Potential impact of climate change on salinity of the Delaware Estuary

A report to the Partnership for the Delaware Estuary

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March 22, 2010

1. Introduction

Here we explore the potential impacts of climate change on the salinity of the Delaware Estuary. We present a preliminary synthesis of historical salinity data in the Delaware Estuary, which aims to quantify the sensitivity of salinity to streamflow. We also consult the literature on this sensitivity as well as the sensitivity of salinity in the Delaware Estuary to sea-level change.

2. Sensitivity of Delaware Estuary salinity to streamflow

A report by Haskin (1972) related salinity at five locations in the Delaware Estuary to flow of the Delaware River at Trenton. The five locations are, in order of increasing salinity: Arnolds Bed, Cohansey Bed, Shell Rock Bed, Bennies Bed, and Miah Maull Ground. Salinity was regressed vs. the prior 30-day average streamflow for two time periods, 1927-1952 and 1953-1968. A clear decrease in salinity with streamflow was found for all sites and both time periods, and a significant increase in salinity was found from the earlier period to the later period at the two most seaward sites, particularly at high flows. We attempted to reproduce the results of Haskin (1972) and to extend his analysis by including more recent salinity measurements.

2.1. Data sets

We acquired a portion of the original data in Haskin (1972) from Susan Ford (Haskin Shellfish Research Laboratory) in June 2009. The data were in the form of punch cards, which we had read in July 2009. We do not know what fraction of the data in Haskin (1972) we acquired because the size of the data set is not discussed in the report. It appears we are missing some data, however, because Haskin's analysis begins in 1927 whereas the punch card data start in 1929. Furthermore, Haskin presents an analysis of Bennies Bed before 1953 whereas the punch card data for that site start in 1953.

Dr. Ford also provided us with electronic text files of salinity data collected in the Delaware Estuary between 1953 and 1990, including the five locations analyzed by Haskin (1972). Figure 1 shows a time series from this data set at Cohansey Bed, which was one of the most frequently sampled sites. The annual cycle, which is mirror image of the annual cycle in streamflow, with a slight lag (Wong, 1995), can be clearly seen, as

can the greater frequency of summer sampling. Further, there is strong interannual variability resulting from streamflow, as evidenced from the high salinity during the 1960s drought.

2.2. Salinity data analysis

Following Haskin (1972), we regressed salinity (S) vs. the prior 30-day average flow at Trenton (Q). We then fit an exponential curve to the data and computed 95% confidence intervals through bootstrapping with replacement (Efron and Tibshirani, 1993). Results are shown for Shell Rock Bed using the 1953-1990 data (Figure 2). Though there is a statistically significant relationship between flow and salinity, there is a great deal of scatter in the data, indicating that individual salinity measurements are significantly influenced by other processes besides streamflow during the past 30 days. The other sites have a similar degree of scatter (not shown). Haskin (1972) did not present raw data plots, so we cannot directly compare our results with his.

Figure 3 shows that the functional fits of salinity vs. streamflow in the Haskin (1972) study are reproduced in the current analysis. Specifically, we find that the regression-modeled salinity at a given streamflow in the middle part of the century is greater than it is in the early part of the 20th century. We employed slightly different time periods but the results are nonetheless in agreement with those of Haskin (1972). However, our confidence intervals are much larger and suggest no significant change in the salinity-streamflow relationship. This is not surprising given the large scatter of the data shown in Figure 2.

The errors in the salinity-streamflow relationship increase with flow, which likely results from the very infrequent sampling during the winter (Figure 1), when flows are relatively high. Given the few measurements made outside the summer, we focused on the change in salinity for a given change in streamflow (dS/dQ) for the period of greatest data density. We did this by finding the numerical average of the salinity data for each site and computing dS/dQ of the functional fit at this salinity (Table 1). Values of dS/dQ at the five sites range from -1.5 to -2.3 per 100 m^3 s^{-1}, with a mean of -1.8 per 100 m^3 s^{-1} (note that salinity is a unitless quantity).

2.3. Other studies

Salinity in Delaware Bay was described as weakly sensitive to streamflow by Garvine et al. (1992), who estimated a dS/dQ of only -0.57 per 100 m^3 s^{-1} in the upper Bay (Reedy Island Jetty, average salinity = 4.3). Unpublished work by Katz et al. (2010), analyzing the same data set, however, showed a 75% larger sensitivity, with a dS/dQ of -1.0 per 100 m^3 s^{-1} (Figure 4). We believe the difference is due to the fact that Garvine et al. (1992) regressed daily flow vs. (lagged) daily salinity whereas Katz et al. (2009) regressed monthly averages. Wong (1995), regressing climatologies of monthly salinity and flow, also found dS/dQ = -1.0 per 100 m^3 s^{-1} at Reedy Island Jetty. A similar situation exists further downstream in the Estuary at Ship John Shoal (average salinity = 14), where Garvine et al. (1992) found dS/dQ = -0.77 per 100 m^3 s^{-1} based on daily data whereas Wong (1995) found -1.2 per 100 m^3 s^{-1} based on monthly climatologies. A likely

explanation for the weak sensitivity found by Garvine et al. (1992) is that salinity is far from equilibrium with streamflow on short (i.e., daily) timescales.

Figure 5 summarizes our analysis of the sensitivity of Delaware Estuary salinity to streamflow at Trenton. We include the above estimates plus additional estimates at higher salinities from Garvine et al. (1992). For the problem of estimating the response of salinity to climate-induced changes in streamflow, we believe that the equilibrium sensitivity of S to Q is most relevant. This means that the estimates of Garvine et al. (1992) are likely to be too low for this purpose. The remaining estimates of dS/dQ are between about -1 and -2 per 100 m^3 s^{-1}. We are not aware of any studies that have estimated dS/dQ landward of Reedy Island Jetty. The lack of such estimates is unfortunate in light of the importance of this region for human and industrial water use.

2.4. Impact of changing streamflow on salinity

Streamflow projections are highly uncertain in the Mid-Atlantic Region mainly because the precipitation change is poorly known. This, in turn, is due to the fact that the mid-Atlantic lies at the transition region between projected subtropical precipitation decreases to the south and subpolar precipitation increases to the north. Global Climate Models (GCMs) put this transition at slightly different latitudes, leading to great uncertainty even in the sign of projected precipitation change in the Mid-Atlantic Region. The projections lean towards increases, but this will be offset by increased evaporation, making the sign of projected runoff even more uncertain than the sign of projected precipitation. Multi-GCM averages general predict very slight increases (<5%) in annual runoff by the end of the 21st Century (Milly et al., 2008; Milly et al., 2005).

Najjar et al. (2009) surveyed the literature and found a range of -40% to +30% change in annual streamflow for an approximate doubling of atmospheric CO_2. With a mean streamflow at Trenton of about 330 m^3 s^{-1} (Wong, 1995), the change in projected streamflow for a CO_2 doubling is roughly ±100 m^3 s^{-1}. Based on the data analysis and literature synthesis above, dS/dQ is between about -1 and -2 per 100 m^3 s^{-1} and thus we estimate mean salinity changes in the estuary seaward of Reedy Island Jetty of approximately ±1 to 2.

Precipitation (and thus runoff) projections in the Mid-Atlantic Region have greater consensus in winter than summer (Najjar et al., 2009); most models predict increasing precipitation in the Mid-Atlantic Region during winter, when the latitudinal boundary between projected precipitation increases and decreases moves southward. Warming will also result in more precipitation as rain instead of snow during the winter. Furthermore, drought frequency is expected to increase in the summer in the Mid-Atlantic (Hayhoe et al., 2007). Thus it appears likely that the amplitude of the annual cycle in streamflow will increase, which would increase the annual cycle in the salinity of the Delaware Estuary.

Finally, the combination of projected increases in precipitation intensity and the number of dry days per year (Najjar, 2009a) is likely to make precipitation, and thus runoff, more variable in the future on short time scales.

3. Sensitivity of salinity to sea level

Katz et al. (2010) found that, after accounting for streamflow influences, salinity in the upper part of the Delaware Estuary is increasing with time, and suggested that at least part of this increase is due to sea level rise. From the linear trends in salinity residual and sea level anomaly, they computed a salinity change per unit of sea-level rise ($\Delta S/\Delta H$) of 7.1 ± 3.4 m.

Two numerical modeling studies were conducted under low-flow conditions with sea-level rise in order to quantify a worst-case scenario of salt water intrusion in Delaware Bay. 1-D modeling by Hull and Tortoriello (1979) found that the maximum 60-day salinity increase near Reedy Island during a 15-month simulation was 0.38 for a sea-level rise of 0.13 m, corresponding to $\Delta S/\Delta H = 2.8$ m^{-1}. 3-D modeling by US Army Corps of Engineers (1997) estimated a salinity increase of 0.3 at a location 23 km upstream of Reedy Island as a result of a 0.3 m sea-level rise, yielding $\Delta S/\Delta H = 1$ m^{-1}. Thus models predict much smaller long-term increases than have been observed, which suggests that other factors, such as bathymetric changes (e.g., resulting from dredging) may be important.

Sea-level rise make bring other changes in estuarine circulation that affect salinity. For example, sea-level rise will also likely lead to a larger tidal range, a result that has been shown by Walters (1992) for the Delaware Estuary and Zhong et al. (2008) for the Chesapeake Bay. With an increased tidal range, we can expect an increase in the salinity range over the tidal cycle.

4. Summary

Our current understanding of how future climate change may impact the salinity of the Delaware Estuary is poor. We have a weak understanding of how runoff may change in the estuary's watershed on annual, seasonal, and synoptic (weather) time scales. The current literature suggests a tendency for modest increases in annual streamflow and somewhat greater increases in winter streamflow over the 21st Century. The literature also suggests increases in synoptic precipitation variability and intense extratropical cycles (which would increase storm surges) on hemispheric scales though regional forecasts are highly uncertain (Lambert and Fyfe, 2006). All of these factors conspire with the likely increase in the annual streamflow cycle and tidal range to increase variability in estuarine salinity. However, we are far from making quantitative estimates of the change in salinity variability.

Sea-levels are very likely to increase in the Mid-Atlantic Region (Najjar, 2009b), and this is likely (in the absence of other changes) to increase estuarine salinity. However, current estimates of the sensitivity of Delaware Estuary salinity to sea level are know to, at best, a factor of two, and only in the upper portion of the estuary.

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Table 1. Salinity data from Haskin Shellfish Research Laboratory, 1953-1990.

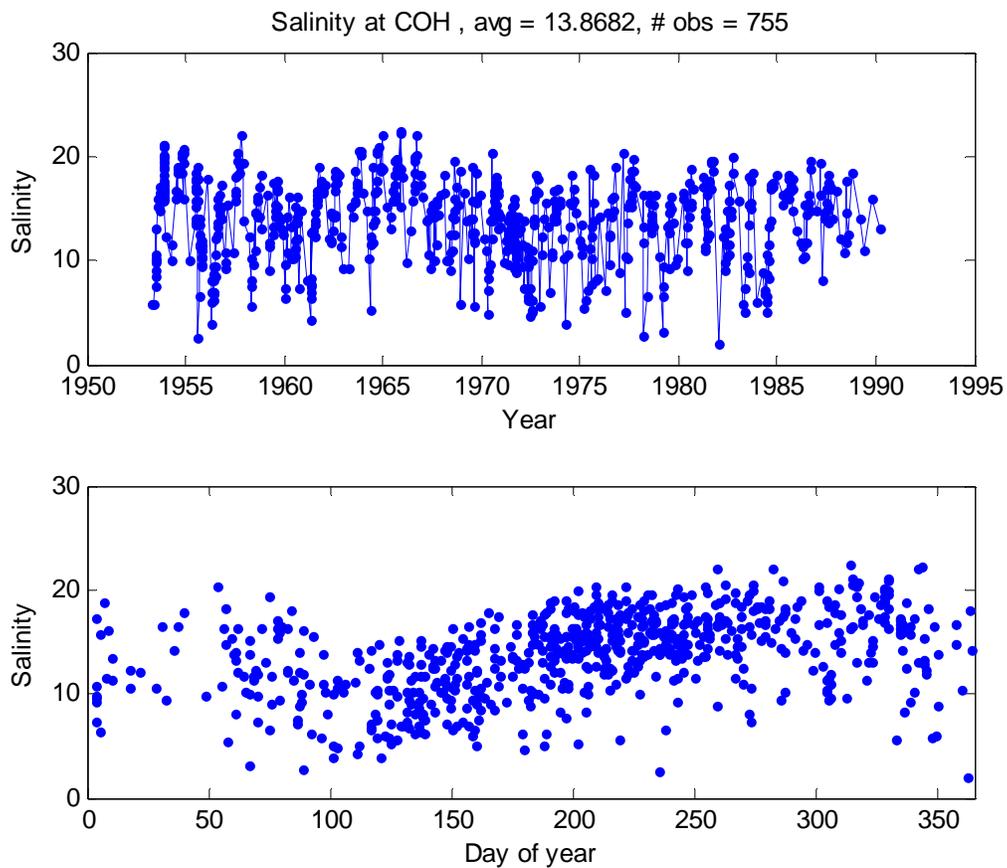| Location	Number of observations	Average S	dS/dQ (per $100 \text{ m}^3 \text{ s}^{-1}$)
Arnolds Bed	455	11.4	-2.3
Cohansey Bed	755	13.9	-1.7
Shell Rock Bed	695	14.9	-1.5
Bennies Bed	573	16.8	-1.6
Miah Maull	480	23.4	-1.9

Fig. 1. Salinity at Cohansey Bed. Top panel show salinity as a function of time between 1953 and 1990. Bottom panel shows salinity vs. day of year.