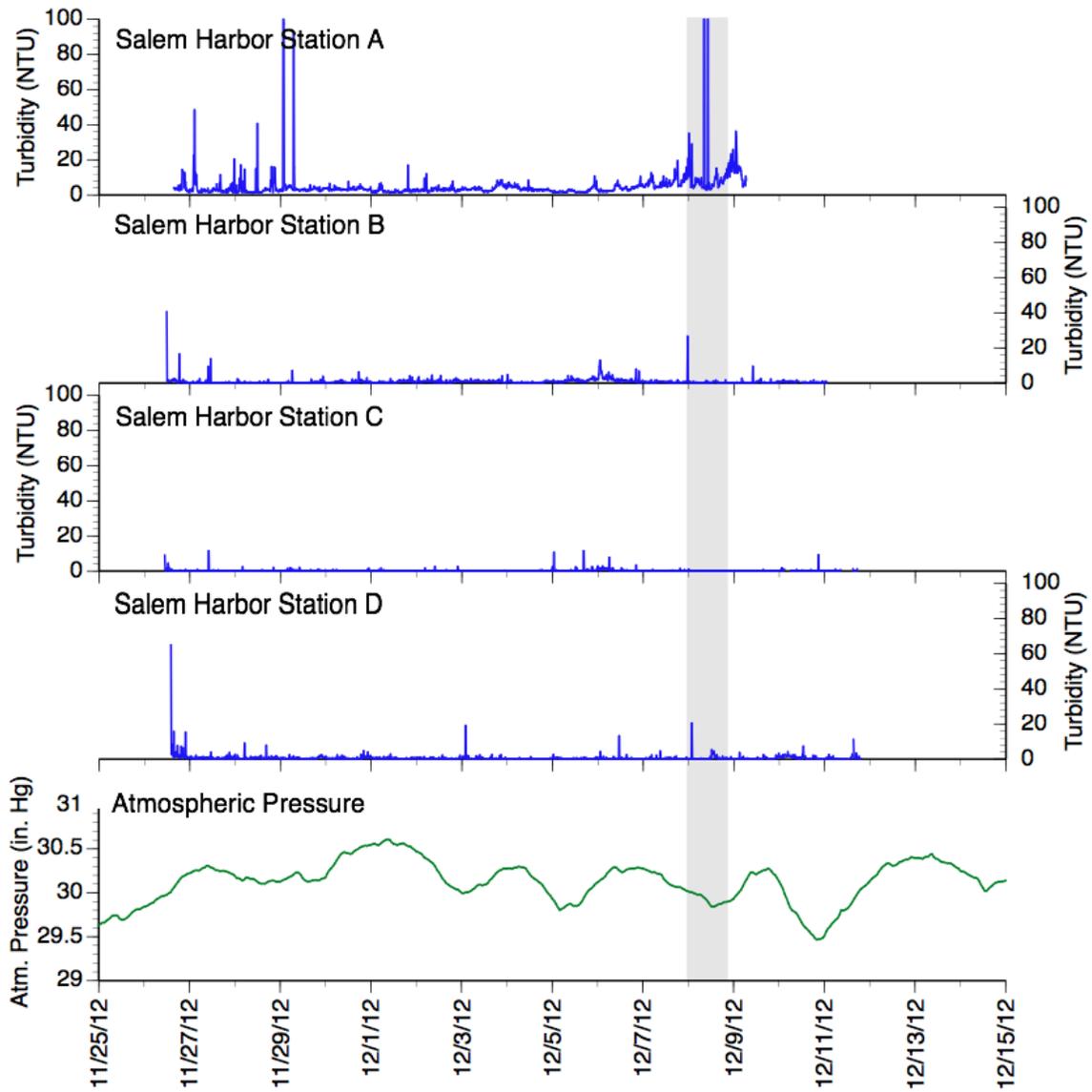


Figure 12: Turbidity and atmospheric pressure data for the period November 25 – December 15, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Atmospheric pressure data are hourly averages.

Runoff and Stream Discharge

This hypothesis will be supported by: 1) turbidity events that are synchronous amongst the five monitoring stations, with larger signals in the stream mouth stations as opposed to more distal stations; and 2) turbidity events that are correlated with rain events.

Spring 2013: Turbidity data from the control, mooring, and South River stations were plotted and analyzed with regard to precipitation (Figure 13). Four specific rain events occurred during the period, May 9-10, May 15-16, May 22, and June 13-14. None of the events have a corresponding clear increase in turbidity in the river station. Increased turbidity is noted during the June 13-14 event in the mooring fields, however this event was a low-pressure system with increased winds as well. Therefore, it is not clear if precipitation had any affect on turbidity at this time. The control site appears to have some correspondence to precipitation, however the timing of the events are not consistent with such a simple linkage.

Summer 2013: Turbidity data from the control, mooring, and Forest River stations were plotted and analyzed with regard to precipitation (Figure 14). Two specific rain events occurred during the period, August 10 and August 15-16. The August 10 event was the largest of the recording period, and weak increases in turbidity were noted at the control station as well as the two mooring sites. The latter precipitation event did not have an evident increase in turbidity at any of the stations.

Fall 2013: Turbidity data from the control, mooring, and South River stations were plotted and analyzed with regard to precipitation (Figure 15). Two specific rain events occurred during the period, December 8 and December 10. The December 8 event corresponds with a spike in turbidity at the control station. Both events have a weak increase in turbidity at the South River station.

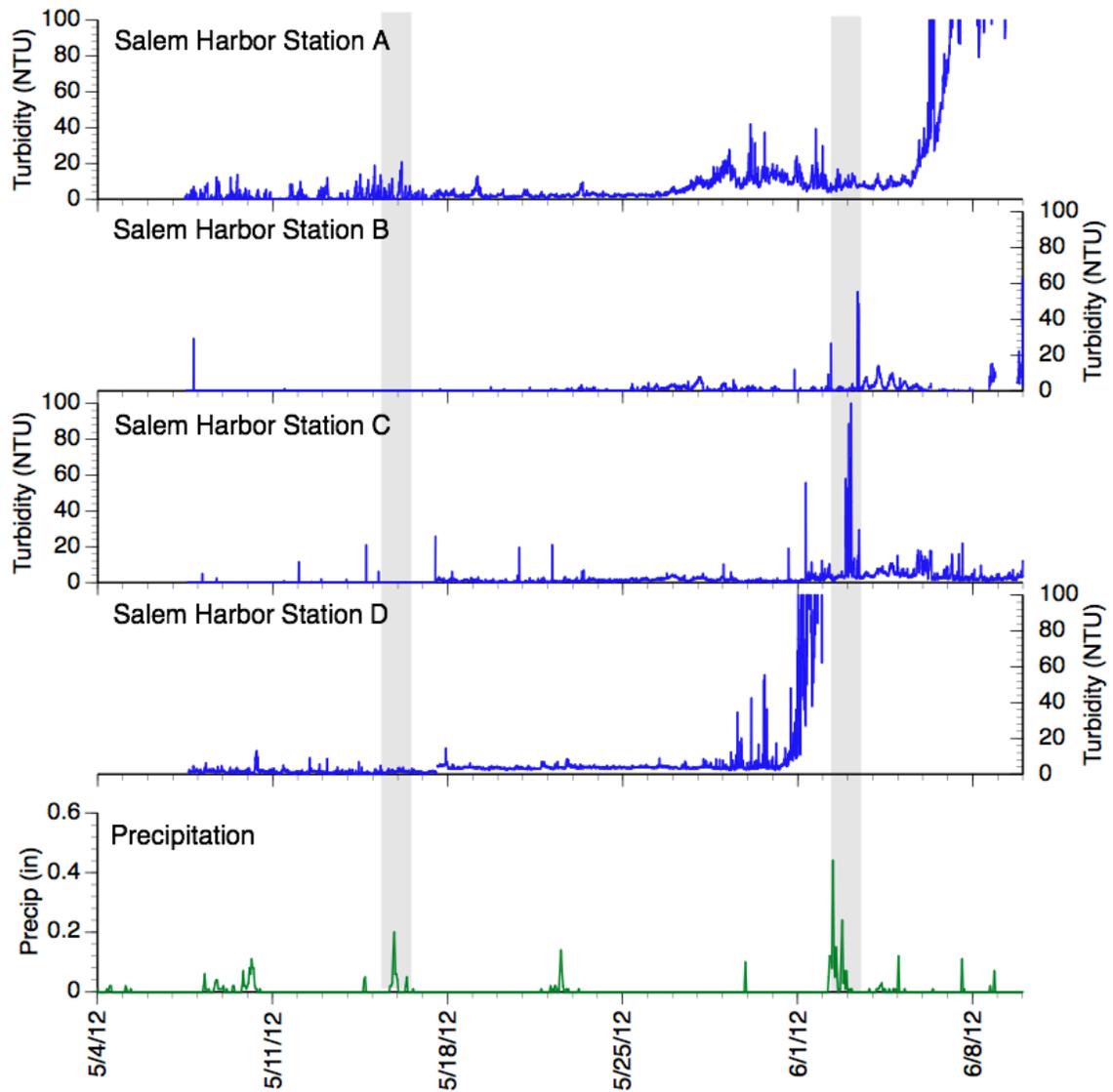


Figure 13: Turbidity and precipitation data for the period May 1 – June 12, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Precipitation data are reported as hourly totals.

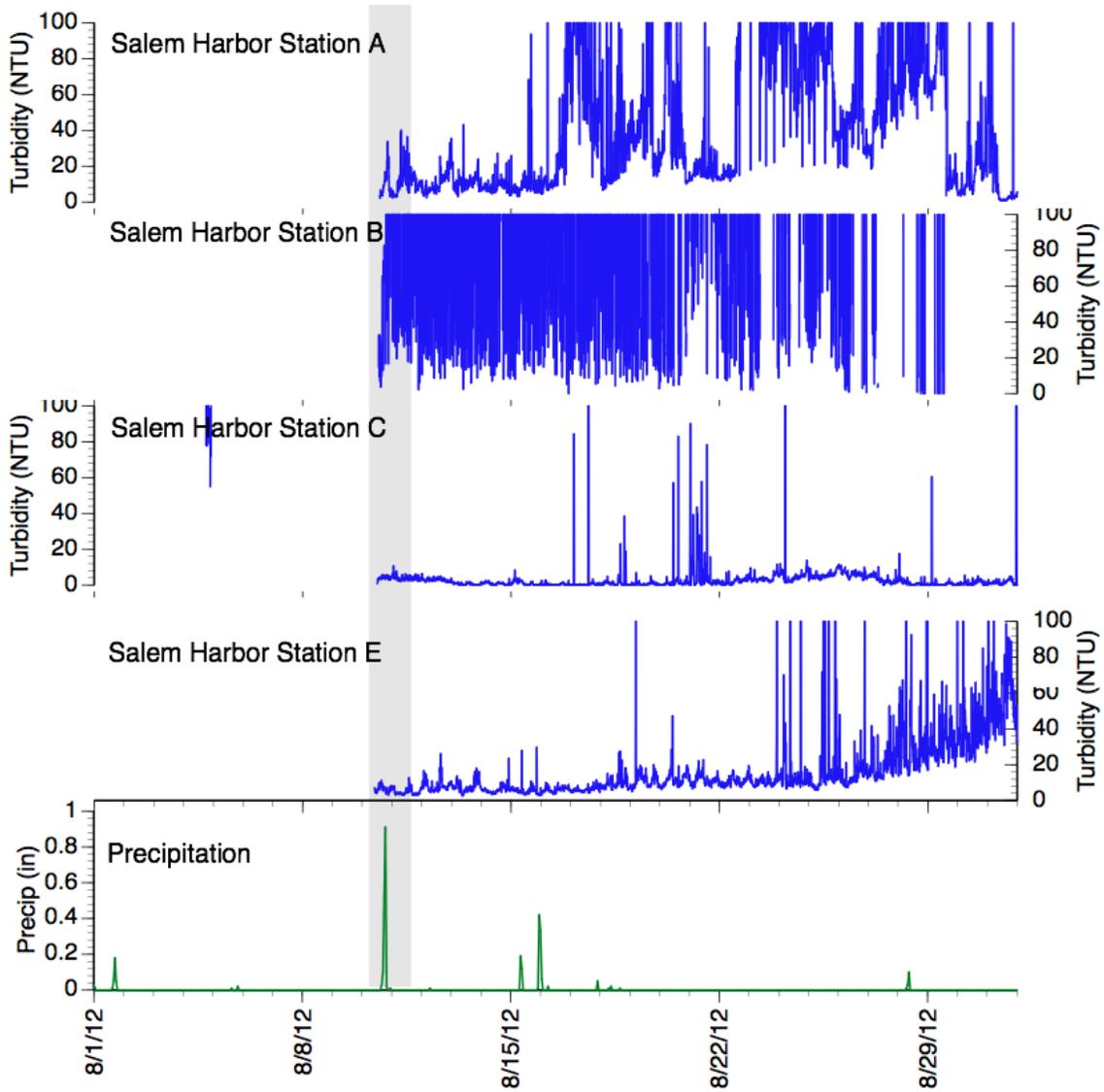


Figure 14: Turbidity and precipitation data for the period August 1 – August 30, 2012. Station A is the control, Stations B and C are within mooring fields, and Station E is at the mouth of the Forest River. Precipitation data are reported as hourly totals.

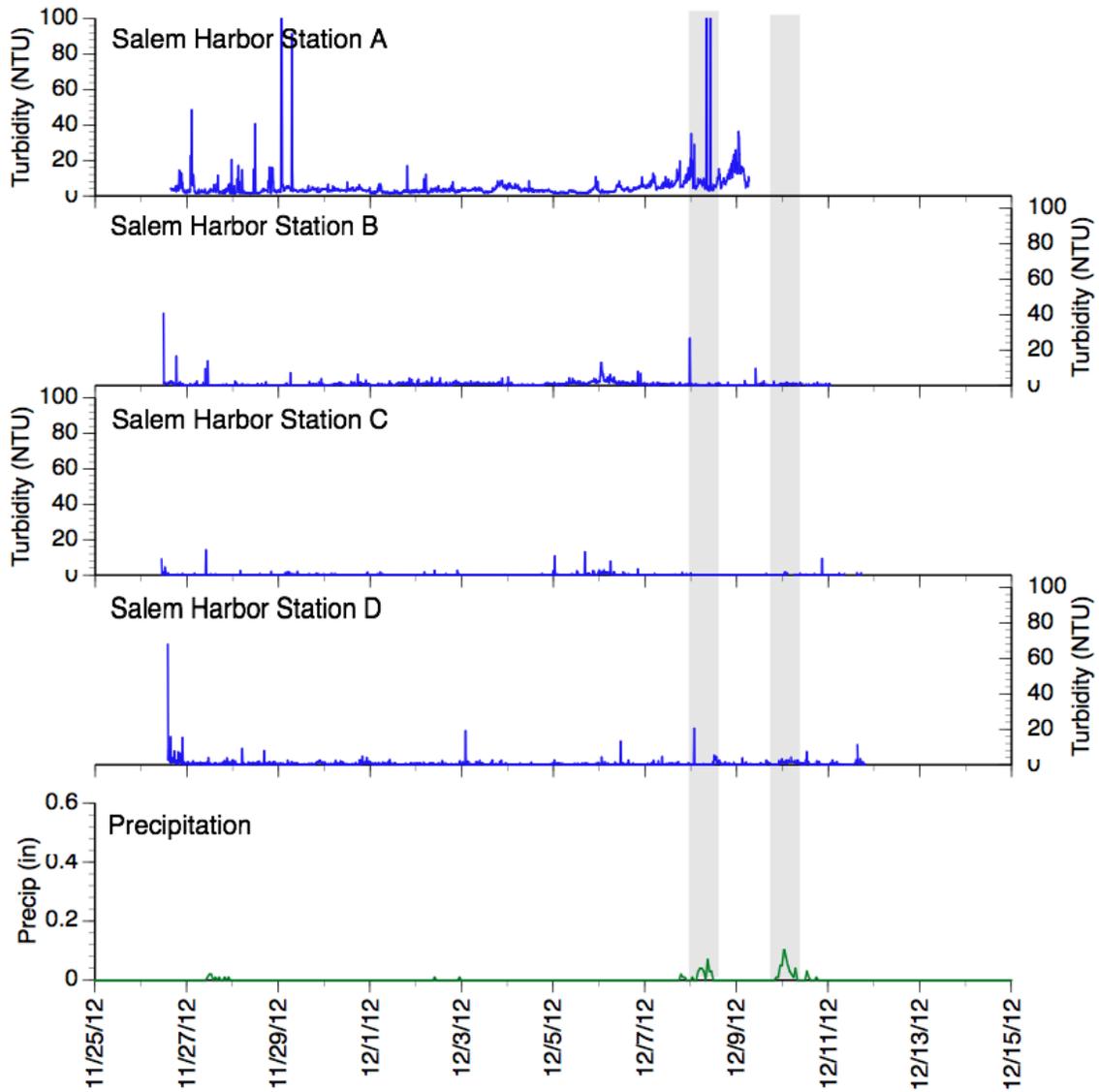


Figure 15: Turbidity and precipitation data for the period November 25 – December 15, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Precipitation data are reported as hourly totals.

Tidal Currents

Support for this hypothesis would be attained if turbidity is observed to increase during peak tidal current flow. Peak ebb and flood flow will occur at mid-tide, and tidal current will reduce to nothing at the high and low tides. Turbidity data from the control, mooring, and river stations were plotted and analyzed with regard to tidal stage during the spring, summer, and fall time periods (Figures 16, 17, 18, respectively). At no time during the record is there a clear increase in turbidity during peak time of tidal flow. Since Salem Harbor does not have a flow constriction, tidal currents are not extreme. The data suggest that tidal currents are not strong enough in Salem Harbor to resuspend bottom sediments at a magnitude that would increase turbidity in the surface waters.

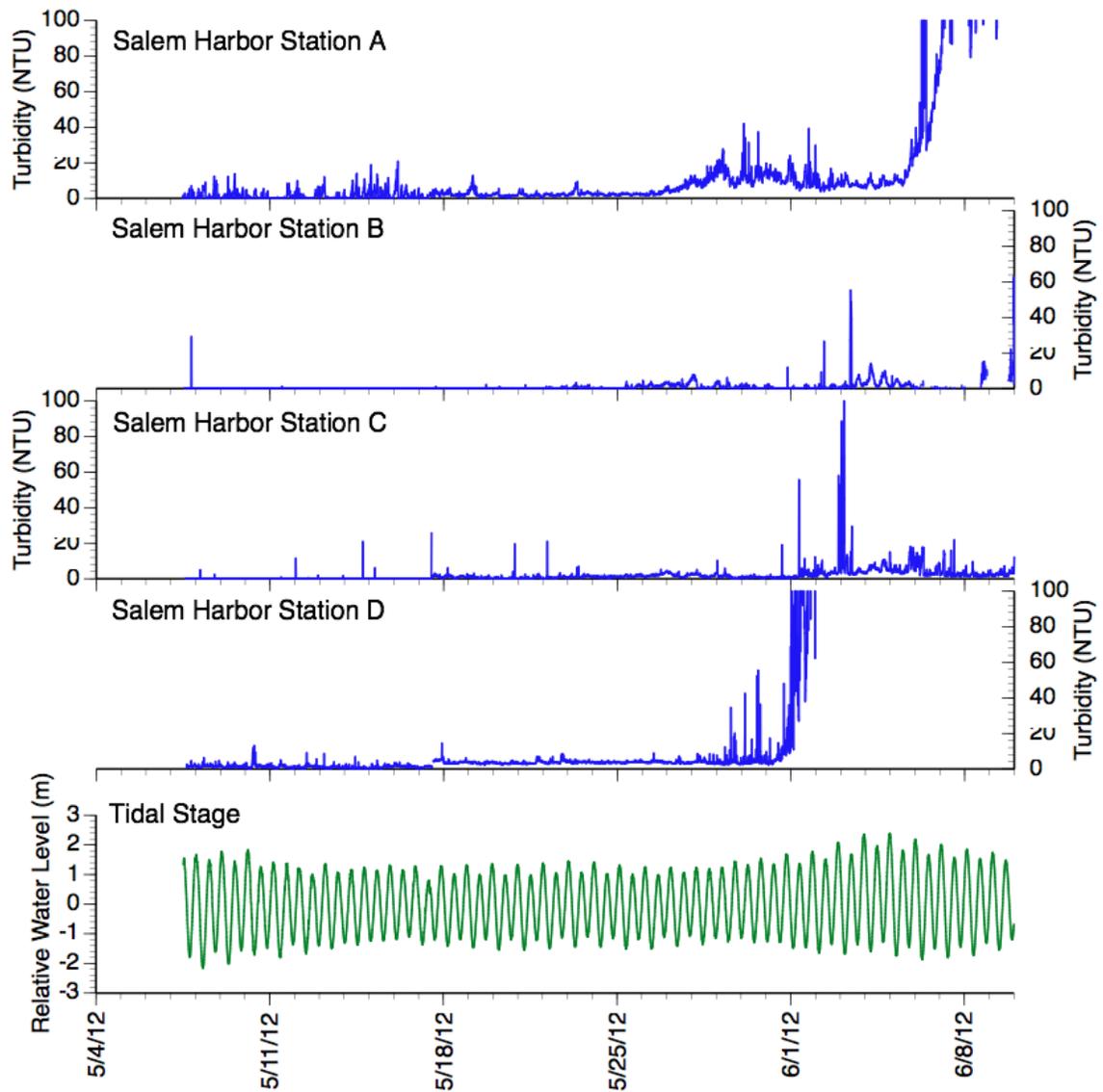


Figure 16: Turbidity and tidal data for the period May 1 – June 12, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Tidal data are reported as deviations from the mean water depth of Salem Harbor Station B, in meters.

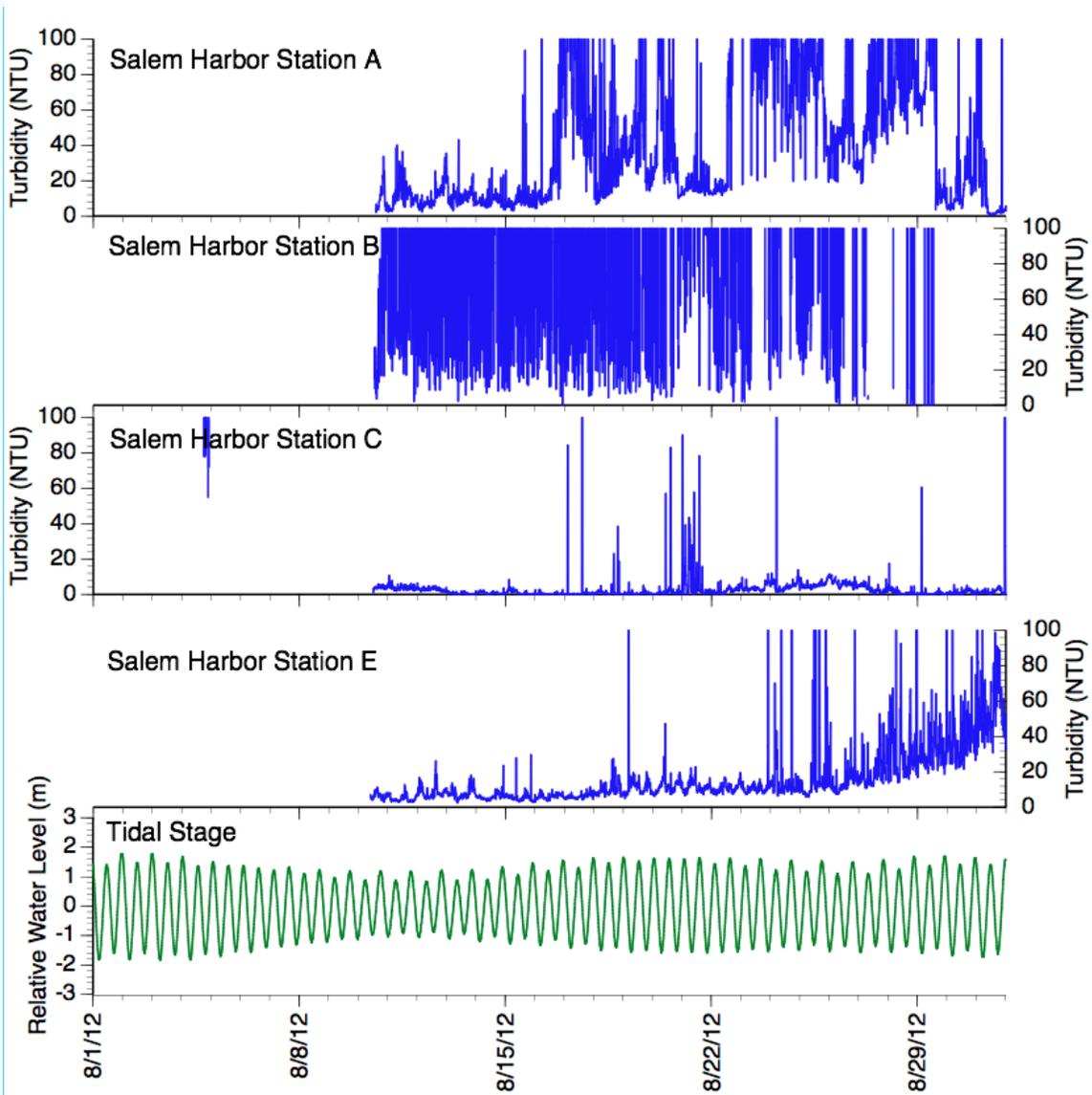


Figure 17: Turbidity and tidal data for the period August 1 – August 30, 2012. Station A is the control, Stations B and C are within mooring fields, and Station E is at the mouth of the Forest River. Tidal data are reported as deviations from the mean water depth of Salem Harbor Station B, in meters.

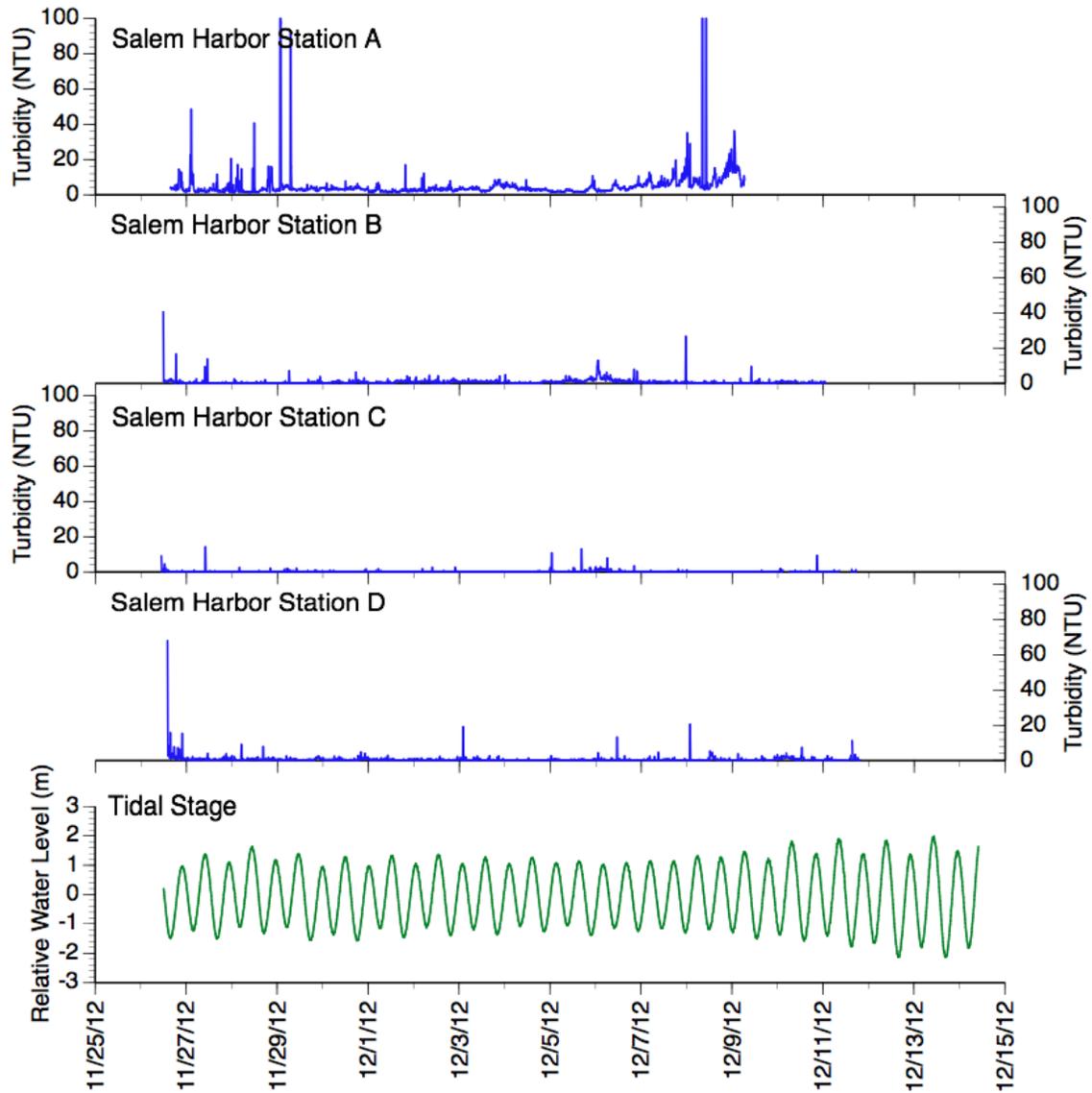


Figure 18: Turbidity and tidal data for the period November 25 – December 15, 2012. Station A is the control, Stations B and C are within mooring fields, and Station D is at the mouth of the South River. Tidal data are reported as deviations from the mean water depth of Salem Harbor Station B, in meters.

Nutrient Fluxes and Phytoplankton Blooms

Although the monitoring network did not quantify nutrients or chlorophyll, it is possible to test this hypothesis in two ways. First, blooms should tend to be longer duration events that occur at predictable times. Therefore, short duration events that occur at non-predicted seasons are likely not associated with blooms. If, however, turbidity events do not correlate with wind or runoff events, then by elimination they are likely associated with increased phytoplankton activity. The data suggest that seasonal phytoplankton productivity patterns are important with regard to turbidity variability in Salem Harbor. The clearest evidence for this interpretation is the increased turbidity values and variability observed during the summer portion of each record (*ie.* Figures 6-18).

Conclusions and Recommendations

There is evidence that wind, precipitation, and organic productivity each influence turbidity events in Salem Harbor. Wind and precipitation effects are most clearly noted during spring and fall, with organic productivity appears to dominate the particulate matter during the summer months. Tidal currents do not appear to be a factor with regard to turbid conditions in the harbor.

It is recommended that continued monitoring be conducted in Salem Harbor in order to:

1. Realize the complete annual cycle of turbidity in Salem Harbor
2. Fill in gaps that resulted from equipment issues during the 2012 monitoring year
3. Reduce biofouling issues by conducting more frequent maintenance trips.

Due to the apparent importance of organic productivity to turbidity dynamics in Salem Harbor, it is recommended that further study include the characterization of the particulate matter that is suspended in the water column.

The recommended continued research in Salem Harbor will be realized with funding secured by Salem Sound Coastwatch from the Massachusetts Environmental Trust (Funding 2013 – 2014). Further n the results of this report will be shared with Salem Sound Coastwatch, and we will discuss strategies for communicating our findings to the public.

References

- Chase, B. C., Plouff, J. H., and Castonguay, W. M., 2002, The marine resources of Salem Sound, 1997: Technical Report TR-6: MA Division of Marine Fisheries.
- Costello, C. T., and Kenworthy, W. J., 2011, Twelve-year mapping and change analysis of eelgrass (*Zostera marina*) areal abundance in Massachusetts (USA) identifies statewide declines: *Estuaries and Coasts*, v. 34, p. 232-242.
- Dennison, W. C., Orth, R. J., Moore, K. A., Stevenson, J. C., Carter, V., Kollar, S., Bergstrom, P. W., and Batiuk, R. A., 1993, Assessing water quality with submersed aquatic vegetation habitat requirements as barometers of Chesapeake Bay health: *Bioscience*, v. 43, p. 86-94.
- Evans, N. T., Ford, K. H., Chase, B. C., and Sheppard, J. J., 2011, Recommended time of year restrictions (TOYs) for coastal alteration projects to protect marine fisheries resources in Massachusetts: Massachusetts Division of Marine Fisheries Technical Report TR-47.
- Moore, K. A., Wetzel, R. L., and Orth, R. J., 1997, Seasonal pulses of turbidity and their relations to eelgrass (*Zostera marina* L.) survival in an estuary: *Journal of Experimental Marine Biology and Ecology*, v. 215, no. 1, p. 115-134.
- Newcombe, C. P., 2003, Impact assesment model or clear water fishes exposed to excessively cloudy water: *Journal of the American Water Resources Association*, v. 39, p. 529-544.
- Newcombe, C. P., and Jensen, J. O. T., 1996, Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact: *North American Journal of Fisheries Management*, v. 16, p. 693-727.
- Nielsen, S. L., Sand-Jensen, J., Borum, J., and Geertz-Hansen, O., 2002, Depth colonization of eelgrass (*Zostera marina*) and macroalgae as determined by water transparency in Danish coastal waters: *Estuaries*, v. 25, no. 5, p. 1025-1032.
- Olesen, B., 1996, Regulation of light attenuation and eelgras *Zostera marina* depth distribution in a Danish embayment: *Marine Ecology Progress Series*, v. 134, p. 187-194.
- Wilber, D. H., and Clarke, D. G., 2001, Biological effects of suspended sediment: a review of suspended sediment impacts on fish and shellfish with relation to dredging activities in estuaries: *North American Journal of Fisheries Management*, v. 21, p. 855-875.
- Zweig, L. D., and Rabeni, C. F., 2001, Biomonitoring for deposited sediment using benthic invertebrates: a test on 4 Missouri streams: *Journal of the North American Benthological Society*, v. 20, no. 6, p. 643-657.

Appendices

- Appendix A: Locations of Salem Harbor Monitoring Stations
- Appendix B: Logging time series from Salem Harbor Buoy Station A
- Appendix C: Logging time series from Salem Harbor Buoy Station B
- Appendix D: Logging time series from Salem Harbor Buoy Station C
- Appendix E: Logging time series from Salem Harbor Buoy Station D
- Appendix F: Logging time series from Salem Harbor Buoy Station E
- Appendix G: Meteorological time series from the Salem State University Weather Station
- Appendix H: Tidal variability of Salem Harbor as recorded by water level at Salem Harbor Buoy Station B

Appendix A: Locations of Salem Harbor Monitoring Stations

Table A1: Salem Harbor Monitoring Stations (as deployed 7 May 2012)

Station	Latitude	Longitude	Descriptor
Salem Harbor A	42.52168	-70.86582	Control
Salem Harbor B	42.51345	-70.87407	East Moorings
Salem Harbor C	42.51608	-70.87800	West Moorings
Salem Harbor D	42.51612	-70.88430	South River
Salem Harbor E	42.50285	-70.88042	Forest River



Figure A1: Locus map of Salem Harbor Monitoring Stations (base image from Google Earth).

Appendix B: Logging time series from Salem Harbor Buoy Station A

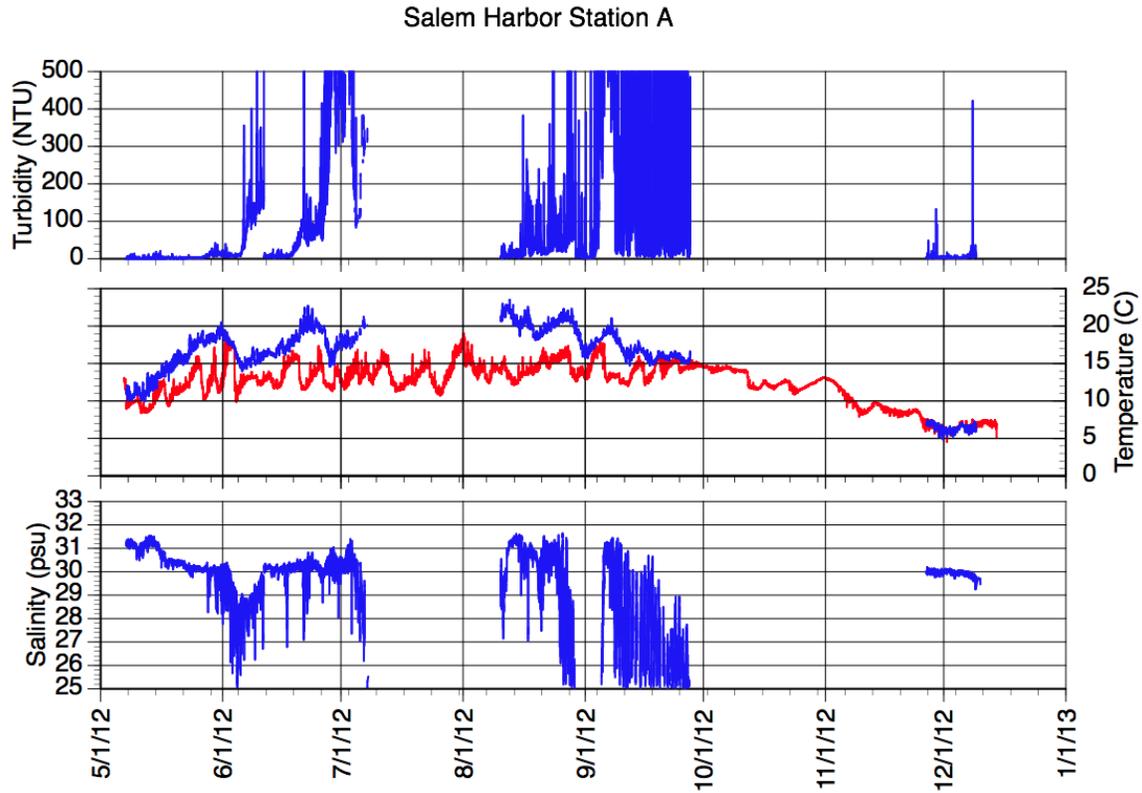


Figure B1: Water monitoring data from Salem Harbor Station A. Surface and bottom water temperatures are plotted in blue and red, respectively.

Appendix C: Logging time series from Salem Harbor Buoy Station B

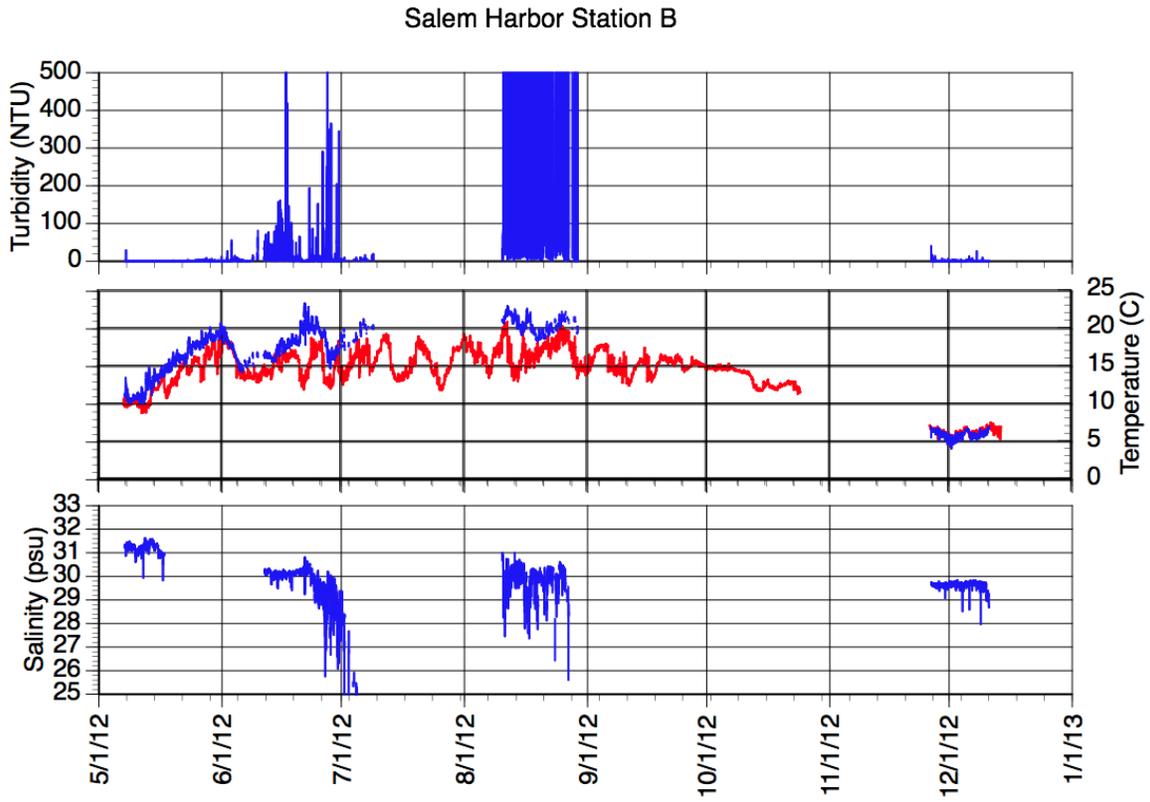


Figure C1: Water monitoring data from Salem Harbor Station B. Surface and bottom water temperatures are plotted in blue and red, respectively.

Appendix D: Logging time series from Salem Harbor Buoy Station C

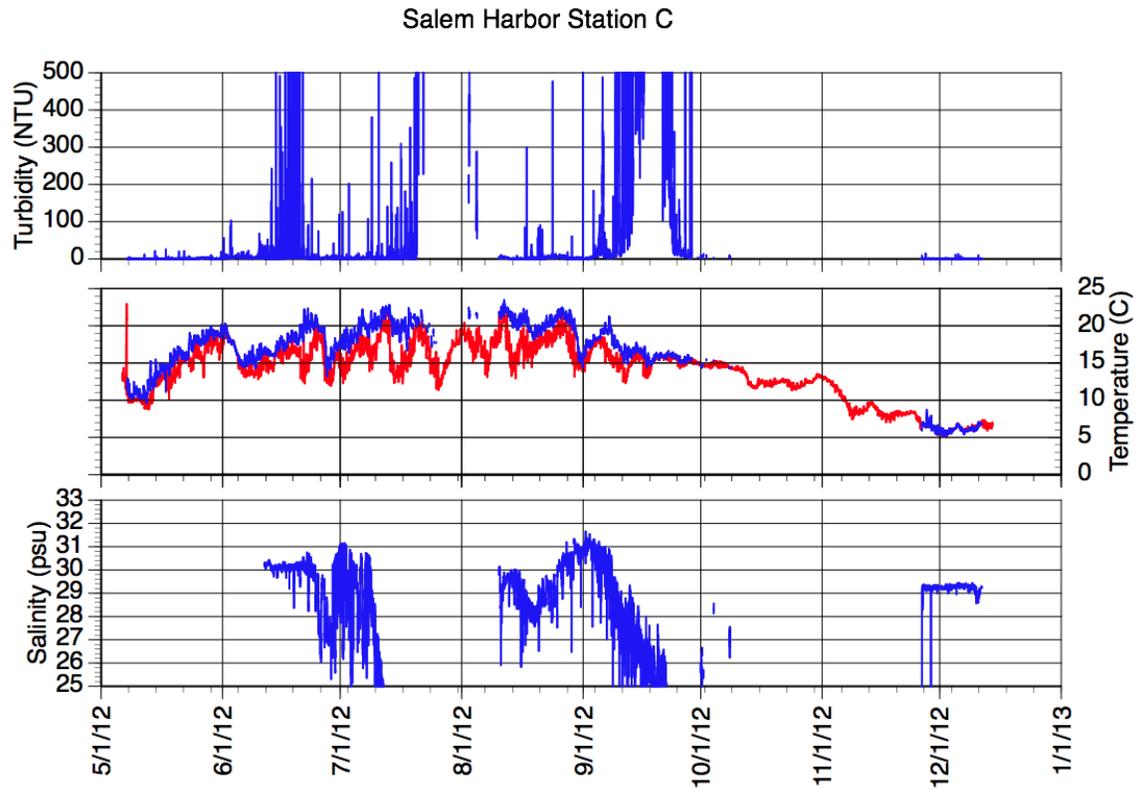


Figure D1: Water monitoring data from Salem Harbor Station C. Surface and bottom water temperatures are plotted in blue and red, respectively.

Appendix E: Logging time series from Salem Harbor Buoy Station D

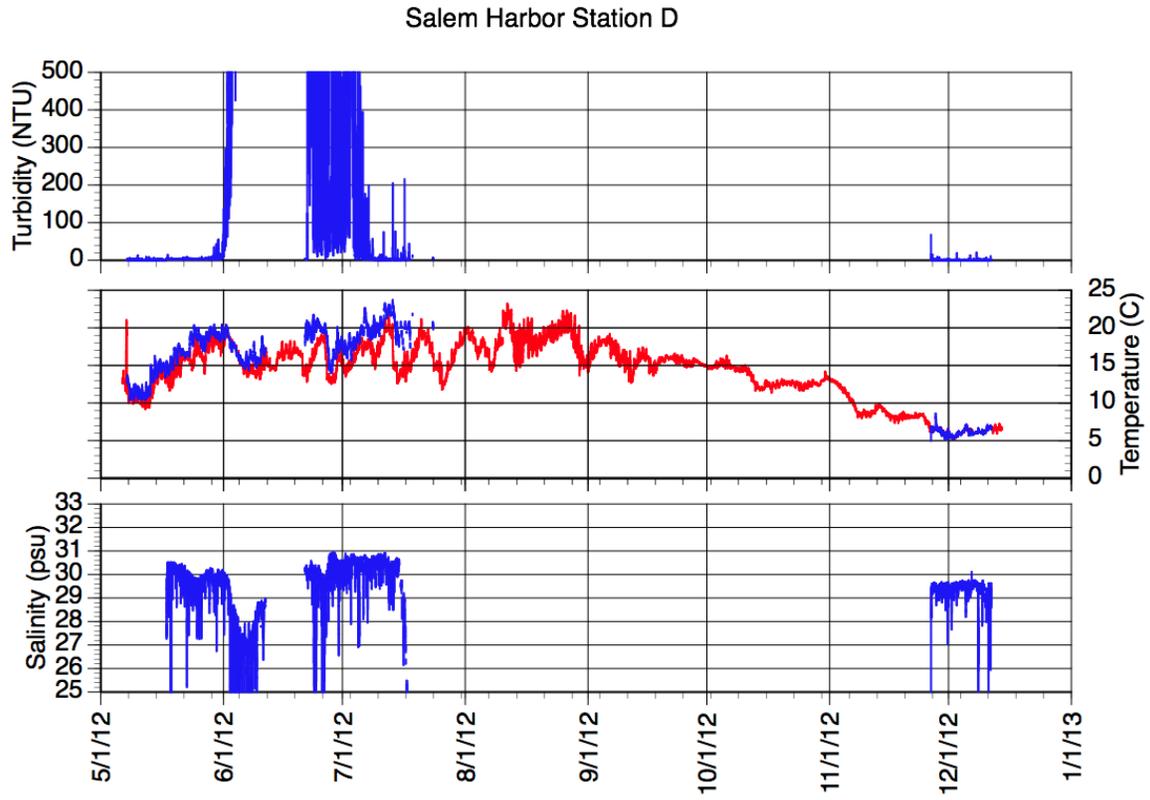


Figure E1: Water monitoring data from Salem Harbor Station D. Surface and bottom water temperatures are plotted in blue and red, respectively.

Appendix F: Logging time series from Salem Harbor Buoy Station E

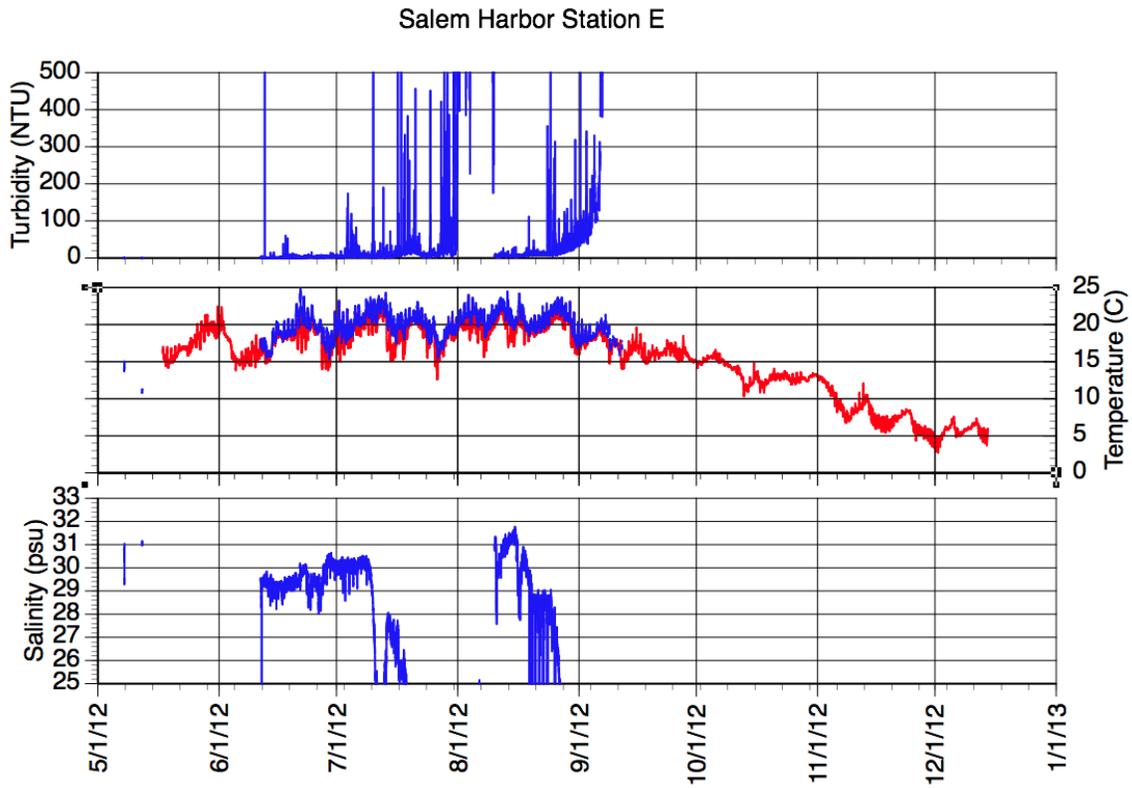


Figure F1: Water monitoring data from Salem Harbor Station E. Surface and bottom water temperatures are plotted in blue and red, respectively.

Appendix G: Meteorological time series from the Salem State University Weather Station

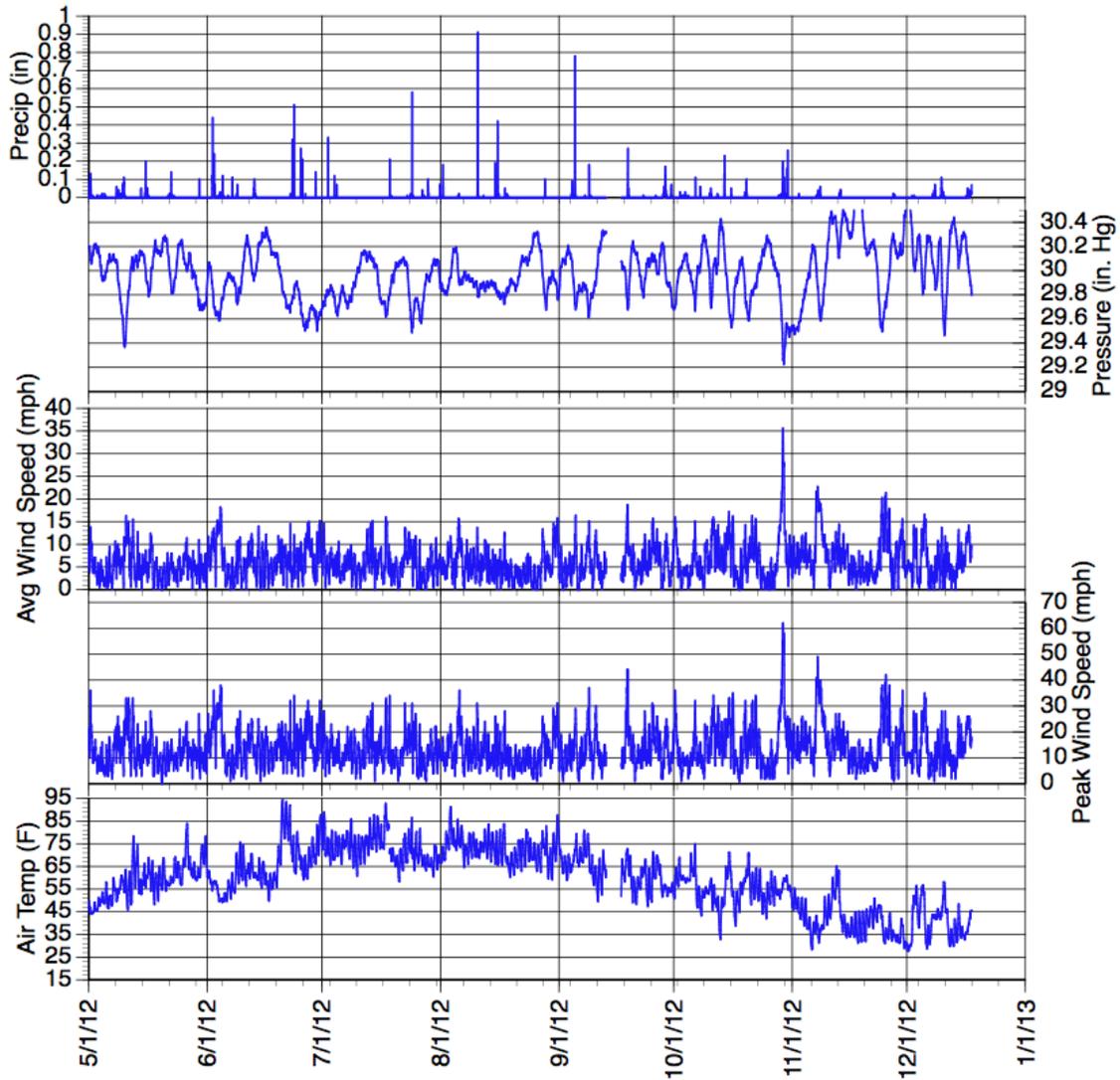


Figure G1: Meteorological data from the Salem State University Weather Station, located on the roof of Meier Hall: 42° 30.18' N x 070° 53.43' W; elevation 37'. From the top: Precipitation (total inches/hour), Atmospheric Pressure (inches Hg), Average Wind Speed (MPH), Peak Wind Speed (MPH), and Air Temperature (°F). Data courtesy of Dr. W. Hamilton, Salem State University Geography Department.

Appendix H: Tidal variability of Salem Harbor as recorded by water level at Salem Harbor Buoy Station B

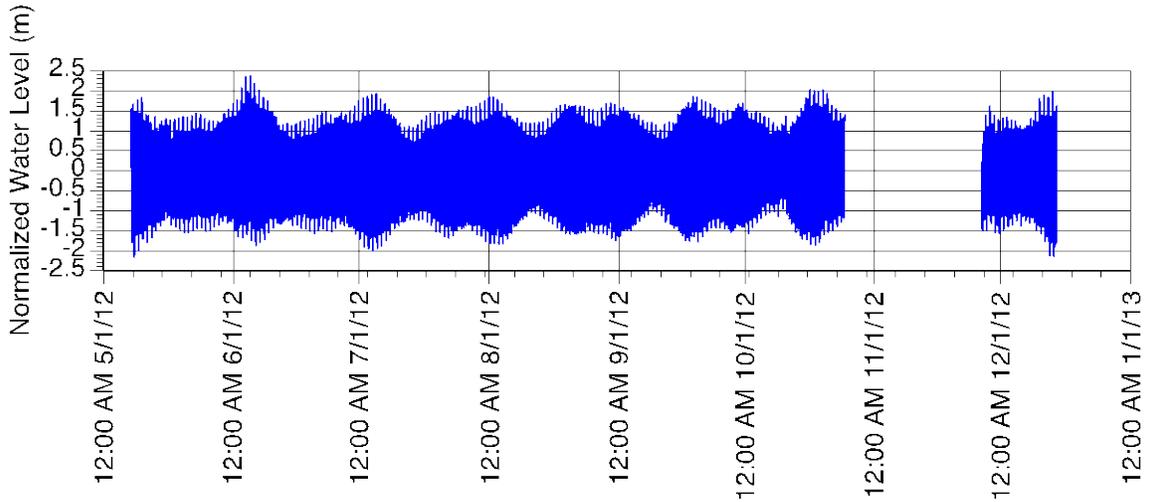


Figure H1: Water level variability recorded at Salem Harbor Buoy Station B. Data are reported as deviations from the time-series mean value, and represent tidal variability of Salem Harbor for the period.