Appendix O.

Oysters in Delaware Bay – Climate Change

John Kraeuter, Rutgers Haskin Shellfish Research Laboratory

Oysters in Delaware Bay – Climate Change

Background

This analysis is based almost entirely on the potential effects of salinity and temperature change on the oyster population on the New Jersey side of Delaware Bay. This portion of the bay has historically supported the largest oyster harvest, mostly because there area of oyster beds is much larger. Beds on the Delaware side of the bay are also harvested both the Delaware and New Jersey beds are actively managed.

The oyster population on the Delaware beds generally behaves in concert with those on the New Jersey side. It is beyond the scope of this analysis to include any of the multitude of other effects such as changes in fishing, shell resources, further channel changes, or changes in the ecology of other species that may affect the oyster and oyster community including changes in the phytoplankton abundance or species composition. For many of these factors there are insufficient data on which to base any predictions.

The data set and the manipulations to yield numbers per square meter are described in Powell et al (2008), but we are excluding the beds above Round Island (Hope Creek, Fishing Creek and Liston Range which we have termed 'new") (Figures 1, 2) because we do not have long term data from these areas. These beds are considered in the response to climate change, but only in general terms because the quantitative data is so limited.

The oyster population in the Delaware estuary exists along a salinity gradient. Substantial areas of oyster resource exist in the lower part of the bay on leased grounds and these, and the oyster resources in the various tributary creeks, are not considered in this analysis because little or no data exist on abundance in these areas. It is known that these populations behave in a manner similar to the populations in the portion of the bay that is surveyed. This surveyed area is known at the Seed Beds because in New Jersey these state controlled beds were, until 1995, and used as a source of seed oysters for planting in the lower bay leased areas. Because oyster disease changed the way in which the resource could be utilized the State of New Jersey began a managed harvest directly from these seed beds, and the area has been managed for direct harvest since that time. The total area of the beds being surveyed is 63,380,896 m^2 (Table 1) and this represents 98% of the oysters in this area of the bay.

By region, there have been substantial changes in the oyster resources in Delaware Bay since the beginning of monitoring in 1953. Since then MSX (*Haplosporidium nelsoni*) and dermo (*Perkinsus marinus*) became epizootic in the bay in 1957 and 1989, respectively. Since their initial proliferation MSX has had a second epizootic in 1985, which apparently allowed the oyster population to develop some resistance (National Academy of Science, 2004). Dermo remains a significant factor with periodic epizootics. The distribution of these two diseases is affected by temperature and salinity (Burreson, et al., 1994, Dungan and Hamilton, 1995, Ford, 1985, Ford and Haskin, 1988, Haskin and Ford, 1982, Soniat, 1985).

Regional Changes

The Delaware Bay New Jersey oyster seed beds can be divided into 5 major areas that reflect the effects of salinity on the oyster population (New, Upper, Upper Central, Central and Lower). Salinity is a factor that may change with sea level rise. It also affects the distribution of the two major oyster diseases, oyster growth rate, predators, fouling community, food levels, turbidity and many other factors that act on oyster distribution. Unfortunately, time series salinity data for much of the Delaware Estuary is limited so we have use river flow at Trenton from the USGS gauging station as a long term surrogate.

There are a number of plausible ways to compare changes in the seed bed oyster population, but we have chosen to break the data set into two periods, 1953 to 2009 and 1985 to 2009. The break incorporates data from the last MSX epizootic and the development of some resistance to that disease in the oyster population, and encompasses the entire period that reflects the importance of dermo in the system. On a few occasions we have also use the time period 1953 to 1989 and 1989 to present to represent the pre dermo and dermo decades. We have not included explicit information on the harvest of oysters from this system but it has been actively managed from the middle of the 1950’s to present, and the is no indication that overharvesting is a significant factor in the oyster population dynamics (Fegley et al 1994 and 2003). There are two components where oyster harvest could have an effect other than overharvest, disruption of the natural beds and the selective removal of the larger individuals. Experiments to evaluate the disruptive effect on the oyster population on the beds have shown that at the current levels of exploitation, there is little discernable effect (Powell et al. 2001). We have no evidence to determine the effects of removal of large, either old or fast growing individuals has on the oyster population or its ability to increase resistance to disease, but information on these effects in currently being collected.

Bay wide there are three major periods that are easily discerned from the data, a period from 1953 to approximately 1969 that included the first MSX epizootic. This period was characterized by low spat settlement, low oyster abundance and mortality was moderate, but with occasional spikes (Figure 3). During this time, oysters in the lower bay leased areas suffered high mortality due to the MSX epizootic and over 90% of the oysters died. The second period from 1969 to 1985 was a period of high oyster abundance and the highest recorded spat set (1972) occurred during a period of generally high spat settlement and low overall mortality. The period ended with a period of drought and the second MSX epizootic in 1985. This epizootic affected oysters farther up the bay than the mid 50’s epizootic and is believed to have been a proximal cause for the population to increase its resistance to this disease. The third period began from 1985 (Figure 4) and has extended to present. Early in this period the numbers of spat began to increase, but this potential recovery appears to have been suppressed by the appearance of the oyster disease dermo in 1989. The nearly doubling of average mortality during this period and in the 2003 to 2006 very low spat settlement has substantially reduce oyster populations to levels of the early 1950’s. The overall effects in the bay are dramatic, but because of the effects of salinity on the distribution of oyster disease (Figure 5) and the effects were not uniform. The region by region changes are described below.

Upper - The beds in this area occupy about 6,370,974 m^2. In general oysters in this area grow slowly and may take 7 or more years to reach market size (Kraeuter et al. 2007), and even then the meat quality is significantly below that in the rest of the bay. As with the rest of the bay, the oyster abundance in this region can be divided into the three major periods (53 to 68, 68 to 85 and 85 to present (Figure 6, Figure 7).

From the earlier period to the later period the Upper portion of the system as experienced about a 60% loss of oysters, and spat set is off by 82%, but the mortality rate is essentially unchanged (4% increase). Mortality was noticeably lower in the period of high abundance from the late 1960's to the late 1980's. Since the 1980's the reduced setting appears to be the dominant factor affection oyster abundance in this region.

The spat/oyster values are off by nearly 56% reflecting the importance of substrate and a decline in recruitment in the area. While oysters in this area are infected with dermo, the intensity of the infection is not high enough to cause significant mortality.

Upper Central – The beds in this area occupy about 21,791,496 m^2, about 35% of the area, but currently support the highest oyster density, oyster abundance (54.5 %) (Table 1) and much of the harvest. Oyster growth in this area is variable, but may take 4 or more years to market size (Kraeuter et al., 2007), and meat quality is dependent on food supplies. Some beds provide oysters of marketable quality meat in some years, while oysters on nearby beds almost never produce marketable meat. Over the 50 + year record, this bay segment has supported much of the harvest when conditions did not favor the oyster population. The 1968 to 1985 period was one of very high abundance good spat set and low mortality (Figure 8). After 1985 spat settlement has been moderate, but due to the lower mortality relative to the Central and Lower portions of the bay, oyster abundance has remained relatively strong (Figure 9). Periods of high mortality and/or low spat settlement have decreased abundance in recent years, but dermo induced mortality is about half that in the lower areas of the bay. This segment of the system, in terms of the oyster population is the most sensitive to salinity fluctuation induced changes (Figure 10) with higher salinity, particularly in the April to June period increasing the probability of significant mortality.

Since 1984, oysters and spat have declined by about 62% and mortality is nearly double, having jumped from about 11% to 19%, reflecting the incursions by MSX and dermo. Spat/oyster has not changed much suggesting that disease induced mortality and loss of substrate are more important in this region than lack of recruits.

Central- The beds in this area occupy about 28,831,757 m^2, about 46 % of the area, but currently support only about 12% of the oyster population **(**Table 1).

The long term record from this portion of the bay is the most dramatic, growth rates are higher and oysters can reach market size in 3 to 4 years (Kraeuter et al., 2007). Meat quality is better than in the Upper Central region. From 1953 to 1968 recruitment and oyster stocks were low (the one high point of the oyster population is believed to be a data error), and mortality relatively high. The 1985 MSX epizootic severely impacted these stocks (Figure 11). After 1968 recruitment increased, mortality declined and the oyster population increased. This condition was maintained until the MSX epizootic of 1985 when the population was again reduced to pre 1968 levels. Recruitment declined below the earlier levels, but more importantly, mortality levels, increased. This higher, dermo induced mortality (Figure 12), and the poor recruitment from 2001 to 2006 has reduced densities on many beds to levels that preclude profitable fishing rendering many of the beds in the area out of production. (Table 2).

From 1984 to present the numbers of oysters have declined by 83% and spat numbers are 71% lower than previously. Average mortality has increased by 100% from 15% to 30%. Spat/oyster has increased by 84% reflecting the importance of substrate and mortality in the dynamics of the area.

Lower- The beds in this area occupy about 5,961,716 m^2, about 9,5 % of the area, but currently support only about 0.2% of the oyster population (Table 1).
Oysters may reach market size in 3 years (Kraeuter et al 2007) and meat quality is typically of marketable condition in most years. Even these oysters, if moved to the down-bay leased grounds can improve markedly in condition in a few weeks to a month. (Kraeuter et al. 2003). With the exception of the high abundance period in the middle 1970's (the one high point in the late 1950's is a data error) this portion of the bay has not supported a dense oyster population (Figure 13, Figure 14). This has been a dynamic area for oysters even before the advent of the two diseases with high per oyster recruitment and high mortality rates. (Figure 15). Prior to the presence of the disease this area was being investigated for means to control oyster drills. These predators were a major factor controlling the oyster population and consumed an estimated 30% of each years spat. There is no current estimate of drill effects, but they are still presumed to be an important factor in this region and in a portion of the Central region as well.

Spat counts in this region are about 77% lower than in previous decades, and the oyster population has dropped by 95%. This precipitous drop reflects the increase in disease related mortality from an average of 18% to 40%. Spat/oyster values have increased by 322% and highlight the fact that if substrate was present and disease related mortality was reduced, this area could return to former productive levels.

River Flow, Temperature and Salinity effects on spat settlement and mortality.

River flow data utilized for this report are those provided by the USGS at the Trenton gauging station and are available for all but the last year of the oyster data set. Data on bottom water temperature and bottom water salinity are available from the Haskin Shellfish Laboratory collections done on bay cruises from 1954 to 1988. These latter data are, by necessity, point estimates and the amount of data collected in any quarter of the year can be very limited. This limitation is especially true for the December to March period when activities in the bay were reduced. The spatial extent of these data is also limited to the NJ side of the bay and focuses on the area from Arnolds bed throughout the bay to near the mouth. The spatial extent, particularly at the upper and lower boundaries of the sampling zone can also be very limited. More thorough data analysis is being conducted in coordination with the efforts to utilize a circulation model of Delaware Bay to model oyster and oyster diseases. This effort could be used to compare retrospective analysis with the Haskin lab and USGS River flow data to obtain better spatial resolution.

Examination of correlations between River flow and annual spat set and mortality based on fall oyster sampling of the seed beds were done for the total bay, Upper, Upper Central, Central and Lower seed beds for the annual average steam flow and quarterly average stream flow (January

– March, April – June, July – September and October to December) for the entire time period (1953 to 2008) and then a reduced data set of 1985 to 2008. The correlations were then compared for significance (Table 3, Table 4). Because of the data limitations and because there are many interrelated factors that affect spat settlement and mortality of oysters most of these correlations are weak and could explain only 10 to 20% of the variation. We have used the statistically significant (5%level) correlations to examine the general direction of the relationship and to compare the sensitivity of the various bay regions. With respect to the latter, there are a number of other plausible ways to separate the seed beds, and these may provide a more insightful analysis, but time and availability of physical data have dictated the current focus.

Monthly average and annual average river flow from the USGS data base clearly shows periods of drought and high flows due to storm events (Figure 16). Monthly average and annual average bottom water temperature and salinity extracted from Haskin Shellfish Research laboratory data sets for the period 1954 to 1988 (Figure 17), show similar periods of drought as increased salinity. Periods of low temperatures are evident in the time series (Figure 16).

River Flow - Spat settlement. For the 1953 to 2008 time period he effects of river flow on spat settlement were generally similar throughout the Bay and were focused in the second quarter or the yearly flow regimes (Table 3). In general, only the entire bay and Upper region showed correlation with the annual river flow data and there was either a negative correlation or one that was indeterminate. The correlation was based on a second order polynomial equation and the curved nature of the relationship can yield high values of set at low and high flows with lower sets in the center. This relationship was often driven by a few very high spat settlement years and the few numbers of points between these and the majority of the data. If the curved nature of the relationship was particularly strong even statistically strong correlations were considered to be “indeterminant”. From the Upper Central to the Lower portion of the bay there was a positive correlation between spat set and flow.

In the reduced data set (1985 to 2008), in contrast to the longer time series, suggests a negative correlation with Bay, Upper and Upper Central spat settlement and yearly and Quarter 4 flow (Table 4). In the Central and lower region there was either no correlation or an indeterminate relationship with quarter 2 flow.

River Flow - Mortality. As a function of Bay wide averages for the 1953 to 2008 there was a negative relationship between river flow for the second quarter and mortality. This same relationship was evident for the Upper Central region and was not significant for the other regions. This reflects the sensitive nature of the area with respect to the salinity gradient. Oysters in the Upper region may experience disease organisms, but these infections rarely cause significant mortality. The Central and Lower regions of the seed beds experience high or very high mortality unless river flow is very high (Table 3). In the 1985 to 2008 time period higher rivers flows decreased mortality for the bay as a whole, but this trend was not significant for individual bay regions (Table 4).

Temperature and Salinity – Spat Settlement. Bay wide spat settlement was negatively correlated with bottom temperature for the third quarter (Table 3). The negative effect of temperature on settlement was also found in the Central region. Significant but indeterminant relationships were found for the second quarter in the Upper and Lower regions with settlement in the Upper Central showing no significant relationship with temperature (Table 3).

Temperature and Salinity – Mortality. Bottom temperature interacts with mortality in the Central region (Q1) and higher temperatures are correlated with increased mortality in the Lower region for the year and in Q2 (Table 3). Mortality is positively correlated with Quarter 3 bottom salinity in the Upper Central and Central regions. Salinity did not affect mortality in the Upper or Lower regions. This is in accord with the non significant of negative associations with river flow (Table 3).

Relationship between mortality and adult oysters, and mortality and spat settlement

Oysters per square meter were compared to mortality in the Upper Central and Central regions of Delaware Bay (Figure 18). Data were averaged for 1953 to 2009, 1953 to 1989 (pre dermo), 1989 to 2009 (dermo period), 1953 to 1984 (MSX period), and 1985 to 2009 (MSX + dermo period). For both bed regions there were highly significant relationships between mortality and oysters m^{-2} (Figure 18), but the lines have different slopes. As with responses to the physical variables, the Upper Central region again shows more sensitivity than the Central region, probably because it has been less affected by disease. This suggests that any increase in disease related mortality in this region will have a greater impact that in the Central region.

Examination of the relationship between spat set and mortality for the entire 1953 to 2009 bay wide data set indicated no relationship between mortality and set in the same year. When the mortality the prior year was compared with set in the following year, set was lower after periods of high mortality (Figure 19 left graph). Because the 1972 spat set was nearly double the size of all others in the 50+ year data set, the analysis was repeated with it removed and the results were similar, no significant difference in the year of a mortality, but spat settlement was negatively affected by high mortality in the prior year (Figure 19 right graph). A similar analysis of the 20 year period of high dermo mortality (1989 to 2009) did not indicate a significant relationship between mortality and spat settlement for either the same year or lagged data.

Vulnerabilities to Climate Change

In general, the oyster population in Delaware Bay is more limited by disease than by recruitment. Equally important is the geographic configuration of the Delaware estuary. The oyster population exists along the salinity gradient, but the bay begins to narrow above the Upper Central region and over 80% of the area occupied by the seed beds is in the Central and Upper Central portions (Table 1). The narrowing of the area means that, while the oyster resource can migrate up estuary in response to increased salinity, the total population of oysters could decline due to loss of area. The potential for lateral expansion of the estuary due to sea level rise would not be sufficient to provide equivalent areas for reef expansion.

In recent years the appearance of dermo in the system has substantially increased mortality, and most dramatically in the Lower and Central regions (Figures 2, 10 and 12). The current oyster industry relies heavily on the beds in the Upper Central regions, just as it did during the 1950's and early 60's low abundance period. The Delaware oyster beds and the New Jersey seed beds are all infected with dermo. The earlier the spring warming, the longer the warm period lasts and the higher the salinity, the greater the possibility for dermo to become epizootic. If the sea level rise affects the salinity in Delaware Bay as much as is predicted in the Chesapeake Bay (1.4 to 3.2 psu) (Naijar et al 2010), and this is coupled with reduced summer river flows, the probability for increased dermo induced mortality is higher. If this mortality occurs it will most likely result in more severe losses over the Upper Central portion of the bay. This is because dermo continues to be a significant factor in the Lower and Central parts of the seed beds. Although high mortality may continue in these regions, the oyster population is larger and denser in the Upper Central region. Given the extreme sensitivity of dermo to salinity in the 10 to 15 psu range (Figure 4), a range that typifies the Upper Central region, a slight (1 to 2 psu) change in salinity over the Upper Central seed beds could dramatically lower the overall oyster population in the bay.

Models of the sensitivity of the Delaware bay oyster resource (Powell et al. 2009 a,b) indicate that below about 1×10^9 oysters on the seed beds it is likely that oyster populations will continue to decline. Based on the potential for increased mortality depicted in figures 5, 10 and 18 one could expect that a few psu increase in salinity would reduce oyster populations on the Upper Central Beds from the current 27 m^{-2} to about 10 m^{-2} and the entire oyster population from 1.111×10^{-9} to 1.072×10^{-9}. An alternate method of estimation (Table 5) suggests a drop of 71% in the Upper Central region and an increase of 38% in the Upper region with little change in the two lower regions. Overall this yields a 21% drop in the seed beds oyster population to 0.888×10^{-9}. These potential decreases could greatly reduce oyster harvest. It is likely that the resource would decline even further if a 1960's or 1980's drought is superimposed on these potential climate change salinity increases. These effects could be ameliorated or exacerbated by changes in the timing and intensity of rainfall events.

Other than sea level rise, other potential causes of increasing salinity in the Delaware estuary are channel deepening, ground water removal and out of basin transfers of freshwater. The addition of water storage facilities in the upper basin could also alter the timing and intensity of the natural cycle of discharge and affect the oyster resource.

The increase in water volume in the estuary brought about by sea level rise and the lateral spread of the estuary boarders may change other hydrodynamic relationships. The Delaware estuary is typically a well mixed system (Sharp et al. 1986), but the added volume and increased temperature may make mid Atlantic estuaries more stratified (Naijar et al. 2010). Increased stratification and the development of a two layered system was predicted to increase advection beneath the pycnocline in the Chesapeake Bay (Naijar et al 2010). Increased winter and spring river flow due to wetter winters is predicted for the mid – Atlantic region and based on current models this should increase spat settlement. The increased advection due to stratification would increase salinity and this in turn, based on the long term averages would increase mortality which may reduce spat set in the following year (Figures 17, 18). The net overall response of the oyster population is difficult to predict, but anything that increases mortality up bay from its current position is likely to reduce the population simply because of the area of bay bottom involved.

The overall ecological effects are difficult to evaluate, but the reef like structure would be substantially altered in the Upper Central part of the bay it the numbers of oysters are greatly reduced. One final unknown is the potential for changes in circulation to affect oyster recruitment. As sea level rises, the shorelines of the bay will certainly change and these changes may affect the position and intensity of tidal induced circulation patterns. These patterns are important for retention of oyster larvae over the seed beds, and significant changes in the circulation pattern has the potential to alter the adult to recruit relationship.

Adaptation

How well the oyster population adapts to potential climate change depends on a large number of unknowns, but the interactions between oyster disease, salinity, temperature and the oyster's ability to adapt to changing disease pressure will play a significant role. Oysters will not disappear from the Delaware estuary, but their populations and regional density may shift and these shifts may be dramatic. The importance of shell to the oyster resource cannot be overemphasized. Powell et al. (2003) reported that the half life for oyster shell in Delaware Bay was on the order of 5 to 10 years and that in order to sustain harvest it would be essential to continue to replenish shell removed from the system. One way to compensate for loss of high quality oyster grounds in higher salinity areas would be to increase the areal extent of the oyster grounds in lower salinity areas. This could be done with shelling programs, but shell is a precious resource and such programs are expensive. The other limitation is the benthic area available above the current seed beds is greatly reduced. Even if shelling could be accomplished, the reduced area of bay bottom will limit the effectiveness of this procedure to augment the oyster population. In order for shelling to be effective it must attract set, and the set must survive. Under existing conditions, the best sites for spat settlement and growth are in the higher salinity portions of the bay, but these are not the best sites for survival. Survival of spat and older oysters is better in the Central and Upper Central portions of the system. Paradoxically, growth and spat settlement are both lower in these regions. If circulation patterns change due to sea level rise, the areas of high settlement could change and disrupt a shelling effort in which shell is placed on the oyster grounds based on current conditions.

Aquaculture and aquaculture techniques could be utilized to assist with adaptation to climate change. Converting the current oyster production system to more intensive aquaculture could augment harvests, but aquaculture techniques offer another possible adaptation, changing of the genetic make up to allow the oysters to become more resistant to disease. This process is underway with the development of stock that are resistant to MSX. The native population in Delaware bay appears to have adapted on its own after the 1985 MSX epizootic (National Research Council, 2004). This result mirrors that from the various selective breeding programs on *C. virginica* that began shortly after the first epizootic in Delaware Bay in the middle 1950's. Using this technology to alter a population as large as that in Delaware bay would require a concerted long term effort and significant expenditures. Removals of oysters from the extreme upper parts of the system (the disease refuge) would be required and these oysters would then be replaced by hatchery produced spat or yearlings of the disease resistant stocks. Through time this constant process would allow more of the bay population to receive genes from the resistant stocks. Concomitantly the resistant stocks would be subject to the bay environment and this exposure through spawning and settling would serve to rid the progeny of any maladaptive traits potentially derived from hatchery procedures. In any event, for aquaculture techniques to be successful on a bay wide basis, they will require some commitment to providing shell for newly setting oysters as with any other effort to increase or maintain oyster grounds.

The above discussion has focused on the oyster with the assumption that maintaining oysters and oyster reefs in the system is a precursor to maintaining many of the species that are typically associated with reef-like structures. How dependent these other species are on the oyster versus alternate types of vertical structure on otherwise sandy or muddy bottoms is relatively unknown. It might be possible to develop artificial structures to mimic oyster reefs and derived some of their benefits without their presence, but the effects of oysters on nutrient cycling and water filtration will not be present. In addition, a natural oyster reef is self replacing; an important factor in a dynamic environment, and this would not be accomplished with artificial structures.

Literature Cited

Burreson, E.M., L. M. Ragone Calvo, J. F. LaPeyre, F. Counts and K.T. Paynter, Jr. 1994. Acute osmotic tolerance of cultured cells of the oyster pathogen *Perkinsus marinus* (Apicomplexa: Perkinsida). Comp. Biochem. Physiol. 109A 575-582.

Cerco, C.F. and M.R. Noel. 2009. Monitoring, modeling, and management impacts of bivalve filter feeders in the oligohaline and tidal fresh regions of the Chesapeake Bay system. Ecol. Model. 221: 1054-1064.

Dungan, C.F. and R.M. Hamilton. 1995. Use of a tetrazolium-based cell proliferation assay to measure effects of in vitro conditions on *Perkinsus marinus* (Apicomplexa) proliferation. J. Euk. Microbiol. 42: 379-388.

Fegley, S.R., S.E. Ford, J.N. Kraeuter, and H.H. Haskin. 2003. The persistence of New Jersey's oyster seedbeds in the presence of MSX disease and harvest: Management's role. J. Shellfish. Res. 22:451-464.

Fegley, S.R. S.E. Ford, J.N. Kraeuter and D.R. Jones. 1994. Relative effects of harvest pressure and disease mortality on the population dynamics of the Eastern osier (*Crassostrea virginica*) in Delaware Bay. National Oceanic and Atmospheric Administration F ina Report. # NA26FL0588. Bivalve, NJ: Haskin Shellfish Research Laboratory, Rutgers University.

Ford, S.E. 1985. Effects of salinity on survival of the MSX parasite *Haplosporidium nelsoni* (Haskin, Stauber and Mackin) in oysters. J. Shellfish. Res. 5: 85-90.
Ford, S.E. and H.H. Haskin. 1988. Comparisonof in vitro salinity tolerance of the oyster parasite *Haplosporidium nelsoni* (SX) and hemocytes from the host *Crassostrea virginica*. Comp. Biochem. Physiol. 90A: 183-187.

Haskin, H.H. and S.E. Ford. 1982. *Haplosporidium nelsoni*(MSX) on Delaware Bay seed oyster beds: a host parasite relationship along a salinity gradient. J. Invert. Pathol. 40: 388-405.

Kraeuter, J.N. S.E. Ford and M. Cummings. 2007. Growth measurement in oysters: A comparison of methods. J. Shellfish Res. 26:479-491.

Kraeuter, J.N., S.E. Ford and W. Canzonier. 2003. Increased biomass yield form Delaware Bay oysters (Crassostrea virginica) by alteration of planting season. J. Shellfish Res. 22:39-49.

Naijar, R.G., C.R. Pyke, M.B. Adams, D. Breitburg, C. Hershner, M. Kemp, M. Howarth, M.R. Mulholland< M. Paolisso, D. Secor, K. Sellner, D. Wardrop and R. Wood. 2010. Potential climate-change impacts on the Chesapeake Bay. Est. Coast. and Shelf Sci. 86: 1-20.

National Research Council, 2004. Nonnative oysters in the Chesapeake Bay. Committee on Nonnative oysters in the Chesapeake Bay, Ocean Studies Board, National Research Council, National Academies of Science. National Academies Press, Washington, DC 325 pp.

Powell, E.N., K.A. Ashton-Alcox, S.E. Banta, and A.J. Bonner. 2001. Impact of repeated dredging on a Delaware Bay oyster reef. Journal of Shellfish Research, 20: 961-975.

Powell, E.N., J.N. Kraeuter and K.A. Ashton-Alcox. 2006. How long does oyster shell last on an oyster reef? Estuarine Coastal and Shelf Sci. 69: 531-542

Powell, E.N., K.A. Ashton-Alcox, J.N. Kraeuter, S.E. Ford and D. Bushek. 2008. Long-term trends in oyster population dynamics in Delaware Bay: Regime shifts and response to disease. J. Shellfish. Res. 27: 729-755.

Powell, E.N., J. M. Klinck, K.A. Ashton-Alcox, and J.N. Kraeuter. 2009a. Multiple stable reference points in oyster populations: biological relationships for the eastern oyster (*Crassostrea virginica*) in Delaware Bay. Fish. Bull. 107: 109-132.

Powell, E.N., K.A. Ashton-Alcox, and J.N. Kraeuter. 2009b. Multiple stable reference points in oyster populations: implications for reference point –based management. Fish. Bull. 107: 133-147.

Sharp, J.H. , L.A. Cifuentes, R.B. Coffin, J. R. Pennock and K-C. Wong. 1986. The influence of river variability on the circulation, chemistry, and microbiology of the Delaware Estuary. Estuaries 9: 261-269.

Soniat, T.M. 1985. Changes in levels of infection of oysters infected by *Perkinsus marinus*, with special reference to the interaction of temperature and salinity upon parasitism.

Bay Area	Bed Area m^2	% Bay Area	% Oyster
Upper	6,370,974	10.12	33.26
Upper Central	21,791,496	34.61	54.51
Central	29,256,711	46.47	12.27
Lower	5,961,716	9.47	0.22
Total	63,380,896		

Table 1. Total oyster grounds on Delaware Bay Seed Beds (NJ) by major region. Percentage of area and percentage of the oysters (2009 estimates).

Bed	Area m^2	Percent of area	Oysters # m^2	Total Oysters
Bennies	8,404,239	13.35	1.29	10,867,214
Benny Sand	3,190,495	5.07	6.75	21,546,712
Nantuxent Point	2,765,542	4.39	11.92	32,965,584
Hog Shoal	1,808,455	2.87	9.62	17,401,198
Strawberry	1,808,668	2.87	0.17	307,934
Hawk's nest	2,021,560	3.21	20.30	41,037,184
Beadons	2,447,474	3.89	1.55	3,799,585
New Beds	4,788,189	7.61	1.63	7,826,497
Vexton	2,022,090	3.21	0.12	250,729

Table 2. Oyster beds in the Central region of Delaware Bay in terms of bed area, percentage of area of total seed area oyster bed, the number of oysters per square meter and total oysters. Benny Sand bed has been heavily subsidized by movement of oysters from up bay beds and shell plantings.

Bed Group		Spat Set				Mortality	
	River Flow	Bottom Temp.	Bottom Salinity		River Flow	Bottom Temp.	Bottom Salinity
Bay	Y, Q2+	Q3-	Y,Q2,Q3-		Q2-	ns	ns
Upper	Y*-	Q2	Y,Q2-		ns	ns	ns
Upper Central	Q2+	ns	Y,Q1,Q2,Q3-		Q2-	ns	Q3+
Central	Q2+	Q3-	Y,Q2,Q3,Q4-		ns	Q1	Q3+
Lower	Q2+	Q2	ns		ns	Y,Q2+	ns

Table 3. Significant correlations (5%) or better 1953 to 2008 between spat settlement and River Flow at Trenton, and Bottom Temperature and Bottom Salinity (Haskin cruise data from 1954 to 1988). Y = year, Q 1, Q2, Q3, Q4 = first, second, third, and fourth quarters of the year. * = Upper only with high spat sets of 1972 and 1973 removed. Signs (+,-) apply to all time periods unless noted with a ? + = positive trend between variables, - = negative trend between variables. If no sign is attached there was an indeterminate relationship.

Bed Group	Spat Set	Mortality
	River Flow	River Flow

Bay	Y, Q4-	Q2-
Upper	Y-	Ns
Upper Central	Y?,Q4-	Ns
Central	Q2	Ns
Lower	ns	Ns

Table 4. Significant correlations (5%) or better 1985 to 2008 between spat settlement and River Flow at Trenton. Y = year, Q 1, Q2, Q3, Q4 = first, second, third, and fourth quarters of the year. Signs (+,-) apply to all time periods unless noted with a ? + = positive trend between variables, - = negative trend between variables. ? means there was an in determinate relationship.

Bed Region	**Oysters m-2 1953 to 1988**	**Oysters m-2 2009**	**% Loss**	**Oysters m-2 Future**	**Bed Area**	**Total oysters 2009**	**Total oysters Future**	**Percentage**
Upper	360	57.85	76	88	6,370,974	368,560,821	560,645,674	52
Upper Central	134	27.72	79	8.04	21,791,496	604,060,258	175,203,625	-71
Central	74	4.65	94	4.65	29,256,711	136,043,706	136,043,706	0
Lower	45	2.7	94	2.7	5,961,716	16,096,632	16,096,632	0
Total						1,124,761,417	887,989,637	-21

Table 5. Potential oyster gain and loss with a salinity shift sufficient to make the oyster disease dermo a more important factor in the Upper Central region of the bay. The shift is based on the losses from the 1953-1988 average number of oysters m^{-2} compared to the 2009 values for the region.

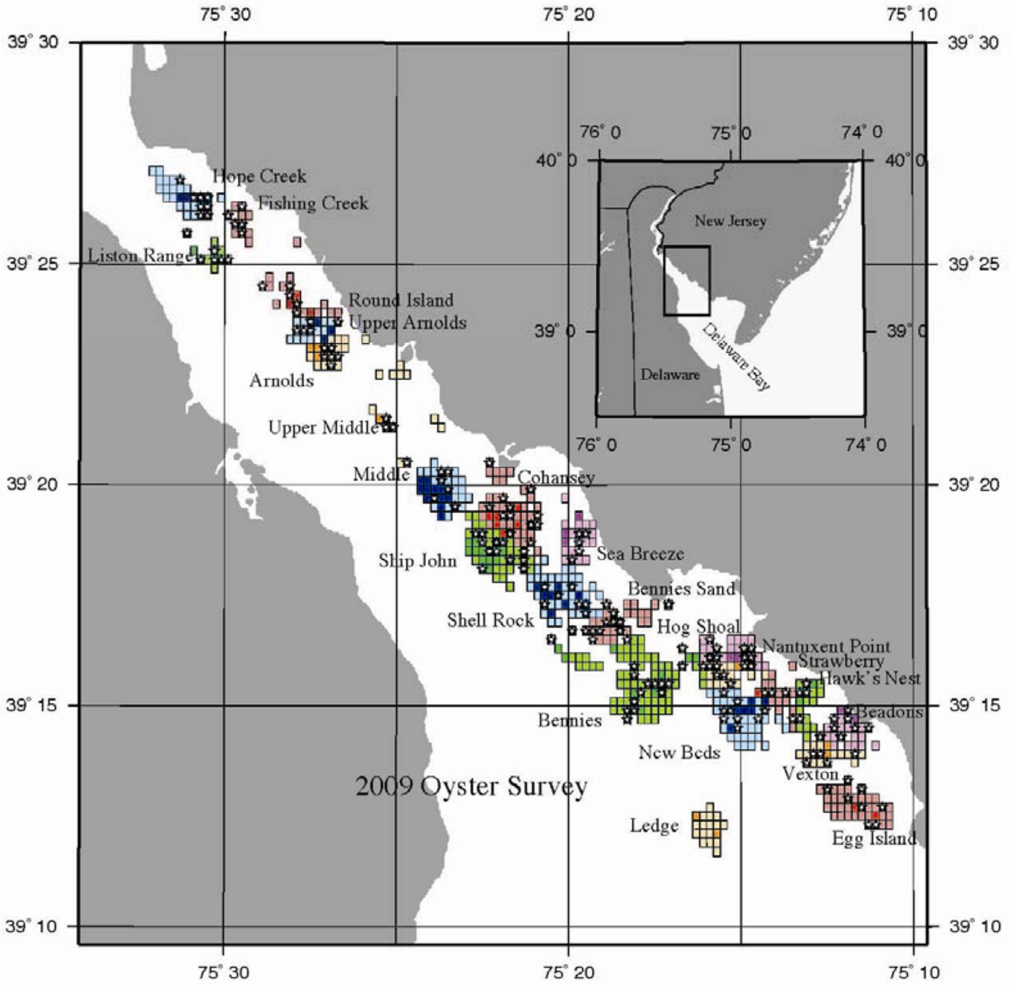

Figure O.1. Delaware Bay (NJ) oyster seed beds. Grids represent area occupied by oysters and represent 98% of the population in the area. More intense color indicates grids containing the top 48% of the population. Lighter color indicates grids with 50% of the population. Each rectangle is approximately 25 acres. Grids sampled in 2009 are highlighted with a star.

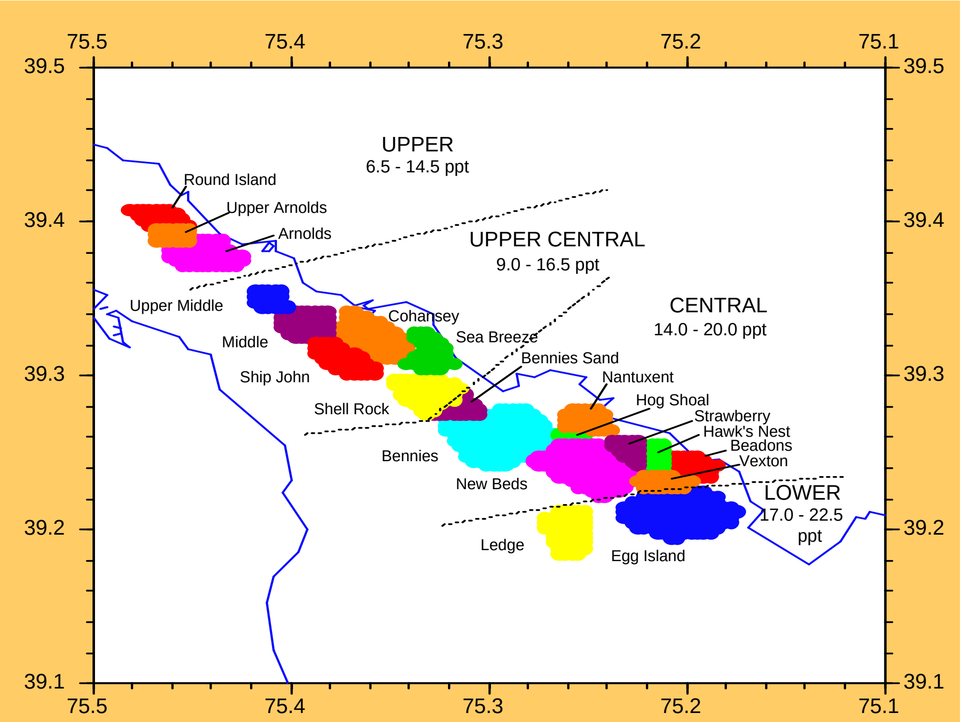

Figure O.2. Delaware Bay seed beds on the New Jersey side of the bay and designation of regions analyzed in this report. General average salinity regime over the bed regions is provided.

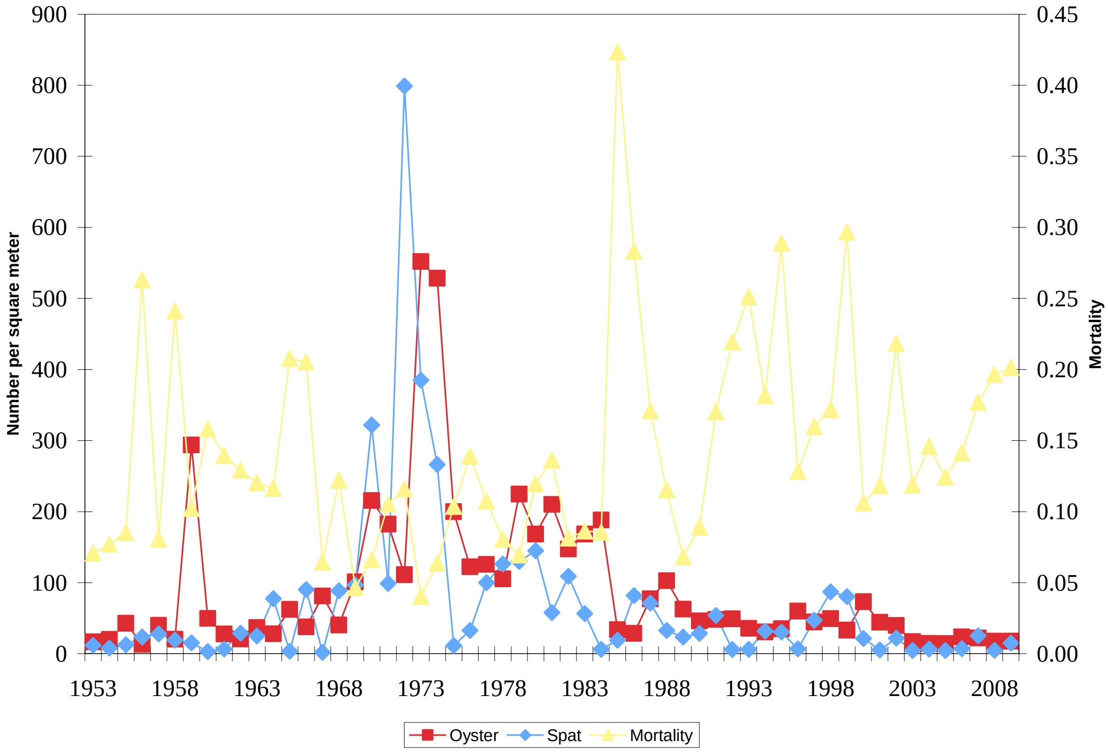

Figure O.3. Bay wide oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

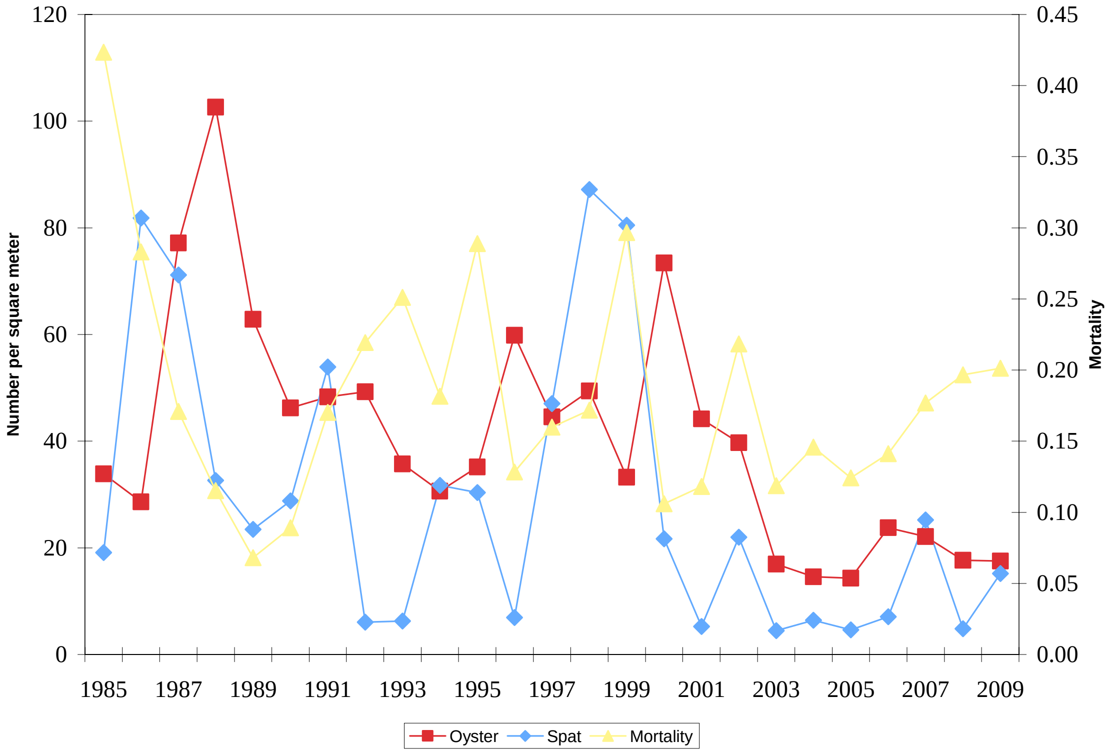

Figure O. 4. Bay wide oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1985 to present.

Dermo, MSX and Salinity (River Flow)

- Compared to MSX, salinity has relatively little effect on dermo prevalence (although disease severity is diminished)

- Dermo causes consistent mortalities on most beds

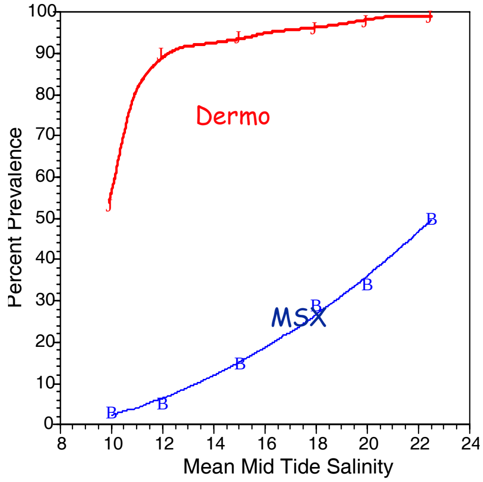

Figure O.5. Data from Susan Ford (HSRL). Comparison of the oyster disease organisms dermo *Perkinsus marinus* and MSX, *Haplosporidium nelsoni* abundance relative to salinity.

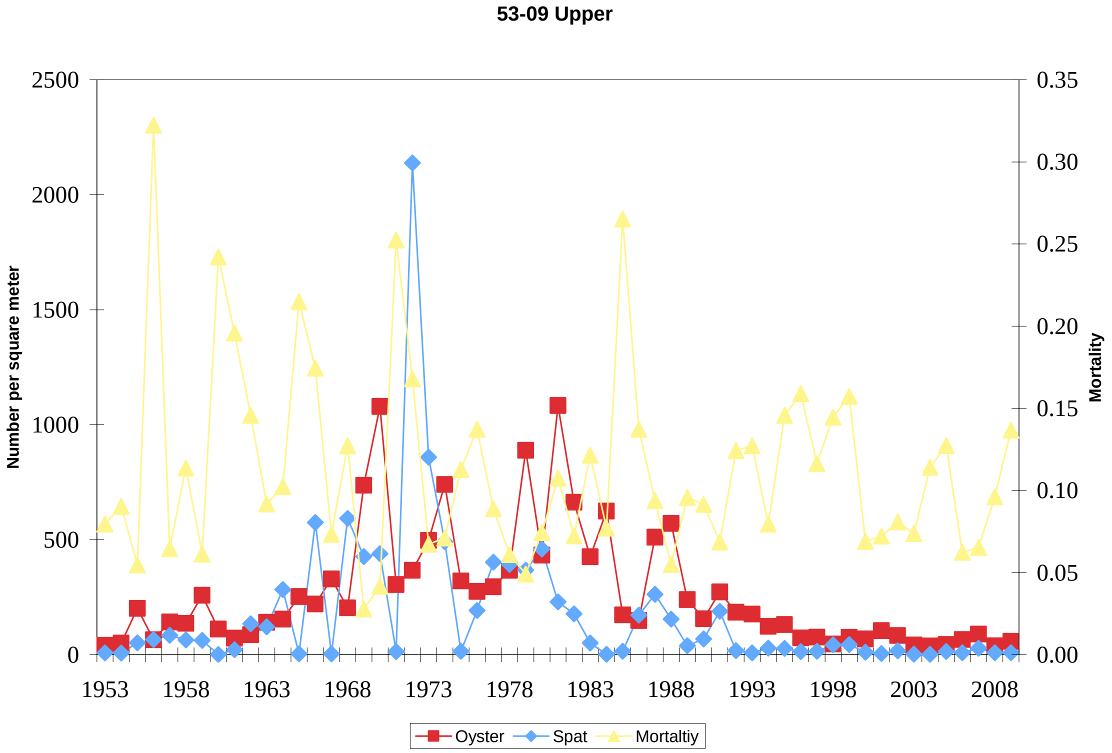

Figure O.6. Upper region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

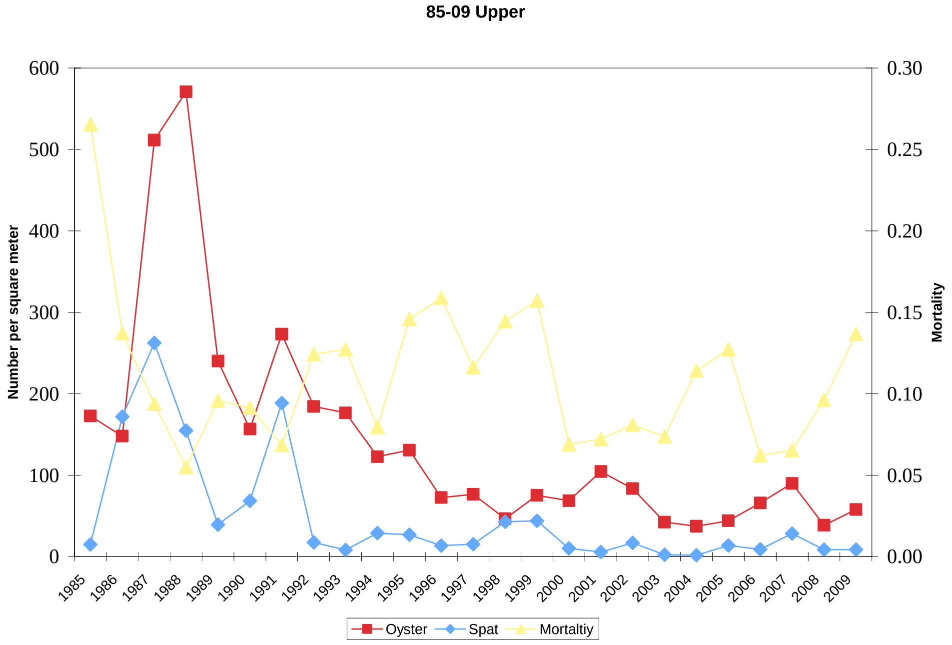

Figure O.7. Upper region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1985 to present.

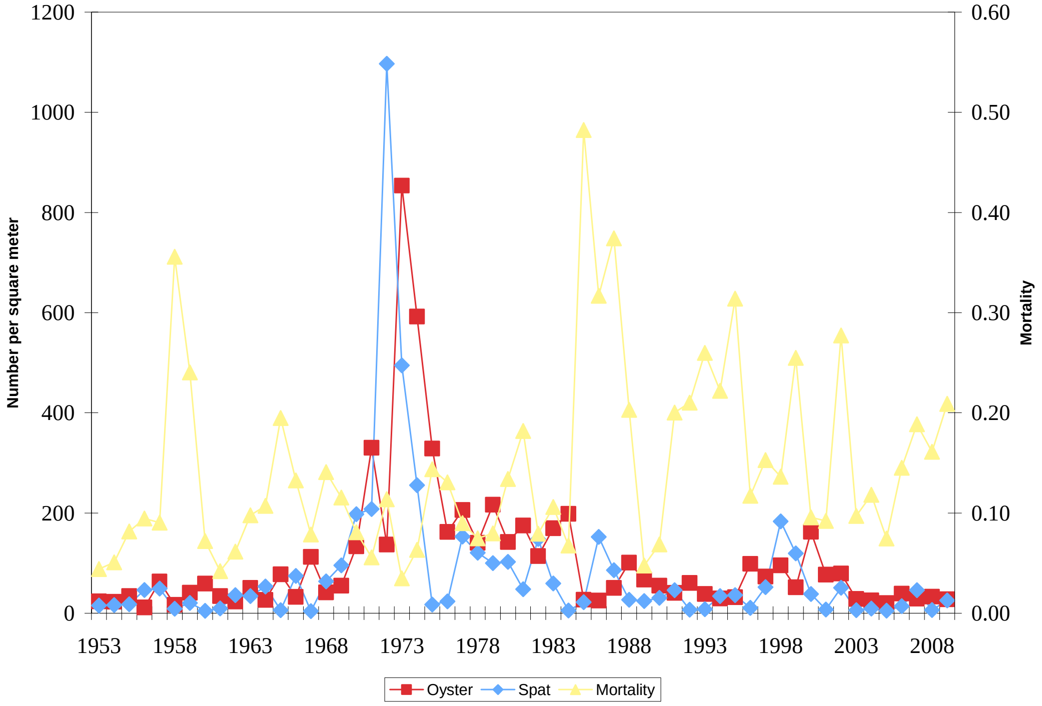

Figure O.8. Upper Central region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

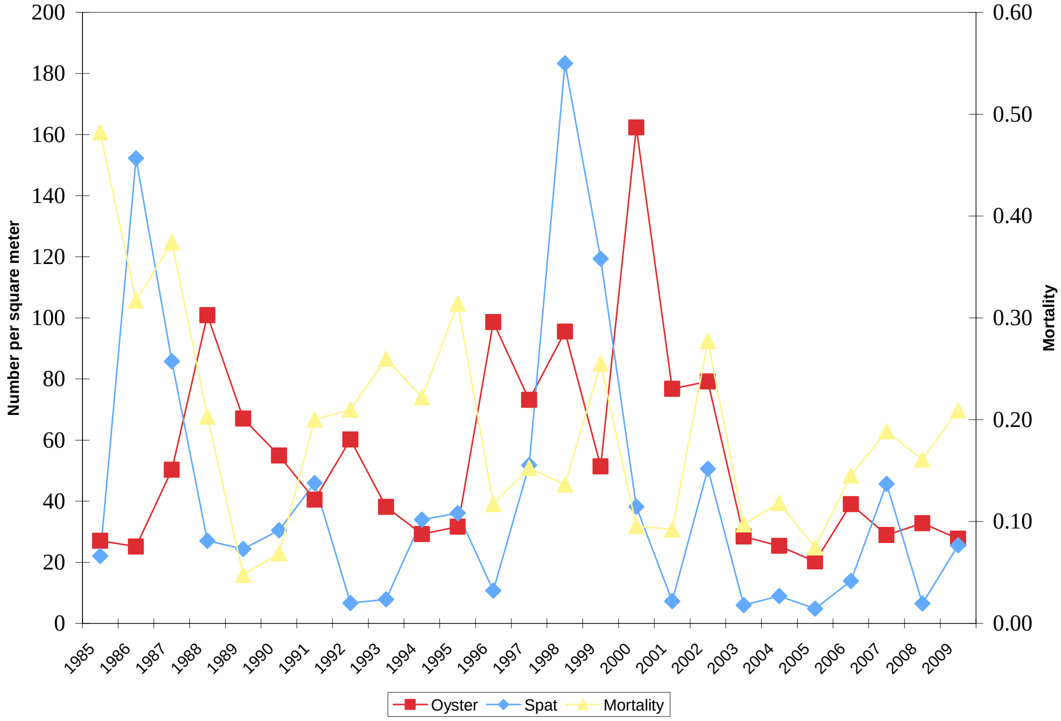

Figure O.9. Upper Central region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1985 to present.

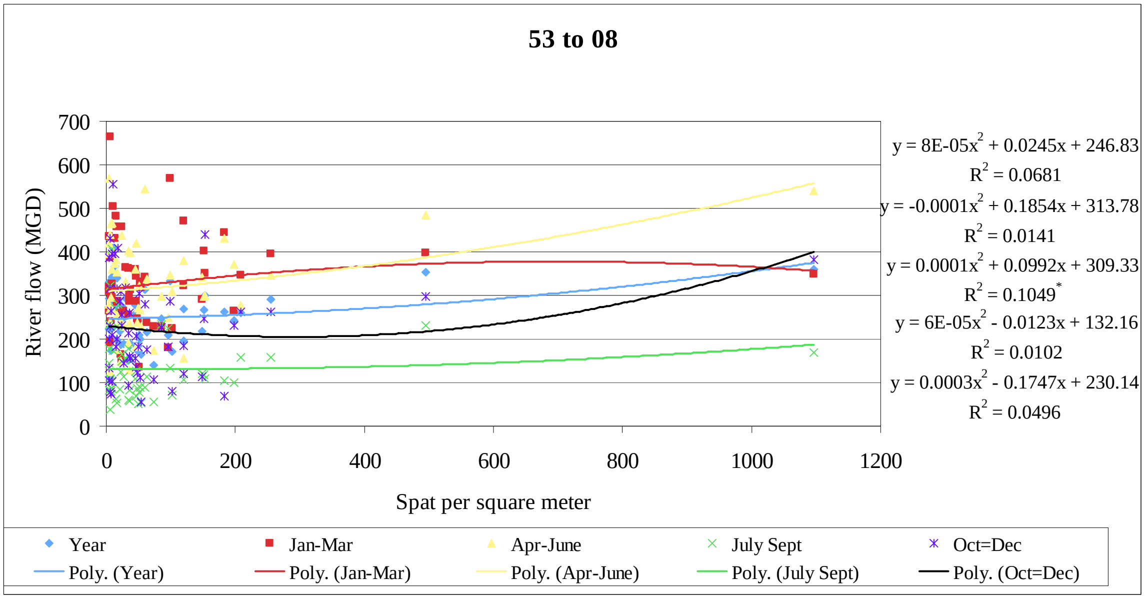

Figure O.10. Upper Central region correlation between river flow (MGD) at Trenton, NJ and fraction of the stock dying in a given year. Equations are associated with different lines (Equation 1 = annual flow, blue), (Equation 2 = Jan to March flow, red), Equation 3 = April to June Flow yellow) (Equation 4 = July to September Flow, green) (Equation 5 = October to December flow, black). The only correlation coefficient that is significant (*) is the April to June flow indicating that the lower the flow (higher the salinity) the greater the mortality.

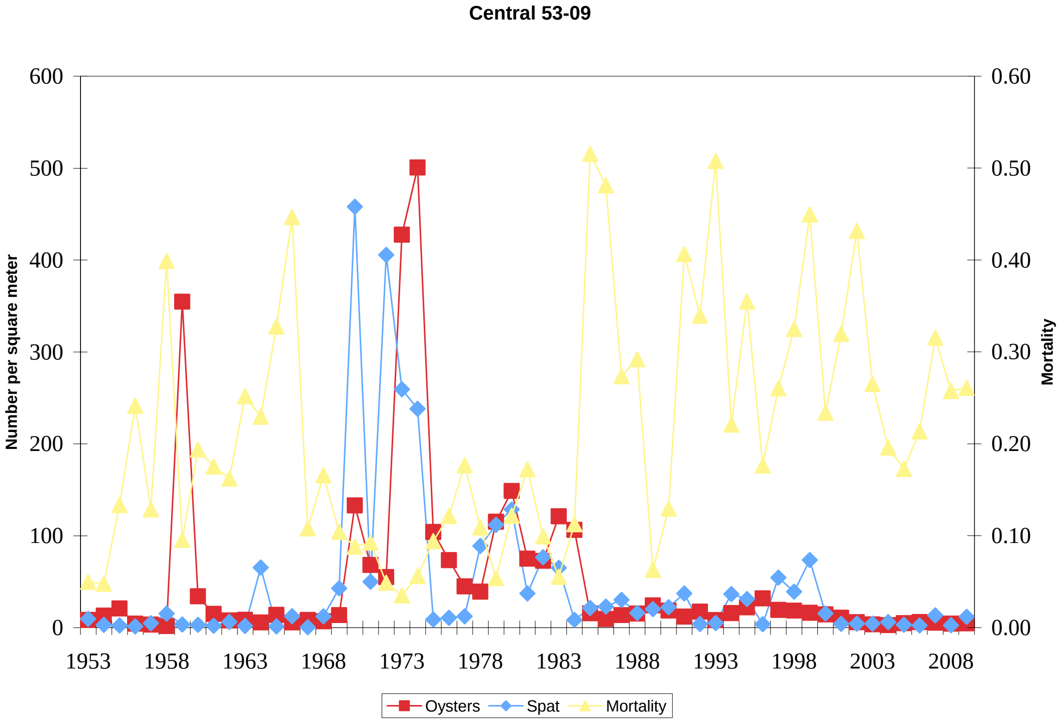

Figure O.11. Central region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

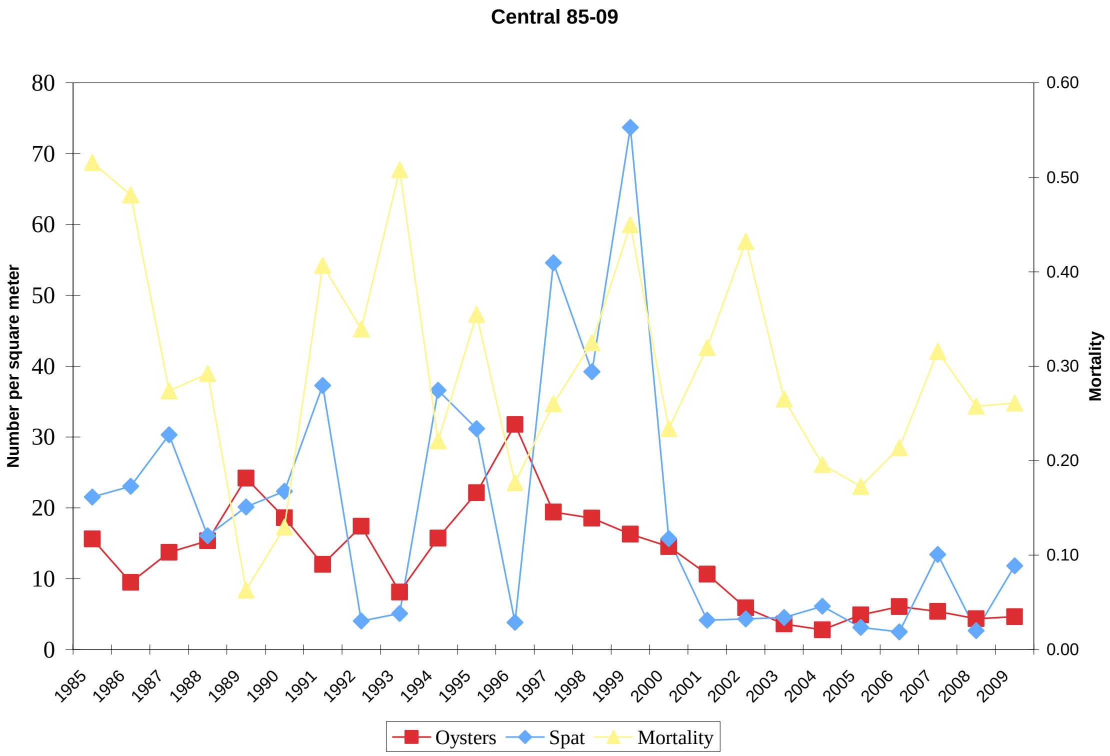

Figure O.12. Central region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1985 to present.

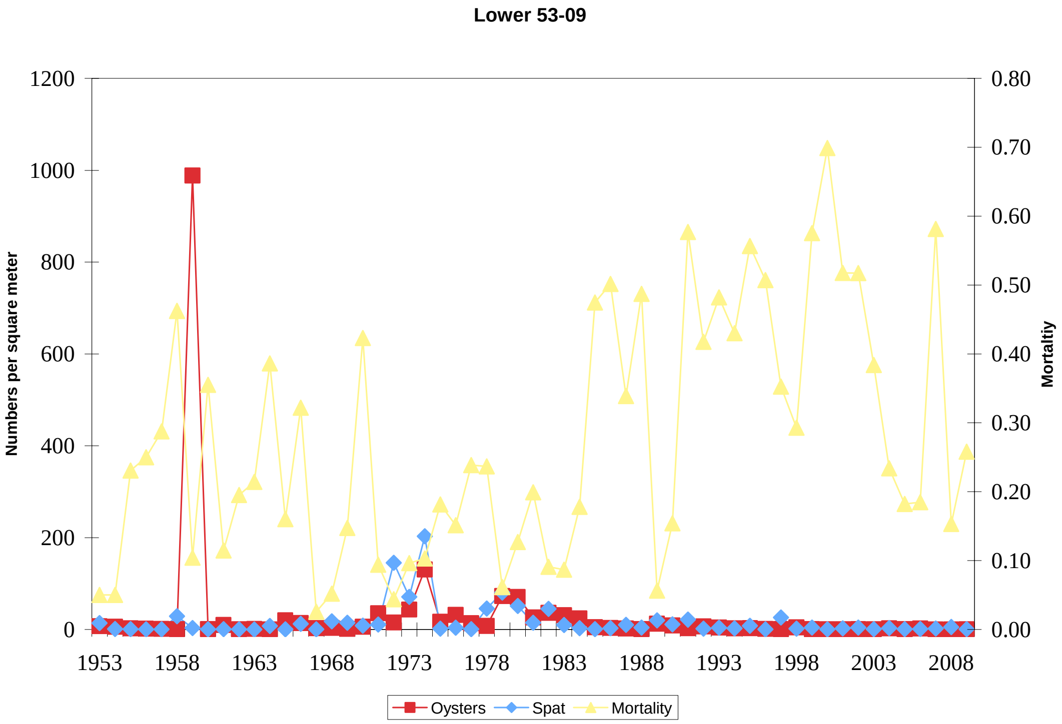

Figure O.13. Lower region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1953 to present.

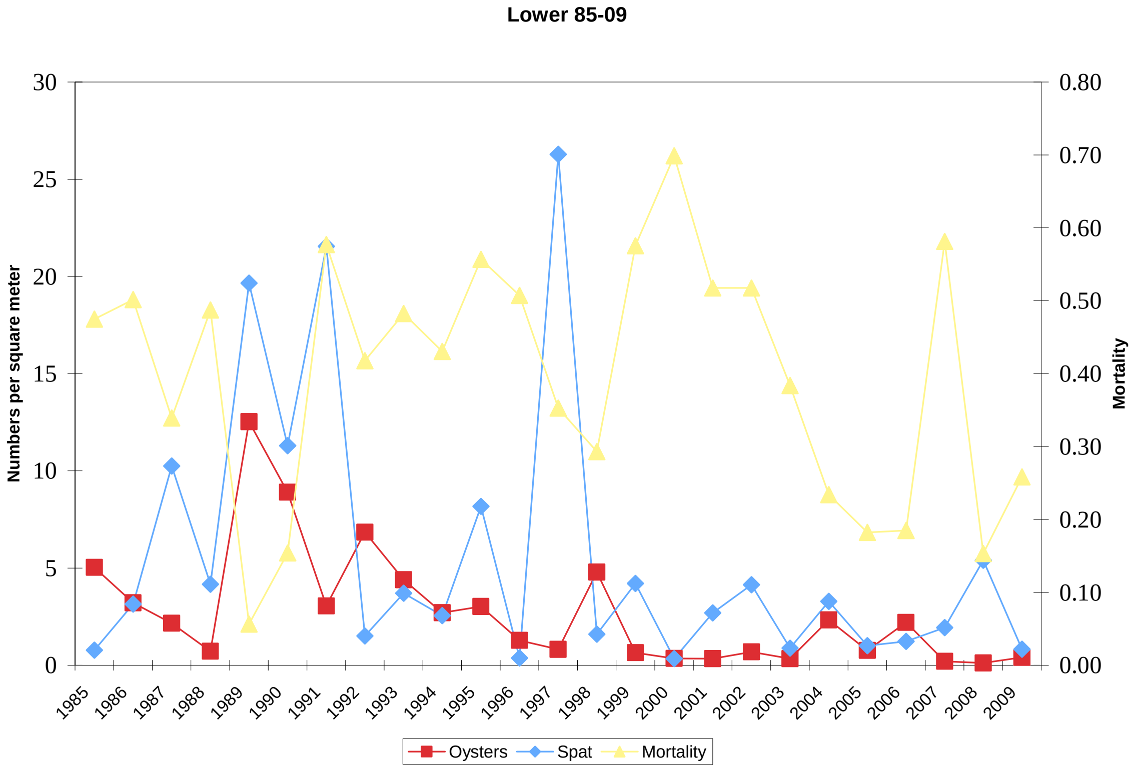

Figure O.14. Lower region oyster and spat abundance and fractional mortality, Delaware Bay Seed Beds (NJ), 1985 to present.

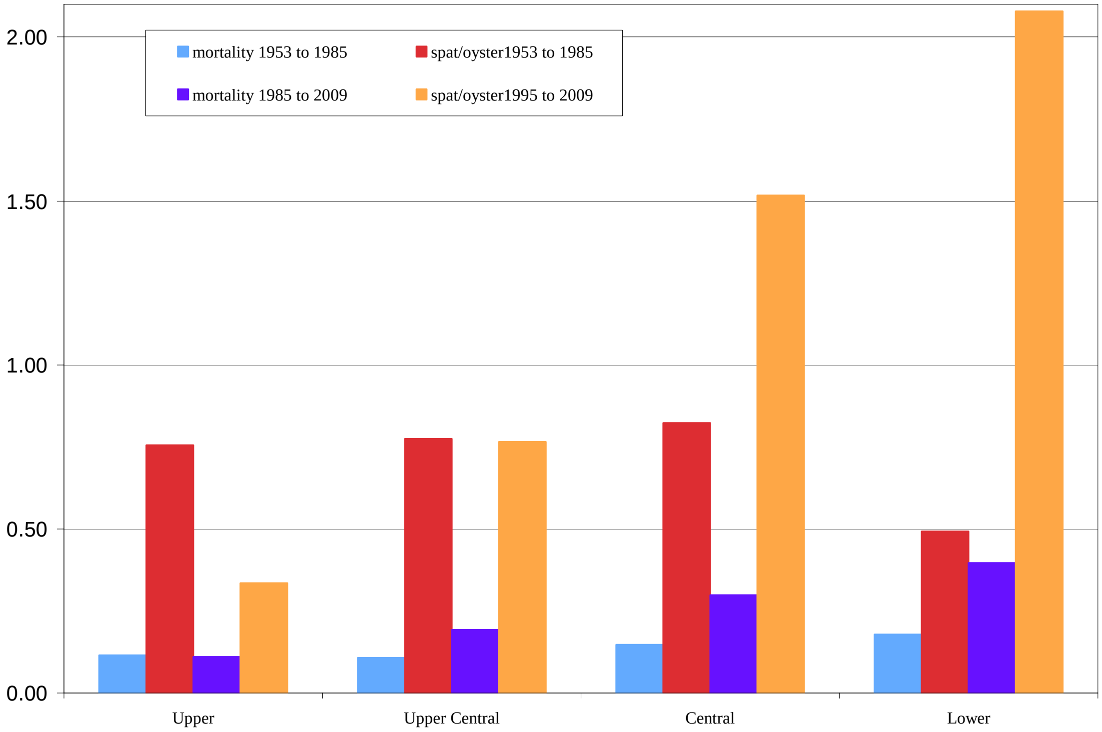

Figure O.15. Changes in average mortality and spat per oyster 1953 to 1985 and 1985 to 2009 along the salinity gradient from the upper NJ seed beds to the lower NJ seed beds. The slight gradient in mortality from upper to lower bay evident in the earlier period increased in the latter period. This is reflective of the increase in dermo activity. Spat recruitment pre adult oyster has decreased in the upper bay during this period, but dramatically increased in the lower portions of the seed beds. The latter increase does not indicate higher numbers of spat per square meter it reflects the reduced numbers of oysters in the area and the continuing settlement.

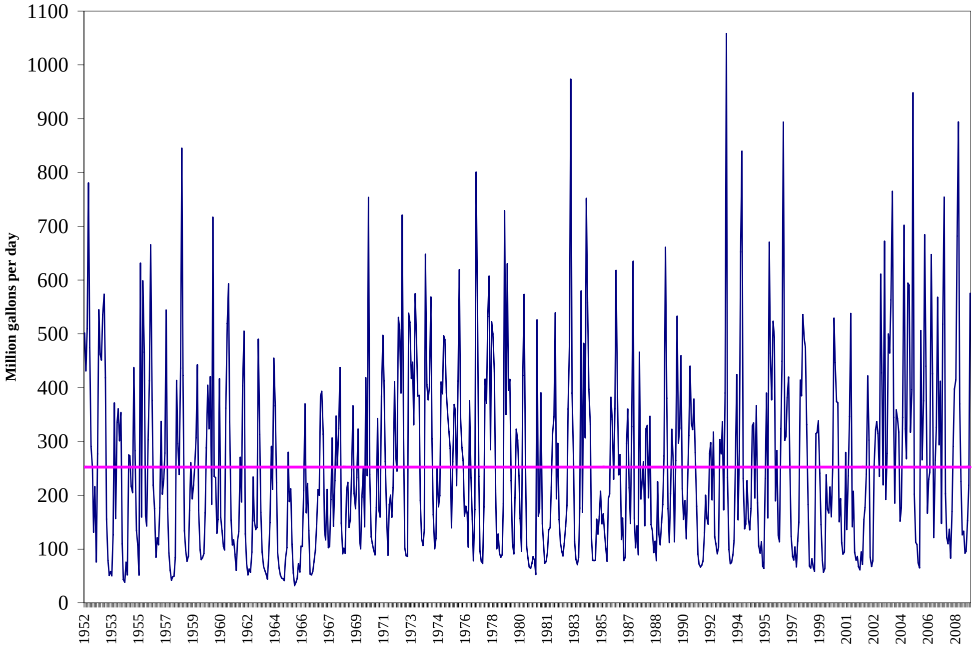

Figure O.16. Monthly average river flow at Trenton from the USGS gauging station in millions of gallons per day. The horizontal line is the average for the period. The extended drought of the middle 1960’s and a less severe period in the middle 1980’s and a third period in the late 1990’s to early 2000’s are evident as are the large storm events.

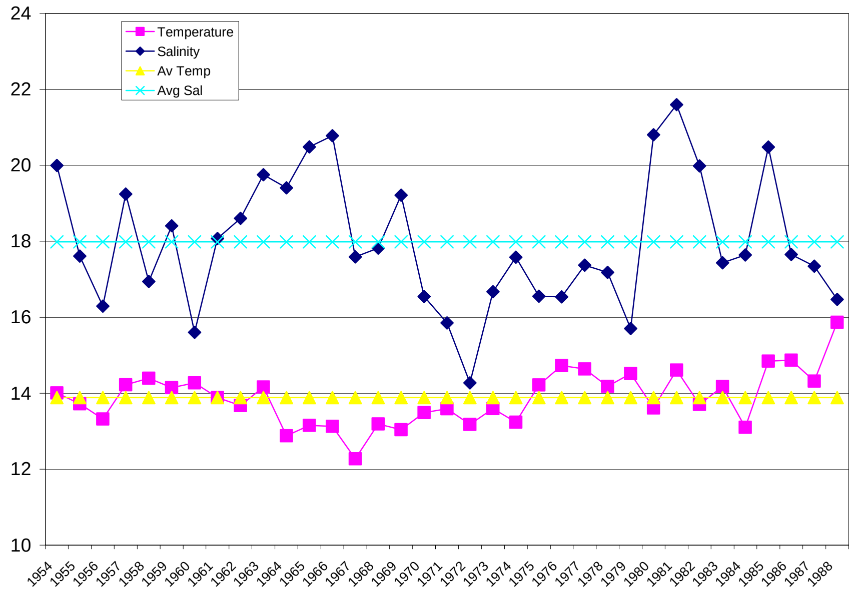

Figure O.17. Annual average bottom water and salinity (°C and psu, respectively). The horizontal lines are averages for the period. The extended drought of the middle 1960's and a less severe period in the early 1980's is evident as is the relatively cool period in the middle to late 1960's.

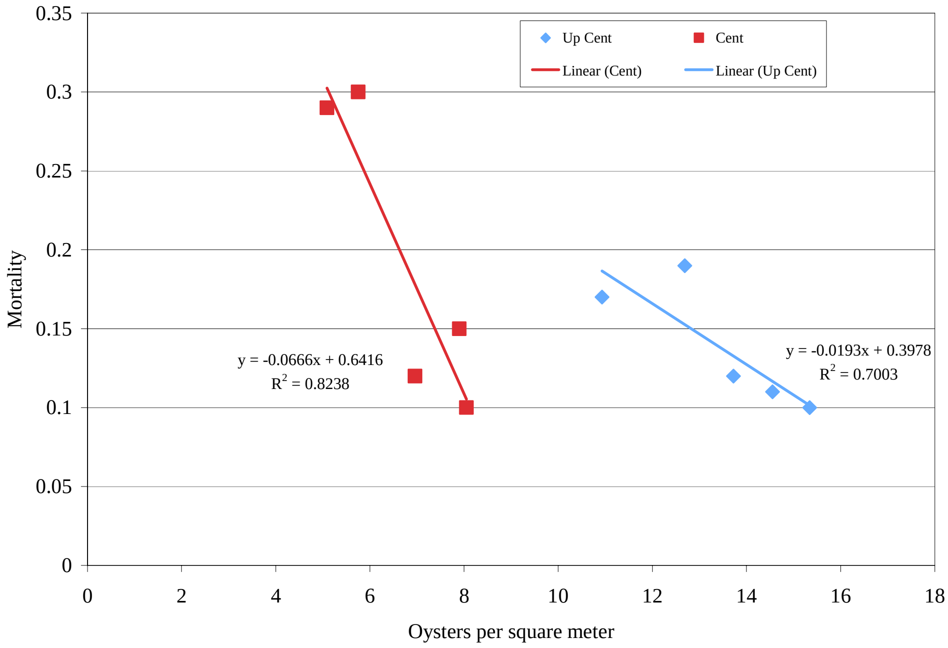

Figure O.18. Oysters per square meter vs mortality for Upper Central and Central beds. Data points are averages for 1953 to 2009 (Total data), 1953 to 1989 (pre dermo), 1989 to 2009 (dermo period), 1953 to 1984 (MSX) and 1985 to 2009 (msx + dermo).

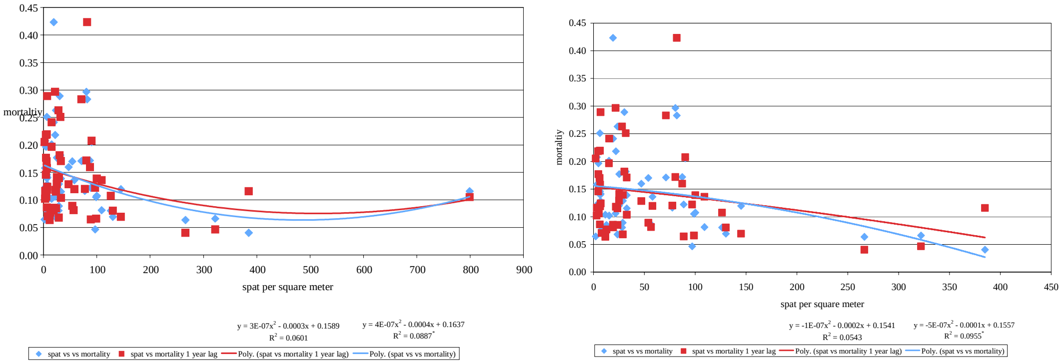

Figure O.19. Relationship (1953 to 2009) between mortality and spat settlement. Left figure = All years included (*) = significant at the 95% level. Right figure = Same data with the 1972 high settlement year data removed.

John: Need temperature data

Need to relate all to 1 oyster per square meter and the size of the beds (total and fraction being surveyed) so that the bay population can be deduced.
Reedy Island- USGS NWIS.
Franklin Institute.
Dave Legates U Del Climatologist
National Weather Mt Holly